AC 2010-245: RECONNECTING CHEMICAL ENGINEERING STUDENTS WITH THE PHYSICAL WORLD

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Reconnecting Chemical Engineering Students with the Physical World

Abstract

There is ample evidence of a growing disconnect between chemical engineering students and the physical world. This chasm is being created by social and technological changes; in particular, the proliferation of microprocessor-based “virtual experiences” for children and adolescents has had an inhibiting effect upon their opportunities to explore forces, causal factors, and effects in the real world. Diminished opportunity to physically experience produces diminished ability to perceive. One predictable result is that students in engineering and the applied sciences struggle to critically evaluate their work in problem-solving exercises.

We made initial efforts to address this problem in 2006 and 2009, when we implemented (on a trial basis) a large-scale field experience in which students used a centrifugal pump (with a 5.5 hp gasoline engine) to fill a 325 gallon polyethylene tank. They also explored the discharge velocities achieved by this pump through nozzles with diameters ranging from 0.453” to 1.055”. The success of this activity led us to undertake some significant changes in our undergraduate laboratory experience. In 2010 we added three completely new experiments to the course; these activities (a student-directed experiment with thermoelectricity, a pump performance module, and a fluid flow experiment of unparalleled flexibility) were designed to encourage exploration, to appeal to students with different learning styles, and to promote physical contact between the student and the underlying phenomena. This paper describes our initial experiences with, student reaction to, and our assessment of, these changes to the laboratory course.

Introduction

The childhood environment for the previous generation of engineers was very different. Grose¹ recently reviewed the formative influences upon six accomplished engineering educators; he found active childhood pursuits in airplanes, chemistry sets, dissection equipment, farm equipment, and electronics. These activities are lost to today’s children; the proliferation of microprocessor-based “virtual experiences” for children and adolescents has had an inhibiting effect upon their opportunities to explore forces, causal relationships, and effects in the real world. Indeed, many of the play activities of children of the 21st century are incomprehensible to previous generations. Diminished opportunity to physically experience produces diminished ability to perceive, and in engineering and the applied sciences the consequences can be catastrophic. Zaslow² (Wall Street Journal, October 6, 2005) described the insidious nature of this development when he observed that “…technology has exacerbated the gulf between
today’s parents and kids in ways we need to notice. It’s easier now for kids to function in their own closed societies, leaving them oblivious to adult culture.”

Of course, some aspects of the disconnect we refer to have been apparent for a long time. In a well-known study, McDermott and Shaffer found that “…students often manipulate formulas without relating the algebraic symbols to concepts.” They observed that the “…typical introductory physics course is a passive learning experience for many students” and they also noted that active mental participation can improve learning outcomes for students. This enhanced participation can be difficult to achieve though, because electronic technology has led to pervasive multi-tasking among adolescents, making conventional classroom instruction (the “transmissionist” model described by Finkelstein) even less effective than it was decades ago. Under present conditions, education in the sciences can result in a veneer of technical sophistication coupled with a complete lack of physical understanding, as noted by Wankat and Oreovicz.

Recently, several educators have employed the battery, light bulb, and wire scenario (students are asked to complete a simple circuit given a bare bulb, a battery, and a single piece of wire) to explore the apparent disconnect between instructional objectives and learner outcomes. In a large study, Slater, Adams, and Brown found that just half of science and engineering students in college could complete a circuit with the single wire, battery, and bulb (58.5% of males and 25% of females). We believe that a significant part of the problem uncovered by these studies stems from isolation of today’s students from the physical world. And, our industrial stakeholders tell us that this is becoming a critical problem in the workplace as well. Increasingly they see new hires who are far more comfortable with their computer screen than they are with the actual production process.

In chemical engineering education, this crisis has revealed itself through students’ staggering inability to critically judge their results in problem-solving exercises. The following example consists of a question and actual student response from a recent Transport Phenomena 1 final exam (the student was a junior):

Gasoline is being pumped 17 miles through nominal 3-inch, schedule-40 steel pipe at a rate of 9500 gal/hr. What horsepower will be required if the pump’s efficiency is about 75%?

The average velocity in the pipe: 

\[ \langle V \rangle = \frac{\dot{M}}{\pi R^2} \]

therefore, 

\[ \langle V \rangle = \frac{4571856}{\pi (0.1278)^2} = 8.9 \times 10^7 \text{ ft/s.} \]

\[ \text{Re} = \frac{d \langle V \rangle \rho}{\mu} = \frac{(0.1278)(8.9 \times 10^7)(55)}{(0.56)(6.72 \times 10^{-4})} = 1.66 \times 10^{12} \]
This Reynolds number verifies turbulent flow;

\[ w = g \Delta z + \frac{1}{2} V^2 \frac{L}{f} \]

so, \( \text{power}=1.66 \times 10^{16} \text{ hp.} \)

The student knew what was needed and followed the necessary steps. However, he made a conversion (dimensional) error in the very first step and failed to recognize that his computed average velocity was ridiculously large. Nor was he perturbed by the resulting Reynolds number. The student determined the required power from the macroscopic mechanical energy balance; the result is nine orders of magnitude larger than the combined power of the five F-1 engines of a Saturn V launch vehicle.

The influences that have brought engineering education to this point are many and varied. While it is easy to assign blame to PlayStation, Xbox, or even Wii, the reality is much more complicated. Examine the differences between the engine compartments of two plain Chevrolets: a 2.2 liter four of 2002 (134 CID, about 115 hp) on the left and the 216 CID “stovebolt six” of 1950 (about 90 hp) on the right. Which might allow a novice to repair electrical (ignition) or fuel delivery problems?

![Figure 1. Comparison of engine compartments for two Chevrolets, a 2002 2.2 liter four on the left and a 1950 216 CID six on the right. Photo courtesy of L. Glasgow.](image)

In the previous era it was common to find engineering students with experience in automobile maintenance and repair; such students were already accustomed to diagnosing problems and many were keenly interested in improving the performance of their vehicles. Unfortunately, the complexity of modern machines has made it extremely difficult for an adolescent to learn much about routine maintenance, let alone actual repair.

As the depth of this crisis became clear, we noted that some of the experiments in our first undergraduate laboratory experience were not assisting the affected students in any meaningful way. For example, with the existing fluid flow apparatus we measure friction factors for flow of water through tubes (10 ft long) at Reynolds numbers ranging from about 10,000 to 100,000, and determine the approximate velocity distribution for
flow in a 2 inch ID acrylic plastic tube. Students tend to conduct this experiment mechanically; they derive little benefit from its execution and their conclusions tend toward the banal. Part of the difficulty is that the experiment completely fails to provide a somatic connection between the students and the phenomena associated with fluid motion.

Figure 2. Existing fluid flow apparatus in ChE 535, Transport Phenomena Laboratory. Photo courtesy of L. Glasgow.

The results are of indifferent quality and apparatus itself offers little flexibility as to procedure; both the execution and the outcome are tightly constrained. These features do not allow the student to see the uncertainties and complexities that arise in engineering applications in the physical world. Most of the experiments that we use in the first chemical engineering laboratory experience fit this very same pattern. They are precisely the type of experiences that Sheppard et al.\textsuperscript{7} have called into question.

**The Initial Effort: A Field-Scale Experience in Water Transfer by Pumping**

Drawing inspiration from L. Ford’s\textsuperscript{8} description, we decided to explore possible benefits of an experiment in which the connection between the student and the physical world was both immediate and intimate. We asked volunteers (35 total participants) to consider the operation of a 2x2 inch, 5.5 hp centrifugal pump rated at 200 gpm with 10 ft head. They were to examine the discharge through constrictions (left) and through 25 ft of 1.5 inch diameter hose (and into a tank, right).
Among the questions posed for student exploration were:

- What is discharge rate for these flows?
- What is the discharge velocity?
- Can one person hold the discharge hose?
- Is the pump meeting its rated capacity?
- Can we estimate the pump efficiency? How?
- How many horsepower are actually being used to move the water?

The student-directed activity was initiated by trading pressure for kinetic energy; the pump’s discharge was routed through different discharge fittings (nozzles).
Figure 6. The discharge velocity can be estimated from both the horizontal distance traveled by the jet (from an initial height, $h$, of 5.83 ft) and from the macroscopic mechanical energy balance (using kinetic energy, pressure, and loss terms). The two relations are shown below. Photo courtesy of L. Glasgow.

$$V_2 = L \sqrt{\frac{g}{2h}}$$  
$$V_2 = \sqrt{\frac{2g_e (P_1 - P_2)}{\rho(1+e_v)}}$$

(1a and 1b)

The data obtained allowed the students to compare the experimentally-measured velocities with those calculated using the mechanical energy balance (MEB); the table shown below contains student-generated data and velocities computed with equations (1a) and (1b).
The students also tested the pump delivery rate by discharge into a tank. 

Figure 7. Students are shown filling a 325 gallon tank through 27 ft of 1 ½ inch hose. The measured flow rate was 96 gpm. The same experiment was carried out using 51 ft of 2 inch hose and the delivery rate was found to be 164 gpm. MEB calculations for the latter case show that only about 2.5 hp (assuming $\eta=70\%$) should be required for the transfer. Photo courtesy of L. Glasgow.

The students also drained the tank; they found experimentally that the initial rate of discharge was about 130 gpm with a total time of about 7 minutes required to “empty” the tank by gravity. Torricelli’s theorem, $V_0 = \sqrt{2gh}$, indicated that the initial flow rate should be about 150 gpm. This scenario was used later as a quiz problem in the lecture.
course and the student success rate was very high among the participants in the field exercise.

Each student was asked to complete a questionnaire following the field activity; the responses were compiled and evaluated and some salient findings are highlighted below.

- 82% of the students had not operated a pump to transfer water.
- 75% of the participants had seen the Bernoulli equation in engineering physics, but most noted that they had not used it for any “real” purpose. Consequently they saw little or no connection between the equation and pump operation and discharge.
- 70% of the participants noted that they enjoyed the opportunity to learn outside of the classroom; many observed that the experiential nature of the exercise was useful to them.
- 50% of the students reported that the measured water velocities corresponded to their expectations. But the other half admitted that they had no idea what the water velocities would be either in the 2 inch hose or through the constriction.

Typical Participant Comments:

“Wow, that was fun. Low stress, and we just got to learn.”
“I really enjoyed the experiment because seeing a topic in the real world augments my enthusiasm.”
“I think you should really encourage students to do this. It’s really easy to get caught up in the book and calculator part of fluid flow and forget about the actual physical, wet part of it.”
“This was a great experiment because it allowed everyone to get hands-on experience.”
“Just a small pump can move a lot of water fast! Lawn mowers are almost that size and what they do is not as impressive.”
“I enjoyed an afternoon with practical application and not just book work.”
“The most interesting thing I learned was the actual complexity of the emptying-tank problem. I had never really considered a horizontal cylindrical tank as it empties and the changing surface area at the top of the water.”
“It was a very useful exercise to gain real-world experience and perspective.”
“I liked actually seeing the nozzle size and the relation to the velocity escaping the hose.”
“I was shocked to learn how much the surface roughness affects the jet distance. The steel pipe felt pretty smooth but its distance was greatly shorter than the PVC.”
“I enjoyed getting the practical experience and being able to actually see the types of things that we’ve been discussing in class. It was interesting to compare the pump’s rating against its actual performance.”

One Measure of the Effectiveness of the Field Exercise

Of course, evidence gathered from a single experience with a limited number of test subjects can only be regarded as anecdotal. Nevertheless, a final exam question was
designed for ChE 530 (Transport Phenomena 1) to see if the field activity had any discernable impact upon the students’ ability to critically assess their results.

A centrifugal pump with a motor rated at 5.5 hp was used to fill a 325 gallon polyethylene tank. The tank was filled in 3.43 minutes, meaning that the average delivery rate was about 95 gpm. The water temperature was only 39 °F, so the viscosity of the water was 1.58 cp. The water was pumped from a pond, through a 1 ½ inch PVC manifold (with valve), and then through about 27 ft of 1 ½ inch hose. There was a change in elevation (+) of about 11 ft. If the pump efficiency was 75%, what power (hp) was actually required?

Four classifications were used to characterize the 38 responses:

1. Problem was accurately worked 49%
2. Problem worked with minor numerical error(s) 27%
3. Fundamental conceptual error occurred 11%
4. Major numerical error was undetected 19%

The fractions of students in categories 1 and 2 were significantly higher than achieved with similar problems in recent years. The fraction reported for 4 was lower, in accord with one of our objectives. Our initial experiences with this field activity were first reported by Glasgow.

Improving the Laboratory Course

The field experience described above was successful and it exceeded our expectations on every level. Consequently, we decided to make fundamental changes to our laboratory course, ChE 535. We obtained a grant through the NSF-CCLI program (now TUES) at the beginning of 2009 to implement several new laboratory activities designed to: promote visual and tactile learning, provide a more intimate connection between the student and the physical phenomenon, and introduce some of the complexities (ambiguities) of “real-world” engineering. In particular, we utilized the work of Feisel and Rosa along with the ABET-sponsored colloquy of 2002 (funded by the Sloan Foundation) to formalize our objectives. Four are absolutely central to the changes implemented in ChE 535:

Experiment. Devise an experimental approach, specify appropriate equipment and procedures, implement those procedures, and interpret the resulting data.

Data Analysis. Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments.

Creativity. Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving.

Sensory Awareness. Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.
The first of the new experiments is an investigation of thermoelectricity; we managed to get the preliminary version of the activity ready for an inaugural trial in the spring semester of 2009. The experiment (entitled, *An Engineering Investigation: Evaluation of Thermoelectric Modules*) is set before the student in a “nontraditional” way (lacking explicit directions) and the presentation is provided in the appendix.

**Student Perceptions and Assessment**

At the end of the spring semester in 2009, we administered an assessment instrument to all of the students completing ChE 535; we sought to determine whether the thermoelectric module was an effective step towards our objectives. Half of the questions posed were designed to reveal the students’ impressions of their personal learning style. 95% of the participants thought tactile strategies helped them understand concepts and 95% thought that the exploratory strategy of the thermoelectric experiment was an aid to their understanding. However, 60% of the students indicated a strong preference for instructor-directed activities; only 36% favored a student-directed model. This finding is of concern to us and it is indicative of one aspect of the problem that we are trying to address. Of course, it may also be related to one of the common characteristics of chemical engineering students; i.e., they tend to be very goal-oriented with a sharp focus on academic achievement.

Nevertheless, the written responses to the question, “What was the most engaging feature of the experiment?” were encouraging, and some samples are provided below:

“The opportunity to take a real-world problem and try to solve it as a team of engineers.”

“The most engaging part of the experiment was designing the experimental procedure.”

“Being able to come up with our own plan of action and testing it to see if it was effective.”

“The most interesting feature of the experiment was how it tied to a major concern in the world today—recycling waste energy. The fact that we were able to evaluate a possible solution for recycling thermal waste energy was very interesting.”

“Just that we got to do a procedure that we came up with. Made us think of different ways we could run the experiment. The real applications—trying to find ways to test the efficiency using real physical things, not just saying it works or it doesn’t based on a graph.”

“This experiment forced us to draw on past experiments to determine the best method of determining the amount of heat transferred through the device. The fact that the experiment forced us to think back on this and other transport concepts was a strong learning feature.”
Full implementation of the changes made to ChE 535 will occur in the spring semester, 2010. All of the juniors will perform the revised thermoelectric experiment as well as two new fluid flow experiments. A complete assessment of the results will be performed at the end of the semester, and we should have a much clearer picture of the effectiveness of the new experiences by mid-summer, 2010.

Conclusions

The activities described here promote the development of physical reasoning through implementation of practical, somatically-rich learning experiences. The importance of this approach cannot be over-emphasized. Many students who select engineering as a course of study do so because they are visual and tactile learners. Yet their opportunities to use these learning styles have been compromised by recent technological developments; the problem has been compounded by the inability of traditional engineering education to cope with the disconnected student. Weith recently noted that tinkering—seeing with your hands—is crucial to the development of engineering creativity. We would add that “tinkering” on a physically-relevant scale can help reconnect engineering students with the larger world and promote the development of engineering judgment (of course, this also contributes directly to their ability to critically evaluate results in problem-solving exercises).

The results that we obtained from the trial program in 2006, and from our experiences in ChE 535 in 2009 and 2010, are encouraging. We have acquired anecdotal evidence that these efforts can help with the reconnection of engineering students to the physical world around them. We should have a much more complete picture of the results of our efforts at the end of the spring semester (June 2010). At the same time, we recognize that a few isolated experiences (whatever their intrinsic value) cannot possibly achieve all of the desired goals. We would like to develop an expanded program of activities that will reach beyond ChE 535 to include our underclassmen as well; we envision a sequence of activities for freshmen, sophomores, and juniors to achieve reconnection and exploit (longitudinally) the advantages of somatically-enriched contextual learning.

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Literature Cited

Appendix:

An Engineering Investigation: Evaluation of Thermoelectric Modules

Introduction

Let’s begin by thinking about the usual flux-driving force pairs that we study in transport phenomena.
Note that the familiar gradient transport mechanisms are shown in **boldface** on the diagonal. Of course, we can use a velocity gradient to transport momentum (*Newton’s law*) or a temperature gradient to transport heat (*Fourier’s law*). But there are other couplings we might wish to consider as well. For example, we might seek a connection between thermal energy and electricity (*Peltier or Seebeck effects*). This would be particularly attractive for processes that generate large amounts of waste heat.

Very recently, Casten and Schewe (“Getting the Most from Energy,” *American Scientist,* 97:26, 2009) reviewed progress in the overall energy usage efficiency for the United States. They noted that in coal-burning power plants, only 30 to 35% of the heating value of the fuel is converted to electricity. Many processes are worse; for example, only 5% of the energy supplied to an incandescent lamp is converted to light. Overall in the U.S., every Btu of power (useful work) is accompanied by 7 Btu’s of waste heat. This profligacy is neither desirable nor sustainable. Casten and Schewe note that in the U.S., recycled energy is only 8% of the total energy used, while in Denmark that fraction is greater than 50%. They point out that even the small-scale recovery of waste energy—if applied to a very large number of systems—could be significant.

**Historical Perspective**

In 1821 Thomas Johann Seebeck found that if two dissimilar metallic wires were soldered together to form a loop and then exposed to a temperature gradient an electric current was generated. Independently, Jean Charles Athanase Peltier discovered that if a current was applied to this loop one junction would cool and the other would warm. This phenomenon is known as the Peltier-Seebeck effect (or the thermoelectric effect) and is the basis for both thermocouples and thermoelectric devices. Examples of historic thermoelectric devices can be found at [www.dself.dsl.pipex.com/MUSEUM/POWER/thermoelectric/thermoelectric.htm](http://www.dself.dsl.pipex.com/MUSEUM/POWER/thermoelectric/thermoelectric.htm).

Modern thermoelectric devices use p and n-type semiconductors (such as Bi₂Te₃) rather than dissimilar metals. Because of their ruggedness and longevity, these devices are commonly used in applications where unattended operation in remote locations is required, both terrestrial and extra-terrestrial.

For example, thermoelectric devices have been employed frequently in the space program. They have been utilized by NASA (as well as the former U.S.S.R.) since the
1960’s, and thermoelectric power was used in the Apollo, Viking, Pioneer, Voyager, Ulysses, Galileo, Cassini, and Pluto New Horizons missions. The Voyager spacecraft, launched in 1977, are still functional and have reached the outer edge of our solar system. The Apollo missions used the SNAP-27 radioisotope thermoelectric generator as highlighted below. A similar system will be used to power the Mars Science Laboratory, the next generation of Mars Rover, which will launch in 2011.

![Figure 2: A display in the Smithsonian National Air and Space Museum describing the SNAP-27 module used in the Apollo missions. To zoom in and read the text, visit the course website. Photo courtesy of L. Glasgow.](image)

The Scenario

We know that internal combustion engines discard large quantities of thermal energy to the surroundings. In fact, typical exhaust temperatures for an automobile are on the order of 1000 °F (at the exhaust manifold). In an era in which efficiency is critical, it makes sense for us to try to recover some of this energy. If we could convert that large $\Delta T$ into electricity, we could use it to recharge a battery, provide lighting, or even run an electric motor. One might imagine building a hybrid automobile with improved fuel efficiency. Let’s obtain a semi-quantitative picture of the amount of energy available. Suppose we write

$$Q = hA\Delta T.$$ 

We plan to exchange heat between the exhaust manifold and the ambient air, and we assume $T_\infty = 100$ °F. Ducting will carry the air from the front of the vehicle to the exchanger. We estimate the available heat transfer surface area at about 1 ft$^2$ (is this reasonable?). We select an arbitrary value for the heat transfer coefficient, say 100 Btu/(hr ft$^2$ °F); although this is too large to be realistic, we find
Q = (100)(1)(900) = 90,000 Btu/hr.

This rate of heat transfer corresponds to about 35 hp or 26 kW. If this were realizable we would not need much of an IC engine at all! However, it is likely that $h$ would be no more than 10% of the value used above; this still corresponds to 3.5 hp or 3 kW which is a significant fraction of the power required to propel a small car at freeway speeds.

**The Experiment**

Thermoelectric devices are commercially available; see the photos provided below. If we transfer heat through one, we can obtain electrical energy. Our task is to figure out if this is practical in automotive applications. **What must we be able to measure in order to assess this?**

Figure 3. Hi-Z™ thermoelectric device, with the “cold” side shown on the left and the “hot” side shown on the right. Photos courtesy of L. Glasgow.

Inspect the available equipment items. We have a heat source, a heat sink, the thermoelectric device, ceramic isolators (why?), special thermal grease (why?), and some elementary DC circuit components.

It should be obvious to you that intimate thermal contact between the heat transfer surfaces is crucial. In fact, Hi-Z™ recommends installation with a compressive load of 200 psi utilizing a $\Delta T$ of about 200 °C. We are not able to meet these exact criteria with our apparatus, but we can still make the required evaluation. We are able to examine, to a limited extent, the effect of changing the compressive load on both the heat transferred through the device and the power obtained from the device. For the springs used in our apparatus, $k = 14$ lb/in and $x_0 = 1.44$ in (or 3.65 cm).

A critical objective: We must be able to estimate the rate at which heat is transferred through the thermoelectric device. In fact, figuring out alternative means to accomplish this is an important first step. **How might this be done?**
We must also be able to estimate the rate at which power is generated by the device, given a known thermal transfer rate. Therefore, we need to know the difference between open circuit voltage and load voltage, how such voltages are measured, and how power, amperage, and resistance are measured.

To obtain maximum power from a thermoelectric module the load resistance must be closely matched to the internal resistance of the module, which is a function of temperature. A procedure for determining the internal resistance of the module can be found in the manual “Use, Application and Testing of Hi-Z Thermoelectric Modules.”

Optimally, we would like to determine the ratio: \( \frac{\text{power obtained from device}}{\text{heat transferred through the device}} \). We have to evaluate whether or not the achievable efficiencies warrant automotive installations (while this will not be a cheap modification, there are no moving parts so longevity should be good).

Inspect the available equipment, formulate a plan of action, and discuss the problem and your approach with the instructor. Carry out the investigation and obtain the data you need for your evaluation.