STUDENTS LEARN WITHOUT LECTURES:
Scaffolded Problem-Based Learning in an Applied Fluid Flow and Heat Transfer Course

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Active learning encompasses many teaching methods where students participate in meaningful learning activities and are engaged in the learning process.[1] Active learning

- *Increases the percentage of students who understand concepts*[1]
- *Improves long-term retention of the material*[2]
- *Has been linked to more enjoyment of the course and higher graduation rates*[3]
- *Leads to increased confidence*[4]

Problem-based learning (PBL), a type of active learning, provides students with a real problem to solve, and this problem drives the learning.[5] A relevant problem is introduced at the beginning of an instruction cycle and is used to provide context and motivation for the students to learn.[1] The problem is open-ended, ambiguous, and has many possible solutions. PBL has been shown to

- *Increase students' problem-solving and critical thinking skills*[6,7]
- *Increase students' conceptual understanding*[8] *and knowledge retention*[1]
- *Develop more positive attitudes*[1] *and a deeper approach to learning*[5]

Trade-offs exist when using PBL in the classroom. For instance, PBL emphasizes in-depth inquiry over coverage, so some content must be omitted. Thus, the problems must be designed to cover the core fundamentals in the course. However, since the students are better equipped to be lifelong learners this is usually not a problem—the students are able to learn on their own.[5]

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Lehigh Valley natives love A-Treat soda. It has been a valley favorite since 1918, and when the plant abruptly closed in January 2015, the soda, especially the orange cream flavor, became a big seller on eBay. The soda proved to be so popular that in August 2015, The Jaindl Companies purchased the A-Treat brand, and The Coca-Cola Company began to bottle the soda. Ten flavors are now available (Orange Cream, Black Cherry, Birch Beer, Cream, Big Blue, Ginger Ale, Sarsaparilla, Orange, Root Beer, Grapefruit and Diet Cream), much to the delight of locals

But – the old bottling facility in Allentown is sitting empty and unused. What can be done? Last summer, I had a bumper crop of tomatoes, and developed a prize-winning ketchup recipe. Can I use a facility that used to bottle soda, and use it to bottle ketchup?

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http://eastpenn.thelehighvalleypress.com/system/files/styles/imported/private/2015/08/06/20150806-145124-pic-839875230.jpg?itok=wMqIpJ-1

A quick look inside the plant provided this information:

Storage tank dimensions:	1.2m in diameter by 1.7m high
Elevation from pump to top of line:	3m
Elevation from top of line to bottle filling opening:	-0.5m
Pipes:	1 inch Sch 40
Total pipe length:	50m

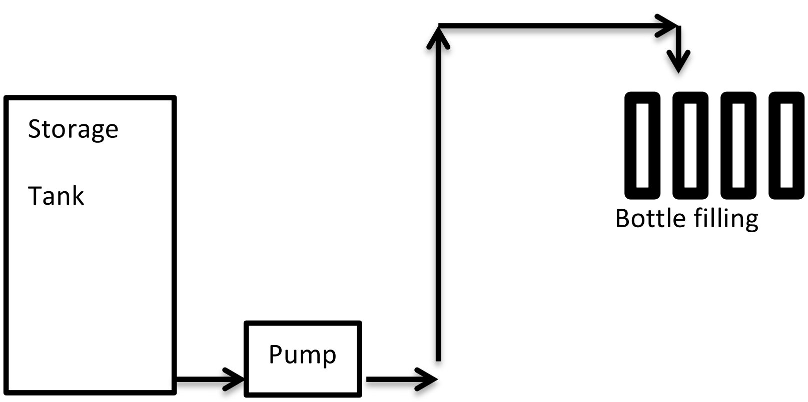

Figure 1. *PBL Problem Statement for Module 1.*

Scaffolding, or providing learning support for the students in some way, can influence the success of learning from PBL.[9] Scaffolding can help reduce the mental effort in remembering and combining several concepts and provide guidance along the way. This trains students to think as disciplinary experts.[10] Providing models of "expert" solutions or sample structures for solving complex tasks are typical examples of scaffolding. While scaffolded PBL is most common in medical schools, it has been applied in an engineering classroom.[11]

This paper will describe two modules developed for an applied fluid flow and heat transfer course. Each module contains a PBL scenario surrounded by active-learning exercises. The students began each 3-week module with a familiarization exercise. During the next class period, one member of each PBL "home" group learned a subset of the material in a "subject" group, and then returned and taught the material to the "home" group during a jigsaw activity, which provided the scaffolding for the PBL. Outside of class, each group performed a laboratory experiment. The modules concluded with a gallery walk, where each group showcased a poster describing their final solution or information on various equipment types. Combining the multiple modes led to equivalent student learning with minimal instructor lectures.

THE COURSE

"Applied Fluid Flow and Heat Transfer in Food Engineering" is a third-year course taught to 15-20 chemical engineering students who choose a nontraditional applied fluid flow and heat transfer course option. The same instructor taught a traditional course to the remaining 15-20 third-year students. All students had completed a theoretical transport phenomena course the previous semester. Both courses meet twice a week for a 1-hour period and once a week for a 2-hour problem-solving period, use the same textbook,[12] and have the same student-learning objectives. Each of the projects described in this paper was assigned over a 3-week period. The learning objectives were used as the basis to develop the projects.

As in most applied fluid flow courses, the mechanical energy balance is a central theme. Many courses have an accompanying laboratory where students pump water through a loop and measure pump power, head, and efficiency. However, many fluids—and most foods—are non-Newtonian, and pumping these fluids can be significantly different from pumping water. The first PBL scenario was designed to illustrate the differences.

Heat exchanger design is the second major concept for the course. Again, students often operate a heat exchanger in an accompanying laboratory course, and learn to calculate heat transfer coefficients in the different configurations. The PBL scenario for this module required students to choose a type of heat exchanger and size it for an ill-defined system.

TABLE 1
PBL Learning Objectives for Module 1

Learning Objectives: At the end of the project, the students will be able to
Explain how a non-Newtonian fluid's viscosity is characterized
Describe how a pseudoplastic fluid behaves when sheared
Discuss why different pump types are used for non-Newtonian fluids
Create a pump characteristic curve
Explain the difference in the curves for Newtonian and non-Newtonian fluids
Compare friction losses for the two types of fluids
Apply the mechanical energy balance to various pumping situations for both Newtonian and non-Newtonian fluids.

PROJECT 1: MECHANICAL ENERGY BALANCE

An effective project for PBL should be realistic; scenarios familiar to the students are especially successful.[10] In this project the students determined if a recently abandoned local soda-bottling factory could be used to bottle ketchup. The problem statement is shown in Figure 1 and the learning objectives are summarized in Table 1.

The students participated in a ranking exercise on the first day of the module for the familiarization component. Groups were provided with toothpicks, popsicle sticks, and small containers of 10 fluids, such as mayonnaise, olive oil, corn syrup, and ketchup. They poked, stirred, and poured them, and then ranked them in order of increasing viscosity. Each group put their list on the blackboard to compare rankings. A discussion on non-Newtonian viscosity followed.

The next class period introduced the PBL scenario. After reading the problem statement the groups spent about 10 minutes brainstorming questions they had about the process and the project, and what information they would need to complete it. No formal lecture was given in class, but links to relevant information were provided and the instructor circulated around the classroom, answering some questions. While a simple schematic of the pipeline system was provided on the handout, the problem statement was intentionally ambiguous. Each group developed the pipeline schematic based on its own ideas (for example, the number of elbows needed and the type and number of valves likely to be in an old factory) so each solution was different.

That same day students next participated in a jigsaw activity, where one person from each "home" group joined to form an "expert" group on a topic. Each expert group completed a worksheet on one of three topics: Bernoulli equation applications, friction loss calculations, or power law fluid characterization. The worksheets are designed to build upon what students learned the previous semester, by asking both descriptive and quantitative questions. They then lead the students through the material in the textbook, requiring them to apply the equations to a practical but straightforward problem. As an example, the worksheet for the power law fluid group is shown in Figure 2. The worksheets provide more structure than is usually present in PBL activities, but the scaffolding they provide can increase the success of the students.[9,10]

After 45 minutes in the expert groups, the students returned to their home groups and taught what they had learned to the other members. The instructor circulated and listened to the explanations, ensuring that the material was communicated correctly. During the remaining class periods, the students worked on the projects in their groups while the instructor listened to the discussions, interjecting only when necessary.

The experiment was done in the midst of the PBL, outside of class. Four concentrations of xanthan gum in water (a power law fluid substituting for ketchup) were provided. First, the students used a Model DV-II + Pro Viscometer Brookfield viscometer to characterize the solutions' viscosity, placing 400 mL of the solution in a 600 mL beaker and noting the apparent viscosity at spindle speeds from 20 to 200 rpm. All experiments were conducted at room temperature, which remained at 23 – 25 C. Next, the students created head versus capacity curves for a small centrifugal pump and capacity versus power supplied curves for a small diaphragm pump. Collecting the data took about 3 hours. Supplies and equipment were purchased online for about $200. A detailed procedure and typical results from the experiment have been published.[13]

On the final day of the project the students participated in a Gallery Walk. During the first 25 minutes of class, the students used markers and Post-It poster paper to describe the main elements of their solution: could the soda bottling factory be used to pump ketchup? The students had some time to read each poster, and then the groups explained their projects during the final 20 minutes of class.

Student learning

Using multiple types of delivery modes in the classroom generally leads to more learning.[14] In this module students learned from five different types of presentation activities. After each exercise, the students were given time to reflect and note what they had observed and learned, an important component for learning.[15]

The students had used the Brookfield viscometer to characterize the viscosity of 10W30 motor oil the previous semester. They determined it was a non-Newtonian fluid, but most had not thought deeply about what that meant. During the ranking exercise, as they poked and stirred various fluids, they recognized that some fluids became easier to move the faster they were stirred. Ranking the fluids was not an easy task—and there was no unique solution—but they were able to categorize the fluids into groups. This led to a discussion of apparent viscosity, and shear rates present in pipes and pumps, which are important when pumping non-Newtonian fluids.

During the jigsaw activity the next day the students were fully engaged in learning the material assigned to them. Their strong theoretical background from the transport phenomena course the previous semester made it possible—they were not beginning learners.[1] Using their textbook and the handouts provided, they figured out how to set up and solve applications of the Bernoulli equation and calculate friction losses in a typical system. The third group learned how to characterize a power law fluid, and how to adjust the Reynolds number and friction factor equations for these fluids. As the students returned to their home group the professor circulated and eavesdropped as each student taught the other students what he or she had learned. The professor carefully corrected the few misconceptions. The method of instruction appeared effective as the students completed a final problem encompassing all concepts before they left the classroom.

While the experiments were completed outside of class time, the students continued to interact with the instructor when they had questions. For example, they were familiar with the operation of the Brookfield viscometer, but the analysis of a power law fluid was new. The equation for the apparent viscosity of a non-Newtonian fluid (η_{app}) as a function of shear rate ($\dot{\gamma}$) is

$$\eta_{app} = K\dot{\gamma}^{n-1} \tag{1}$$

where K is the flow consistency index and n is the flow behavior index. During the jigsaw exercise, the students used this equation to determine the parameters for mustard by plotting the natural log of the apparent viscosity as a function of the natural log of the shear rate. The indices can be found from the slope and intercept. As part of the experiment, they created the plot for the xanthan gum solutions and determined its parameters. They recognized that the fluid was shear thinning because the flow behavior index was less than 1.

After completing the pumping experiments, the students clearly recognized that the centrifugal pump had more trouble pumping the viscous solutions, and could explain why. They expected similar results for the diaphragm pump. When the results were different than they expected, the students contacted the instructor complaining that the pump wasn't working. Instead of answering their questions, the instructor reminded them of the literature that had been provided. Eventually, the students understood their results.[13]

Creating a poster requires students to prioritize their results, an important step in learning. One group had sketched out a plan for their poster before coming to class, but the markers and large Post-It sheets were not provided in advance. Students were actively engaged in debating which information to include on the posters. During the quiet gallery walk, students read the posters and wrote down questions they had while comparing others' work with their own. Each group then presented a 3-minute pitch for their poster and answered questions from their classmates. Their comfort in using the new vocabulary—shear thinning, flow characterization index, diaphragm pump, etc.—was evident while listening to their presentations. Through the gallery walk, it was clear that

Exploring Non-Newtonian Fluids

During the Brookfield Viscometer lab last semester, you found that the 10W30 and 10W40 motor oils were non-Newtonian fluids, and followed the Arrhenius equation as the temperature changed.

What determined that the motor oils were non-Newtonian?

Ketchup is a non-Newtonian fluid. What properties of ketchup do you think cause this?

What additional information about ketchup would be helpful to answer this?

How do you think the flow and pumping of non-Newtonian ketchup will differ from the flow and pumping of Newtonian soda?

Skim pages 47 – 52 and answer the following questions.

The viscosity of a power law fluid differs from a Newtonian fluid by:

The equation for a power law fluid is:

where *n* is ________________________ and *K* is ______________________________

Sketch a plot of the behavior for a power law fluid with n < 1 on the graph below.

Apparent

viscosity

Shear rate

The viscosity of store brand mustard at room temperature for a range of spindle speeds was measured using the Brookfield Viscometer, and the data is shown below.

Spindle Speed	Apparent Viscosity		Spindle Speed	Apparent Viscosity
RPM	cP		RPM	cP
20	5760		90	1898
30	4480		100	1800
40	3410		105	1741
50	2960		120	1703
60	2500		140	1446
70	2549		160	1322
80	2190		180	1198
90	1898		200	1166

1. You want to see if the behavior can be modeled by a power law equation. What steps would you perform on the data?

2. Literature values for mustard provide a flow behavior index of 0.25 and a flow consistency index of 42000 cP min^n. Does our data seem to fit these values?

Skim pages 51 – 56 in your textbook and answer the following questions.

If mustard is flowing through a pipe, would the Reynolds number be larger or smaller than a Newtonian fluid with the same apparent viscosity?

How would friction losses be affected?

Would the pressure drop be larger or smaller?

Write the important equations below, and be prepared to explain their use to your group members.

Figure 2. *The worksheet provided to the non-Newtonian fluid expert group.*

TABLE 2
Assessment Results for Module

Assessment Question	Average Score	% of students with score above 75%
1. If you needed to pump honey, what type of pump would you use? Why? Why are centrifugal pumps not used for highly viscous liquids? Sometimes, however, a centrifugal pump is perfect for a shear thinning liquid—why might this be?	95.0%	92%
2. Barbecue sauce is a non-Newtonian liquid. At 20 rpm, its measured viscosity is 75.2 Pa s, and at 90 rpm, its viscosity is 20.5 Pa s. Estimate its flow behavior index and characteristic viscosity in SI units.	85.4%	85%
3. A chemical plant needs to pump 100 L/min of ethanol from the bottom of a storage tank, open to the atmosphere, to a packaging plant according to the diagram below. The ethanol has a density of 700 kg/m^3 and a viscosity of 0.8 cP. What power is needed for the pump if it is 70% efficient? The same chemical plant is being used to pump a shear-thinning liquid with K = 2 Pa s and n = 0.7 and the same density. What power is needed now?	91.5%	89%
4. Sketch a plot of pump capacity as a function of viscosity for both centrifugal and positive displacement pumps.	84.6%	85%
5. The efflux tank is filled with a shear-thinning liquid. At time = 0, the plug is removed and the fluid starts to exit the tank. What happens to the shear rate during the first few seconds? What happens to the viscosity?	87.2%	77%

the groups had met the learning objectives stated in Table 1.

TABLE 3
Assessment of Project for Module 2

Learning Objective	Method of Assessment	Average Score (Range)	Comments
Describe the main types of heat exchanger equipment, and when each is used	Gallery Walk		Posters were clear, and students answered questions correctly.
Summarize the procedure for making cheese and the purpose of each step	Making mozzarella in class		At each step during the process, students were asked why the step was necessary, and what temperature was required. They then provided the next step.
Design a pasteurizer with integrated heat exchange	Project Report	92% (87 – 98%)	Pasteurizer was designed correctly, but many groups forgot to size the holding tube.
Design a heat exchanger, making logical decisions based on limited data	Project Report	89% (78 – 98%)	Most students chose logical plate parameters, and calculated the necessary number of plates and resulting flow rate correctly. Utility calculation was also correct.
Collect data and estimate the specific heat of a liquid	Project Report	94% (87 – 99%)	Students who used the derivative to estimate the specific heat earned higher scores.

Assessment of learning

Table 2 lists the assessment questions and scores from an exam following the PBL module, to measure individual student learning. The questions are listed in order of increasing difficulty according to common definitions of Bloom's Taxonomy levels. As might be expected, the average scores generally decrease with level of difficulty, as does the percentage of students who scored above 75%. However, even as the numbers decrease, the average score is nearly 85% or higher for all questions, and a large majority of the students scored above 75%. The students learned the concepts, even though no formal lectures were provided on the material.

Some similar questions were given to the parallel section of the class taught in the traditional way by the same instructor. The average score for question one (pumping honey) was 91.3%, with 91% of the students scoring over 75%. The ethanol pumping question (number 3) had an average score of 91.7%, and 100% of the students scored above 75%. The scores in the two class sections are not statistically significantly different, as has been shown in other studies.[1]

PROJECT 2: HEAT EXCHANGER DESIGN

The second project focused on heat exchanger design. The students were asked to design two heat exchangers: one to pasteurize milk, and one to warm milk to a specific temperature. The learning objectives are shown in Table 3. The project was tied to a local dairy, Klein Farms, which produces and sells raw milk and a variety of cheeses (see Figure 3 for the problem statement). As the familiarization components, the students read how different cheeses are made and drew process flow diagrams (PFDs), while snacking on cheeses from Klein Farms. The second day, they used the process they had outlined on their PFDs to make mozzarella cheese in class using a simple recipe.[11, 16]

Pasteurization and cheese making both require heating milk to a specific temperature and holding it for a certain time. This concept was integral to the implementation of Project 2. The Klein family was eager to participate in the project, and invited the class to visit the farm, and watch them make a batch of cheese. Each batch heats 100 gallons of milk in a kettle—a scale up factor of 100 compared to the cheese they made in class. As the students watched the process, the Kleins answered the students' questions, and verified the process students had read about and followed in class. The students were also offered a taste of the fresh cheese.

Project 2 required the design of two heat exchangers so Klein Farms could scale their process to 500 gallons, where a kettle would no longer be efficient. Students needed to choose a type of heat exchanger for pasteurization and for cheese making, and determine the design parameters. The instructor provided equations for the density and viscosity of milk (generally a Newtonian liquid) as a function of temperature.[17]

The remaining experiential learning activities in this project included a jigsaw activity with worksheets to recall how to calculate individual and overall heat transfer coefficients, an experiment to determine the specific heat capacity of milk, and a gallery walk to show different types of heat exchangers.

KLEIN FARMS
DAIRY & CREAMERY

Project 2: Milk to Mozzarella

Klein Farms has decided to increase its output of mozzarella cheese, because it is so delicious. Currently, the cheese is heated in kettles, and stirred gently. Increasing the output will require a heat exchanger. They have contracted with your firm to design it. Currently, a batch of cheese uses 100 gallons of milk, and they plan to scale up to 300 – 500 gallons.

The best mozzarella cheese is made from raw milk, however, in order to sell the cheese, the milk must be pasteurized. You will also design the pasteurizer for Klein.

In your report, include a list of references you used to create your design.

Deliverables, due on 3/11/16:

Pasteurizer Design	100 points
• General design	15
• Milk temperature profile	20
• Area and dimensions	20
• Milk flow rates	
• Steam, hot water and/or cooling water flow rates	10
• Individual and overall heat transfer coefficients	30
• Material of construction	5
Mozzarella Heat Exchanger Design	60 points
• General design	10
• Milk temperature profile	
• Area and dimensions	20
• Milk flow rates	5
• Steam, hot water and/or cooling water flow rates	5
• Individual and overall heat transfer coefficients	20
• Material of construction	
Experimental Determination of Heat Capacity	40 points
• Data collection	10
• Calculations	30

Figure 3. *PBL Problem statement for Module 2.*

During the module, brief lectures (10 minutes) provided an introduction to pasteurization, and two methods to design heat exchangers (log mean temperature difference and effectiveness-NTU). The lectures were followed by time for the students to work on example problems and the project.

Results from experimental portion

In the laboratory course the students are taking concurrently, they calculate the individual and overall heat transfer coefficients for a shell and tube heat exchanger. For the project, instead of repeating a similar experiment, they warmed milk with an electrical heater they constructed, measured the temperature increase over time, calculated the energy input, and estimated the specific heat capacity of the milk.[18] This experiment was chosen to give the students an opportunity to observe how electrical energy can be converted into heat, and to calculate the heat supplied from the voltage and current readings. It was simple, took less than an hour, and cost very little. Details of the experiment are provided online.[18]

Students prepared temperature as a function of time plots and analyzed the data in several ways. Most students chose a short time period near the temperature in which they were interested, and estimated Cp at that temperature. A few students fit a polynomial to the data, and used the derivative to find an equation for specific heat of milk as a function of temperature. The error between the measured values and literature values was 20 – 30%, but students recognized that better insulation during data collection would improve the results. In their reports, several students suggested specific ways to reduce heat loss. All of the students were able to complete the calculations.

Student learning

As in Project 1, the students experienced multiple types of delivery modes. Making cheese in the classroom, then seeing it made at the farm reinforced the process and the purpose of each ingredient. Some students contacted the farmers as they worked on their project to verify the cheese-making conditions.

This time they were more familiar with the jigsaw activity and gallery walk. The jigsaw activity helped them efficiently recall the different correlation for the heat transfer coefficients, h, they had learned the previous semester, and they were able to apply them to example and homework problems. They also learned that the correlations used to calculate the film coefficient for flat plate heat exchangers are usually proprietary, but their textbook provided an acceptable one.[12] During the gallery walk, each group prepared a poster describing a different type of heat exchanger, using information from the textbook and brochures from different manufacturers. The students learned about several different types and quickly learned that flat plate heat exchangers are common in the food industry.

After a brief lecture on pasteurization, the students were given a worksheet to design a system given the specific dimensions of the unit. Diagramming the pasteurization process with the regeneration loop in the middle was difficult—many could not visualize how one stream of milk could heat and cool itself. In the future, bringing a long length of tubing to class would simplify the explanation.

The second brief lecture presented the two common methods for designing a heat exchanger, and the situations where each would be best suited. To reinforce the use and necessity of the log mean temperature difference, the students were given an example of a counter-current heat exchanger, and using a think-pair-share exercise, asked to determine temperature driving force. At the end of the discussion, they completed a worksheet using each design method. They referred to these worksheets while working on the project. These mini-lectures and worksheets provided the scaffolding for the PBL.

The design project was open-ended, but this time the students were more comfortable with the process. The groups used both methods of heat exchanger design. One group contacted a heat exchanger manufacturer and used the dimensions of a commercially available flat plate heat exchanger as the basis for their calculations. Another group developed a versatile spreadsheet for the farmer to use to determine how many plates he would need depending on the current amount of milk (the farmers had mentioned the seasonal variation in milk quality and supply). The students recognized one main advantage of the flat plate heat exchanger—it is easy to adapt the size by changing the number of plates.

Assessment of learning

The student learning objectives for this module were as-

TABLE 4
Assessment Results for Module 2. Scores in parenthesis are for students in the traditional course.

Assessment Question	Average Score	% of students with score above 75%
1. What temperature is used to find fluid properties for fluids in different flow configurations (parallel, countercurrent, condensation outside tube)? What is the temperature driving force in these configurations?	74.8% (76.0%)	62% (70%)
2. Raw whole milk at 10 C is to be pasteurized at 72 C in a plate heat exchanger at a rate of 5 kg/s. After pasteurization, it is to be cooled to 5 C. Hot water is available at 6 kg/s at 85 C. Each heat exchanger plate has an area of 0.5 m2. The overall heat transfer coefficient in the regeneration section is 2500 W/m2C. If the regeneration section must achieve 60% of the overall heat transfer, how many plates are required?	94.1%	100%
3. A plate heat exchanger is available to heat water that enters at 10 C using hot water available at 90 C. Both streams flow at 2 kg/s. The heat exchanger has an area of 3 m2, and the overall heat transfer coefficient is estimated to be 5000 W/m2K. What will be the exit temperature of each stream?	92.3% (88.6%)	100% (91%)
Overall Exam	86.9%	92%

sessed primarily in the project reports the students prepared, but other qualitative methods were used as well and are summarized in Table 3.

The project reports were graded according to the checklist given on the assignment (see Figure 3), which corresponded to the different learning objectives. Average scores are shown in Table 3. Students received more credit for careful and accurate work, although all demonstrated an understanding of the concepts.

The exam for this section of the course covered material necessary for the project, but not assessed as part of it. Sample exam questions and scores are shown in Table 4. Where applicable, the average score for the students in the traditional course is shown in parentheses. Again, due to the small class sizes, the differences are not statistically significant.

As has been seen in previous years, the students are still uncertain what temperature to use for physical properties (first question), even though they learned it the previous semester, and did it correctly on the projects. An average of 75% on this question is similar to the average over the past four years. The students performed well on an exam problem similar to the project and on a problem using the alternative design method.

DISCUSSION AND CONCLUSION

The students in the PBL/active learning course learned the material as well as the students taught by the traditional method. Student comments during the semester were favorable. Developing and testing the activities took significant instructor time before the course was offered, as mentioned in a survey of chemical engineering faculty.[19] The class also required more preparation time during the semester than preparing the traditional lectures. However, the excitement in the classroom and the student learning made it worthwhile.

Developing a good scenario for a PBL experience also requires considerable time, energy, and thought. At least one solution should be worked out in advance to ensure it is feasible, and that the student learning objectives can be achieved. The problem will likely frustrate students at points, but if they persevere they will have a great sense of satisfaction. This was evident when the students proudly presented their project reports.

In this instance, the PBL project was implemented in a class of 15-20 students. While it is difficult to scale up the process, it can be accomplished. For example, the wandering facilitation model is used at larger institutions.[10] The facilitators, either the professor or TAs, rotate among groups, spending as much time as needed with the different groups. Having the groups perform their calculations on white boards or large poster sheets allows the facilitators to quickly assess progress and address misconceptions as needed. To avoid the common pitfalls in developing PBL assignments, reading background literature is highly recommended—the references provide many helpful suggestions.[5,10]

The two modules presented in this paper could be adapted to many situations. Tying the project to a local business worked well. Reading the local news can lead to ideas. For example, several cities have set aside a common space where start-ups can share equipment as they test their innovations. Perhaps students could see if this existing equipment could be used for their own new process. Waste-to-energy conversion projects have recently been in the news and could also become the basis of a PBL module. The possibilities are endless.

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REFERENCES

1. Prince, M., "Does Active Learning Work? A Review of the Research," *J. Eng. Ed.*, **93**, 223 (2004)
2. Felder, R.M., D.R. Woods, J.E. Stice, and A. Rugarcia, "The Future of Engineering Education: II. Teaching Methods That Work," *Chem. Eng. Ed.*, **34**, 26 (2000)
3. Rich, E., T. Sloan, and B. Kennedy, "The Effect of Problem-Based, Experiential Learning on Undergraduate Business Students," *Athens State University College of Business Journal* (2015). Accessed via <http://www.athens.edu/business-journal/spring-2015/the-effect-of-problem-basedexperiential- learning-on-undergraduate-business-students/> on 23 May 2016
4. Kirkham, K., and L. Seymour, "The Value of Teaching Using a Live ERP System With Resource Constraints," World Conference on Computers in Education (WCCE), Cape Town (2005)
5. Woods, D.R., *Preparing for PBL*, 3rd Ed, (2006). Accessed via <http://chemeng.mcmaster.ca/sites/default/files/media/Woods-Preparing-for-PBL.pdf> on 22 December 2016
6. Savery, J., "Overview of Problem-Based Learning: Definitions and Distinctions," *The Interdisciplinary Journal of Problem-based Learning*, **1**, 9 (2006)
7. Reynolds, M.J., and D.R. Hancock, "Problem-Based Learning in a Higher Education Environmental Biotechnology Course," *Innovations in Education and Teaching International*, **42**, 175 (2010)
8. Yadav, A., D. Subedi, M.A. Lundeberg, and C.F. Bunting, "Problem-Based Learning: Influence on Students' Learning in an Electrical Engineering Course," *J. Eng. Ed.*, **100**, 253 (2011)
9. Greening, T., "Scaffolding for Success in PBL," Medical Education Online [serial online], **3**, 4. Accessed via <http://www.med-ed-online.org/f0000012.htm> on 22 December 2016
10. Hmelo-Silver, C.E., "Problem-Based Learning: What and How Do Students Learn?," *Educational Psychology Review*, **16**, 235 (2004)
11. Lape, N., "Tiered Scaffolding of Problem-Based Learning Techniques in a Thermodynamics Course," American Society for Engineering Education (ASEE), Vancouver, Canada (2011)
12. McCabe, W.L., J.C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering*, Boston: McGraw-Hill (2005)
13. Piergiovanni, P.R., "Laboratory Experiment: Pumping Power Law Fluids," *Chem. Eng. Ed.*, **51**(2), 53 (2017)
14. Moor, S.S., and P.R. Piergiovanni, "A Multimodal Approach to Classroom Learning: An Example From a Process Control Course," *Intl. J. Eng. Ed.*, **26**, 1 (2010)
15. Dewey, J., *Democracy and Education; An Introduction to the Philosophy of Education*, New York: The Macmillan Company, 1916
16. Wallace, J., "Ricki's 30 Minute Mozzarella Without Using a Microwave," (2007). Accessed via <http://www.cheesemaking.com/store/pg/123-Mozzarella-in-30-Minutes-with-NO-Microwave.html> on 20 January 2016
17. Bakshi, A.S., and D.E. Smith, "Effect of Fat Content and Temperature on Viscosity in Relation to Pumping Requirements of Fluid Milk Products," *J. Dairy Science*, **67**, 1157 (1984)
18. Steves, R. "Measure the Specific Heat of Water and Other Fluid," (2007). Accessed <via http://www.instructables.com/id/Measure-the-specific-heat-of-water-and-other-fluid/> on 22 February 2016
19. Prince, M., M. Borrego, C. Henderson, S. Cutler, and J. Froyd, "Use of Research-Based Instructional Strategies in Core Chemical Engineering Courses," *Chem. Eng. Ed.*, **47**(1), 27 (2013) ❐