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Student-centered, Concept-embedded Problem-based Engineering Thermodynamics*

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Classical thermodynamics is restructured to start with practical applications where fundamental principles are introduced just-in-time and on a need-to-have basis. Theoretical information is presented to support the understanding of knowledge as students apply inquiry-based learning. Students assess their own knowledge in the process and produce concept maps linking fundamental principles to basic equations. This approach can be labeled as student-centered, concept-embedded, and problem-based. Students lead the lecture and discover knowledge (concepts) as they need it to solve practical real-world problems. They also gain practice in higher Bloom's Taxonomy levels of cognitive skills such as analysis, synthesis, and evaluation; skills that are much desired of engineers. The classroom format is interactive, somewhat informal, and revolves around students' needs. The traditional coverage of topics is packaged in the form of modules. Effectiveness of these modules is assessed using formative and summative tools and on a continuous basis. Undergraduate engineering students leave the course with enhanced thinking skills, and an increased level of retained knowledge.

INTRODUCTION

PROBLEM-BASED LEARNING (PBL) is an instructional approach which promotes critical thinking by presenting a real-life problem of relevance to the audience. The motivation for solving the problem becomes an automatic part of the solution where students are playing the roles of authentic investigators while instructors are considered facilitators. Since solving a practical problem is the objective, uncovering fundamental principles and concepts are natural consequences of the solution approach. Students are not left wondering if what they are studying has any use, but rather challenged by the excitement and relevancy of solving real-life problems. In engineering, this feeling is a great motivational tool and serves as the anchor to which the sustainability of students' attention is hooked. More than motivation exclusively, a problem-based approach also has been shown to help develop independence in students, along with promoting creativity and critical thinking. There is no doubt that professors and students have to play a different role by engaging in this non-traditional instructional and learning approach. Figure 1 shows a simple comparison of the thought processes associated with traditional learning versus those for problem based learning. At the start, PBL does consume a larger amount of time with the creation of new problems, but as the course is repeated with pre-created and refined problems, the workload becomes reasonably manageable.

Thermodynamics is the first course in the thermal sciences area and students success in future courses is linked directly to what they retain of thermodynamics knowledge. One intent of integrating PBL into Thermodynamics is to enhance knowledge retention. PBL fosters active learning, supports knowledge construction, integrates disciplines, and naturally combines classroom learning with real-life applications. This paper addresses the creation of curricular materials in engineering thermodynamics that are based on problem-based learning coupled with Bloom's Taxonomy of Learning. Formative and summative assessment on using this instructional approach is carried out to examine its effect on students' learning. The curricular materials, or modules, present classical thermodynamics in a restructured format that promotes critical thinking and enhanced retention of knowledge. The motivation for creating such materials is the extensive research on students' learning indicating that students learn better, retain more, and understand to a higher level with active and practical learning environments. The restructured course is comprised of a basic set of four modules, covering typical concepts normally dealt with in engineering thermodynamics. These modules are carefully designed to reflect traditional concepts but made more exciting as students discover the need for the laws and principles through the solution of real-life problems.

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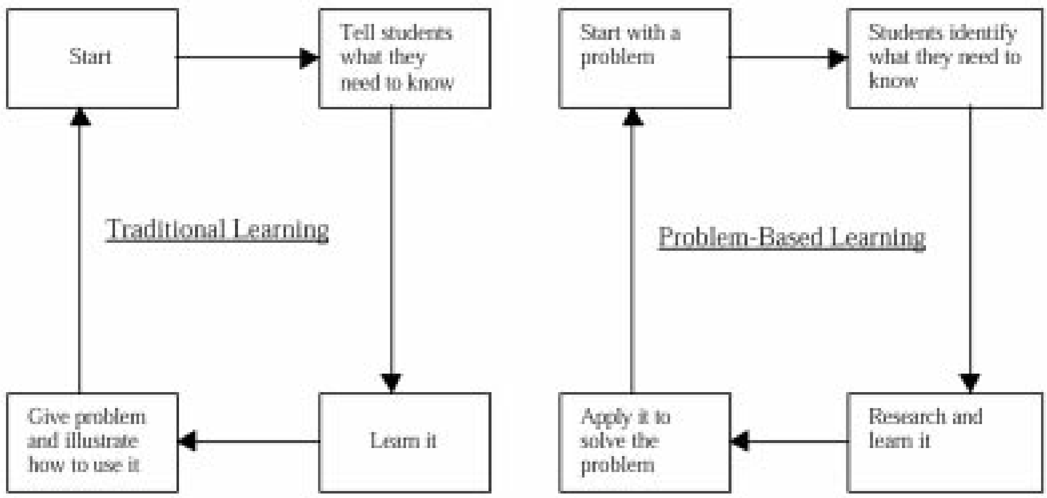

Fig. 1. A simplified schematic of problem-based and traditional learning approaches. Adapted from Mehta [9].

LITERATURE REVIEW

Problem-based learning falls under the umbrella of inquiry-based learning or discovery-based learning. PBL has been used in a number of disciplines, particularly the medical field [1–4] and in other professions [5–8]. Tanner *et al.* reported that an instructional approach founded in PBL has resulted in students praising the 'value of the course', 'relevance', and 'performance of the professor' on course evaluations [6]. Owens *et al.* summarized their integration of inquiry-based instruction and technologically integrated instruction in urban elementary reading programs. Interestingly, the authors comment that in an inquiry-based approach, the children were involved in the synthesis of the questions and then approached the solution as a research opportunity. They also showed examples of elementary students exhibiting the upper levels of cognitive thinking skills outlined in Bloom's Taxonomy of Learning. The topics of research, selected by the students, were of a 'real importance' to them and it drove them to challenge themselves to perform optimally [7]. Jakes *et al.* addressed virtual PBL and devised an eight-step process for conducting online research in an inquiry-based virtual learning environment [8].

While much of the research thus far has been applied mainly to the medical and legal fields, more and more PBL work is appearing in the fields of engineering and applied sciences in both course reform and complete curriculum reform [9–12]. It was shown recently that PBL significantly improves problem analysis and solution, finding and evaluating resources, cooperative teamwork, and communication [9]. In his freshman curriculum reform proposal, Alnajjar discussed the redesign of engineering courses to integrate team-based problem-solving through 'integrated learning blocks' [10]. Shetty *et al.* followed up by proposing curriculum changes to all four years, bringing together faculty from humanities, social science, engineering, mathematics and science to define crossover outcomes for linked courses from those departments. Their concept was to enhance learning by providing students with hands-on and collaborative experience working on real-life engineering problems at all four class levels [10–11].

Meltzer and Greenbowe have observed inconsistencies to approaches in physics-based and chemistry-based thermodynamics, and as such proposed methods for combining departmental resources to design a common course using guided inquiry-based problem sets. These sets are specifically designed to put up roadblocks where students would then develop a regimen of focused practical exercises that would drive them to the solution [12].

Trombulak used PBL as a bridge between upper and lower level students. He addressed a form of peer teaching connecting upper-level students entering the science education fields to students in an introductory-level course. Students of the upper-level course were assigned a group from the introductory-level course to instruct in a laboratory setting. The introductory students set their own course, investigating a query of their own construction. As a result, 87% of the upper-level group and 93% of the introductory group offered positive evaluations of their experience [13]

Ebert-May *et al.* described a curriculum reform study for the purpose of improving biology-related literacy by using inquiry-based instruction. Their students' evaluation provides a positive acceptance of the cooperative, inquiry-based learning environment. The authors determined that inquiry-based cooperative learning is a successful tool for moving the responsibility of learning from the instructor to the students. Also, they reported that students progressed into the higher levels of Bloom's Taxonomy of Learning with questions that are focused mainly on application, analysis, and synthesis [14].

Maskell described the integration of problem-based instruction in an early digital systems course and suggested that the problem-solving skills acquired in such a course support those desired of, or normally associated with, capstone courses [15]. Cawley introduced PBL into a second course in vibrations. A handful of elementary lectures were offered at the beginning of the course, followed by self-guided (in the sense that teams worked together to teach themselves) project assignments that required the use of the concepts traditionally covered in the course. It was suggested that the increased involvement of self-instruction caused students to spend more time working on this particular class. He also commented that students could be overheard during class breaks discussing the project assignments. Because of the team-based nature of the course, individual assessment was quite challenging due to the lack of knowing which team members were 'carrying their weight' and which were not. Otherwise, the students felt that they had achieved a similar understanding to that which they would have obtained via a traditional lecture course [16].

In a related application of just-in-time-learning in a second course in thermodynamics (applied thermodynamics), Lee and Ceylan found that integrating design reinforced course coverage of thermodynamic cycles, psychrometry, and combustion. Additionally they noticed that the integrated design linked ideas across the thermal sciences curriculum, exposed students to open-ended challenges, and emphasized a real-world environment—addressing the need for teamwork, communication, and computer skills. The authors opine that their objectives were successfully met, despite a handful of students' comments indicating an overwhelming workload [17]. When Harmon *et al.* evaluated a capstone design course in environmental engineering focusing on simulation and a PBL design project, the authors noticed that students developed a much deeper understanding of course material, suggesting that the simulation activities outperformed their expectations. Knowledge mapping served as the assessment tool documenting gains in content understanding [18].

In a problem-based course on internal combustion engines, T. Litzinger reported that nearly half of the students reflected positively on the course, while a quarter had no comment. The negative comments made focused primarily on the level of expected knowledge having had little or no prior experience, feelings that an introductory class was delving too much into engine hardware and not enough into how they work [19]. A study by Woods *et al.* compares two tracks of sophomore-level students, one from a traditional multidisciplinary approach (consisting of humanities, social science, science, and engineering), and one from an integrated interdisciplinary program referred to as 'Theme School' where small groups would take a self-directed approach. The 'Theme School' students scored highly on the strategic and 'deep' learning scales of the Lancaster Approaches to Studying Questionnaire (LASQ), while scoring low on the 'surface' learning section [20].

PBL has been integrated into the Massachusetts Institute of Technology Aerospace Engineering program in a curriculum change based in the real-world engineering context of a complete life cycle. Conceiving, designing, implementing and operating (CDIO) was the driving idea. The curriculum builds up to a final capstone design course where students used CDIO to solve a complex problem. The students see the program more interesting having a better learning environment and note that they gain a higher understanding of engineering science [21]. Observing PBL used in a mechanics of materials course, Goulet *et al.* noticed a growth in the 'breadth and depth' of the students' familiarity and understanding of the subject material [22]. A study by Newman *et al.* investigating the integration of inquiry-based learning and multimedia presentation was aimed at two specific groups: engineering juniors and seniors with strong modeling skills but limited knowledge of technology or practice, and working professionals who had become rusty in their skills, but had strong knowledge of technology and practical experience. The pedagogy used consisted of a tiered approach where students would be introduced to elementary concepts followed by progressively more complex concepts which required analysis and information synthesis. The majority of students reflected on the course as having supported their growth of problem-solving skills and of the ability to use the concepts outside of the course [23].

In an assessment of learning techniques at the US Air Force Academy, Havener and Barlow suggest that once subjected to a PBL environment, students should be repeatedly exposed to PBL, otherwise the gains from early PBL work may be lost. The authors also discuss the additional load on faculty presenting PBL courses, as more effort must be expended in learning how to develop objectives, outcomes, and assessment techniques. Due to the unorthodox structure of PBL courses, the classes and associated faculty tend to not be favorably evaluated as in traditional classes by the students. Hence, students need to understand PBL so that they are able to appreciate the usefulness (value and gains) of this pedagogy [24].

PROBLEM-BASED ENGINEERING THERMODYNAMICS (PBET) COURSE STRUCTURE

Figure 2 presents a general skeleton of the restructured engineering thermodynamics course in the form of modules. These modules encompass typical topical coverage [25] but in the context of real-life, open-ended problems. It is also important

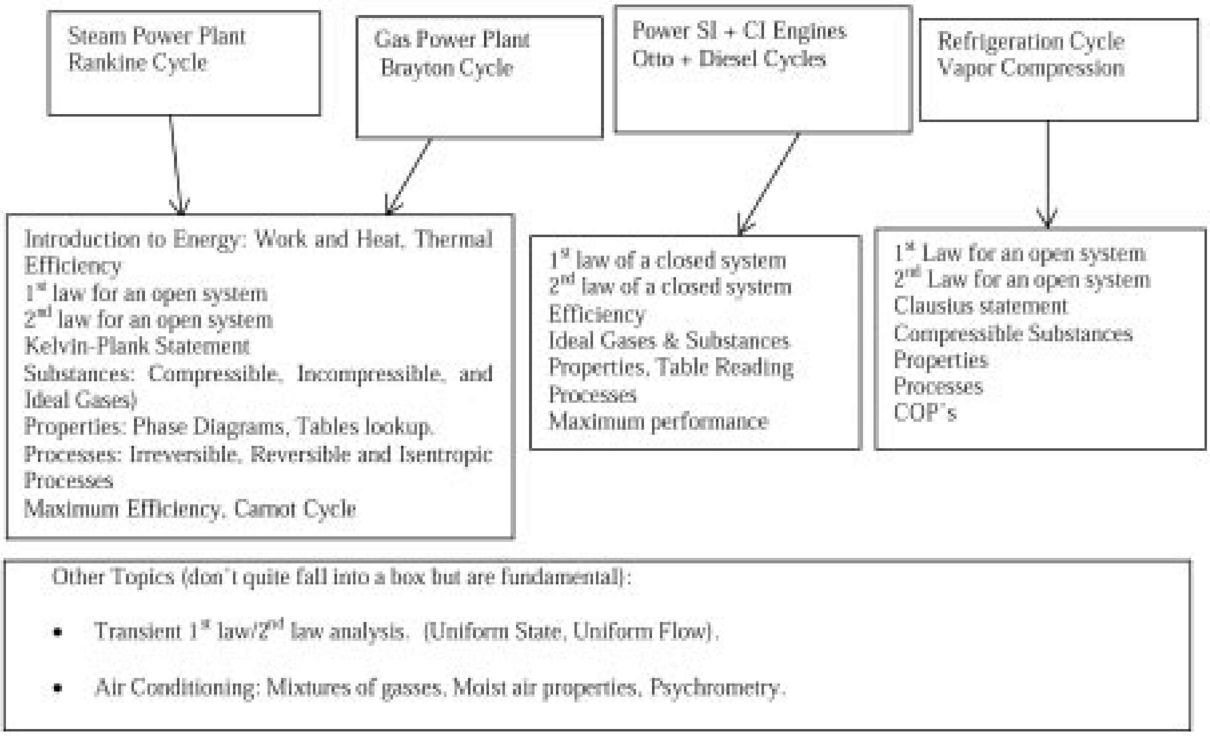

Fig. 2. Modules representing restructured course layout.

to note that the modules-based layout does not compromise typical coverage of topics/concepts of a traditional first course in thermodynamics. For each module, students are faced with a practical problem to solve, which may take up to three weeks.

Module 1

This module deals with spark ignition (SI) engines through a real-life problem bringing about the 1st and the 2nd laws of thermodynamics for a closed system. The course begins with this module intentionally, limiting the scariness of the open-ended nature of PBL, allowing students to recall the familiar ideal gas law, and giving them the opportunity to refer to early sections of their textbook for additional help. Typically, closed systems are featured first in a classical thermodynamics course, and therefore students find it pseudo-natural to refer to the early sections of their textbook. Module 1 concludes with a problem on compression ignition (CI) engines where concepts seen and utilized earlier are reconfirmed and enthalpy is introduced. Module 1 is covered via approximately sixteen hours of instruction time. The professor first introduces the application, followed by the students setting the learning objectives (power and efficiency) of the problem. Normally, the professor leads an interactive discussion, fueled by student input including an online simulation of the operation of an automotive piston-cylinder and an engine demonstrator, allowing the students to visualize how everything comes together in a real engine. The professor then hands over the discussion to students who then describe the processes involved among each other, leading up to the need for and discovery of an energy principle, cueing the professor to introduce the 1st law. The students move into the 2nd law domain, challenged by the professor to raise the efficiency. Here, reversibility and irreversibility are introduced along with the 2nd law, isentropic relations and entropy generation. On occasion, the students would break into 3- or 4-person teams for five-minute brainstorming sessions. Interestingly, students often stayed in class through breaks firing questions back and forth across the room to satisfy their curiosities (a phenomenon seen also during Modules 2, 3, and 4).

For the CI portion of Module 1, the process begins anew but in a rapid manner, building on the material and concepts learned from the SI portion. Similarities to SI engines are pointed out by students, as well as discovering the usefulness of the property, enthalpy. Cooperative teams are again employed to apply the learned principles and confirm their understanding of the 1st and 2nd laws for a closed system. Obviously, this module on internal combustion engines addresses concepts used to analyze Otto and Diesel cycles.

Module 2

Module 2 treats steam power plants and introduces open systems. Students construct their objectives and cast the 1st and 2nd laws for open systems. Here again an online tour of a coal-fueled steam power plant, detailing each component of the plant, is shown in class. The challenge is introducing pure compressible substances and the fact that the ideal gas law does not apply to water. Students start by examining what happens to water as it becomes steam and begin identifying the need for properties of a pure compressible substance, distinctly different from ideal gases. Students plugged through this module along the same lines as in Module 1; they identified the components of the plant and determined the learning objectives for the module, discovering that the 1st law for a closed system requires modification to be used with open systems. Although students reasoned that energy is carried with matter as it flows into and out of devices, they found it difficult to relate to and quantify 'flow work' without the professor's intervention. In addressing the cycle's efficiency, students related to the need for the isentropic efficiencies of devices. Although, in this module, students felt frustrated with their homework assignments and quite overwhelmed, it is in this module where we noticed that students truly believe that they are thinking critically and are not afraid of the open-endedness of the applications. In total, this module consumed sixteen hours of instruction time.

Modules 3 & 4

Module 3 and Module 4 are however seen to be easier by the students since the former deals with gas turbines whose components are open systems and substance an ideal gas, while the latter addresses vapor compression refrigeration whose components are also open systems but having a compressible substance. During Module 3 (four hours of instruction), students felt relieved to get back to an ideal gas model and felt at ease applying the 1st and 2nd laws. Furthermore, the class was relaxed and students were much more confident about their abilities. During Module 4 (four hours of instruction), students showed more signs of critical thinking, as they gained more confidence and proved their abilities by working through the module with relative ease.

It is worth noting that the class session is 120 minutes long, ideally suited for open-ended problems. The classroom environment is rather informal and non-threatening. Initially, students showed no fear as they were not yet worried about their grades. However, students showed some reservation about speaking out as the course progressed and as grades seemed to influence their productivity.

At the conclusion of each module, students are given a reference table, cross referencing discovered knowledge, with their own textbook [25]. This reference table was especially helpful to students as they start preparing for exams and assessment. It also gives them another perspective on thermodynamic concepts. In addition, after each individual lecture and as students solve more aspects of the problem, students individually generate a concept map. Such a concept map presents a concept or a term, what it means to the student (in his/her own words), and any supporting equations. A number of misconceptions and wrong interpretations were uncovered as those concept maps were examined. As an example, some students expressed the 1st law of thermodynamics for a closed system as: $\Delta Q - \Delta W = \Delta E$; indicating that heat transfer and work are properties or that they are present at the beginning and end of the process. An obvious lack of understanding of properties versus path functions. As another example, especially observed in the early part of the course, students tend to seek equations prior to thinking about the governing principles and without checking related assumptions and limitations. Thankfully, this practice (habit) got corrected as the terms progressed and students developed better critical thinking skills. Ultimately, students became concepts-driven as opposed to being equations or 'formulae'-driven.

PBL IMPLEMENTATION AND ASSESSMENT

The PBL instructional approach has been implemented for two terms, Winter and Spring 2002. There are a number of assessment tools which were used to evaluate the impact of PBL on students' learning, problem-solving skills acquisition, and critical thinking skills. The tools are as follows:

- professor's examination of students' quizzes, homework assignments, and mid-term exams;
- senior student observer (co-author of this paper)—a form of peer evaluation;
- professor's diary on every lecture;
- observer's diary on every lecture;
- PBL-focused survey comprised of multiple-choice and written responses;
- common final exam for both PBL students and subject-based learning (SBL) students.

The SBL students are taught in a traditional approach following the textbook sequence and going through the material, subject by subject, topic by topic, as they appear in a traditional textbook.

QUESTIONNAIRE RESULTS

The results presented here feature students' assessment of PBL via a PBL-customized questionnaire. In Table 1, students were asked to rate the contribution of the PBL course in providing them with certain abilities. It is worth noting that the first five entries in Table 1 are levels 2 through 6 of Bloom's Taxonomy of Learning. Results are summarized and tabulated for both Winter and Spring 2002. The spring term results seem much more promising than those obtained for the winter term. This is attributed to the incorporation of lessons learned from the winter term experience and making necessary changes (refinements), and

Table 1. Course contribution to students' abilities as reported by PBL-instructed students (Winter: 40 students, Spring: 23 students).

	Unable to Assess (%)		Minimum (%)		Average (%)		Above Average (%)		High (%)		Rating Factor (Max. = 4)	
Ability	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02
Comprehension	0	0	0	0	29	0	44	35	26	65	2.94	3.65
Application	0	0	12	0	21	0	44	30	24	70	2.82	3.70
Analysis	0	0	0	0	26	0	53	45	21	55	2.95	3.55
Synthesis	3	0	6	0	35	10	56	60	0	30	2.44	3.20
Evaluation	0	0	9	0	47	15	32	45	12	40	2.47	3.25
Creativity	0	0	3	5	29	15	44	35	24	45	2.89	3.20
Technical Maturity	0	0	0	0	24	20	53	10	24	70	3.03	3.50
'Think Better & Retain More'	0	0	9	0	29	0	29	30	32	70	2.82	3.70

the fact that the instructor (first author) perhaps was more comfortable the second time the course was taught in the PBL format. Changes included spreading out the homework load with careful due dates, lessening related frustration, giving two help sessions, handing out summaries and expected outcomes lecture-by-lecture as students proceed in solving the problems, and getting rid of quizzes while increasing the number of mid-term exams from two to four. The 'Rating Factor', in the last column of Table 1, is an indicator of the contribution level of the course in helping students acquire desired abilities. It is computed via:

$$\text{Rating Factor} = (4 \times \text{High}) + (3 \times \text{Above Avg.}) + (2 \times \text{Avg.}) + (1 \times \text{Minimum})$$

Indeed the rating factors for Spring '02 PBL students are considerably higher than those for the Winter '02, showing students as quite receptive to the PBL instructional approach.

Table 2 documents the level of students' agreement with stated features of PBL. Here also, the Spring '02 results are notably higher than those for the Winter '02.

As a final question on the questionnaire, students were asked to select their level of agreement in preferring the PBL approach to instruction over the traditional approach. In the Winter '02 term, 71% of students 'Agreed' and 'Strongly Agreed' with preferring PBL. This percentage rose to an amazingly higher level of 100% for the Spring '02 term. If one were to combine the results of Fig. 3 from both terms and compute a weighted percentage, 81% of the students seem to prefer the PBL environment over the traditional environment.

STUDENTS' COMMENTS AND REFLECTIONS

Comments were solicited from students on three areas of interest:

- how this inquiry-based instructional approach differed from the subject-based traditional approach,
- the greatest and most frustrating features of the PBL approach;
- how inconvenienced they were by not following the textbook sequence.

The following statements are excerpts from students' responses.

Comments on PBL vs. traditional environment

- 'It is more like my co-op learning, where I am faced with a problem so I learn the concepts behind it and use them to solve it. I appreciate the application of the subject matter from the beginning of the problem, as it gives a better understanding of our goal in solving the problem.'

Table 2. Students' responses to PBL model and related features (Winter: 40 students, Spring: 23 students).

	UA (%)		SD (%)		Disagree (%)		Agree (%)		SA (%)		Rating (/4)	
Feature	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02	W '02	Sp '02
Student-Centered	0	0	6	0	9	0	65	65	21	35	3.03	3.35
Enjoyable Class	0	0	6	0	24	0	44	70	26	30	2.9	3.3
Increased Understanding	3	0	3	0	18	0	50	45	26	55	2.93	3.55
Active Engagement	6	0	3	0	18	0	41	45	32	55	2.9	3.55
Confident Problem-Solver	6	0	6	0	41	5	38	45	9	50	2.38	3.45
Stimulated Interest	6	0	3	0	21	0	41	55	29	45	2.84	3.45
Combined Classroom & Real-Life	0	0	0	0	3	0	59	40	38	60	3.35	3.6
Reflective Thinking	6	0	0	0	6	10	68	50	21	40	3	3.3
Material Relevance	0	0	0	0	9	0	65	25	26	75	3.17	3.75
Helped Motivation	0	0	3	0	38	5	41	50	18	45	2.74	3.4

- 'Students learn by doing problems and thinking through concepts instead of just being told this it the way it is.'
- 'I think it made me think more, also made me more curious about all the systems.'
- 'This approach is much more practical and the examples used in class could be applied in work environments.'
- 'It gets the students more involved in the learning process. It also takes us step-by-step through the solution process, much like we may face on the job, and teaches us real-world, practical ways to break the problem down and solve it.'
- 'I feel as though I learned the material better, and will retain the information longer than with the subject-based approach.'
- 'There is a lot of 'stuff' the student must figure out on his own. Sometimes it is very overwhelming.'
- 'Less boring, more class involvement than usual.'
- 'I think it keeps one's understanding constantly in check.'
- 'It promotes concepts instead of equations. That way you will apply the concepts so you can use the appropriate equation.'

Students' comments on their gains

- 'The greatest thing would be the confidence that I have given myself. I came into the course thinking that it was going to be really hard, in fact I heard it was the hardest course in the school. I believe the material is difficult but the approach has made me more confident.'
- [The greatest thing I gained was] 'that classes can be fun and interesting if you have a professor that cares as much as you do. To constantly be looking and re-evaluating your method really shows that you honestly care about our success and it makes coming to class that much more exciting.'
- 'The class challenged me in a number of ways. The greatest thing I realized I had to think more and more and not be afraid of it. Sounds silly, but it is one of those things.'
- 'The ability to think about a problem objectively and visualize a system as well as to see what you need in order to solve a problem.'
- 'Being able to work real-world problems and think about systems as parts and materials not just graphs and charts.'
- 'I think I may have liked the other way better. It would have given me a better grade, but this way may help me retain more over time.'
- 'Greater class participation.'
- 'Well, I would have to say that I learned the material, and the enthusiasm from the professor helped break the ice to the difficulty of the material.'

Students' comments on their frustrations

- 'Self-learning was necessary, since the various examples cannot be fit into the few class hours but had to still be understood. These examples were given as homework and had to be worked on our own.'
- 'The fact that I had to go to the professor's office after every homework assignment.'
- 'There was a lot of information all at once. It was sometimes hard to plow through the concepts without taking a break and using equations.'
- 'Sometimes introductory application with less theory makes the computation more difficult, but by thinking about the problem first then picking out the appropriate equations later increases the understanding of the process.'
- '[I] had to learn how to do homework by myself which was fine because it helped me learn the material but it just took too long to do.'
- 'Sometimes not learning all of the theory beforehand led to some confusion. I do, however think the frustrations actually helped me learn.'
- 'Had to really comprehend what is going on in class. If you do not understand you can become lost very easily.'

Students' comments on not following textbook sequence

- 'It was somewhat inconvenient because the concepts were scattered therefore it made it difficult to look up. You should write a textbook in the sequence that you teach everything.'
- 'I use the textbook for reference and examples, the sequence did not affect me, as far as the text is concerned.'
- 'The sequence of the book wasn't a problem, but the lack of corresponding examples was. A book that is written based on PBL would be very beneficial.'
- 'I really had no problem using the book in a non-sequential manner. I think your concept flow worked very well. The modules at the end made a lot of sense after moving through the beginning ones.'
- 'I thought it was difficult because I couldn't find the info I needed and examples in the book had different approaches to them.'
- 'If the books were designed to follow in the problem based teaching method, much more would be gained.'

COMMON FINAL EXAM RESULTS

A comprehensive common final exam for all students who take this course is normally conducted across all sections. As opposed to students' homework assignments, quizzes, and exams where students solve multi-step problems and are assessed on their display of their thought processes and problem-solving skills; the final exam experience is 70% multiple-choice questions, designed to measure students' achievement of specific course outcomes and 30% 'work-out' problem (typically an analysis of a cyclic device

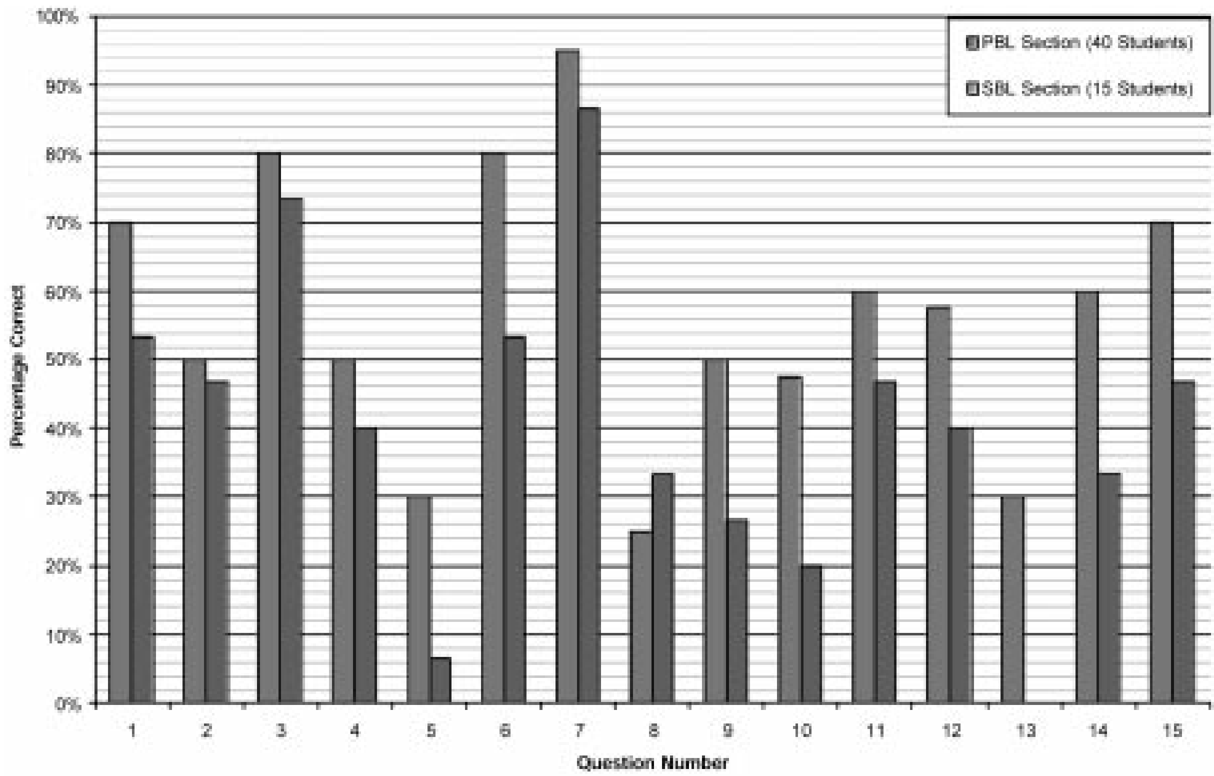

Fig. 3. Common final exam performance comparison of PBL and SBL students (Winter '02); (PBL: 40 students, SBL: 15 students).

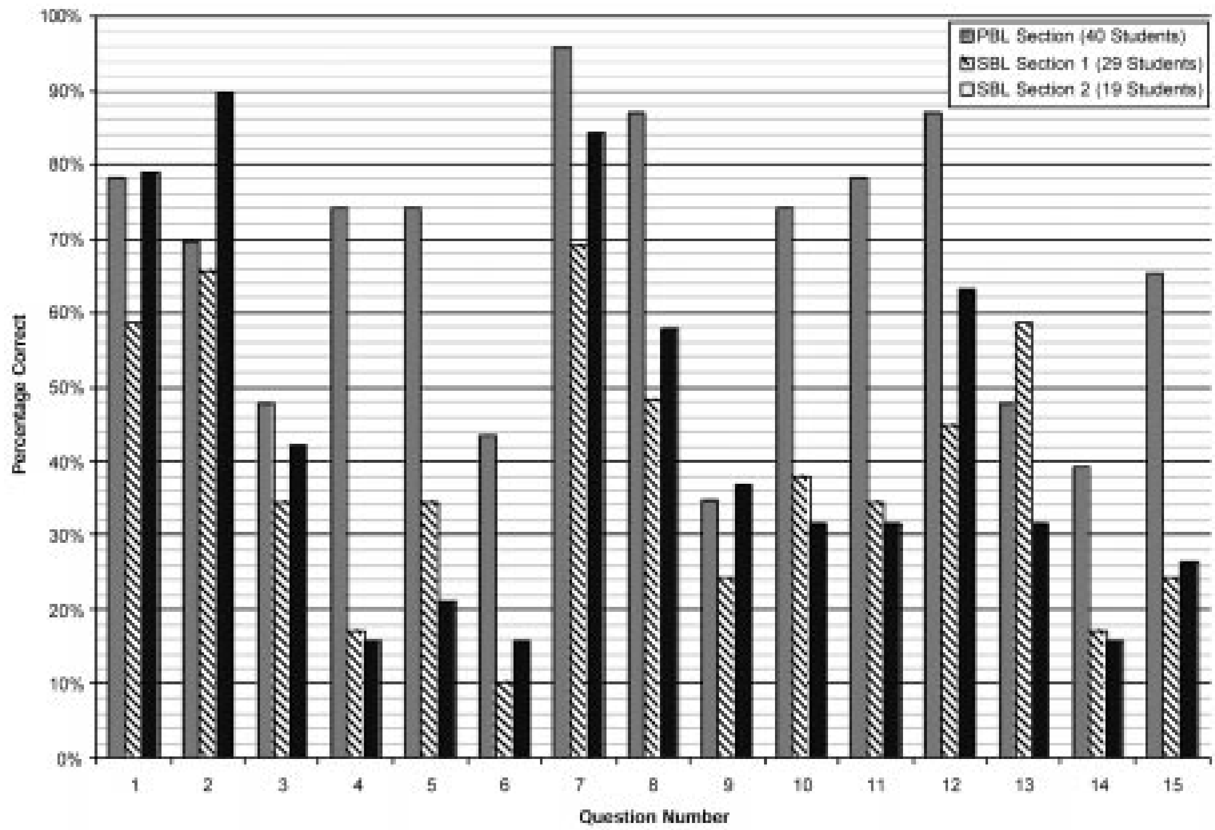

Fig. 4. Common final exam performance comparison of PBL and SBL students (Spring '02); (PBL: 23 students, SBL (2 sections): 48 total students).

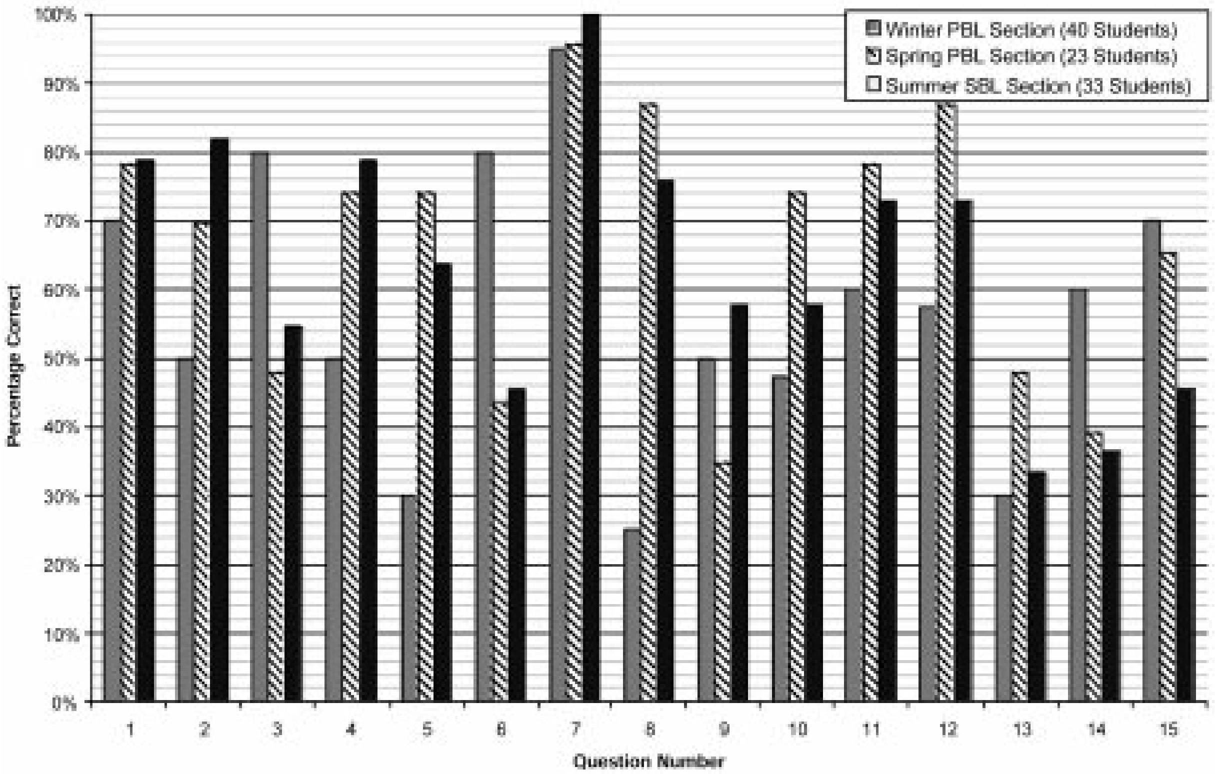

Fig. 5. Comparison of PBL and SBL final exam performance results for a common instructor; (PBL (2 terms): 63 total students, SBL: 33 students).

or a combined 1st and 2nd laws problem). The exam questions were pre-agreed upon by all instructors, co-written, and targets course objectives directed. The Winter '02 final exam results are featured in Fig. 3 for the multiple choice questions of the final exam, comparing the performance of PBL-instructed students to those taught traditionally (SBL-instructed).

PBL students outscored their counterparts on all questions but number 8. Figure 6 presents the same comparison for the Spring '02 final exam results. During the Spring '02 term, there were two sections of Thermodynamics taught using the traditional approach and one section taught using PBL. Here also, the PBL students outperformed their SBL counterparts.

It is also worth noting that different instructors taught the SBL students during the winter and spring terms. Based on the findings presented in Figs 3 and 4, one is tempted to present a strong case for PBL as students clearly outperformed their colleagues who were taught in a traditional manner. Naturally, the question that begs answering is how much of an effect does the instructor have on the performance of his students (PBL or otherwise). In an effort to eliminate this factor, the PBL instructor for the Winter and Spring terms went back and taught the course traditionally (using SBL) during the Summer '02 term. Figure 5 displays students' performance on the final exam for the same instructor using PBL (winter and spring) and SBL (summer). It is difficult from this figure to infer a conclusion and therefore believed to be more useful if one compares the Spring '02 results with the Summer '02 results, as exhibited in Fig. 6, as a difference in performance (PBL–SBL) per question. If one further assumes that a significant difference is a value larger than 5%, then SBL students performed better on three questions (Questions 2, 3, and 9) while the PBL students performed better on seven questions (Questions 5, 8, 10, 11, 12, 13, and 15). With respect to the 'work-out' problem of the final exam, PBL students performed better, averaging 26/30 as opposed to 19/30 for the SBL students. This result is expected since PBL-instructed students had extensive training in solving larger and open-ended problems. There was additionally anecdotal (observation-based) evidence that PBL students were much more excited about thermodynamics and related applications than SBL students.

CONCLUSIONS

This paper presented the successful application of PBL into a first course in engineering thermodynamics. It documented how the course was restructured in terms of modules without compromising traditionally covered topics and concepts. Students' assessment based on two trials, both in reflections and performance, are quite supportive of the PBL instructional approach. Several concluding remarks can be made:

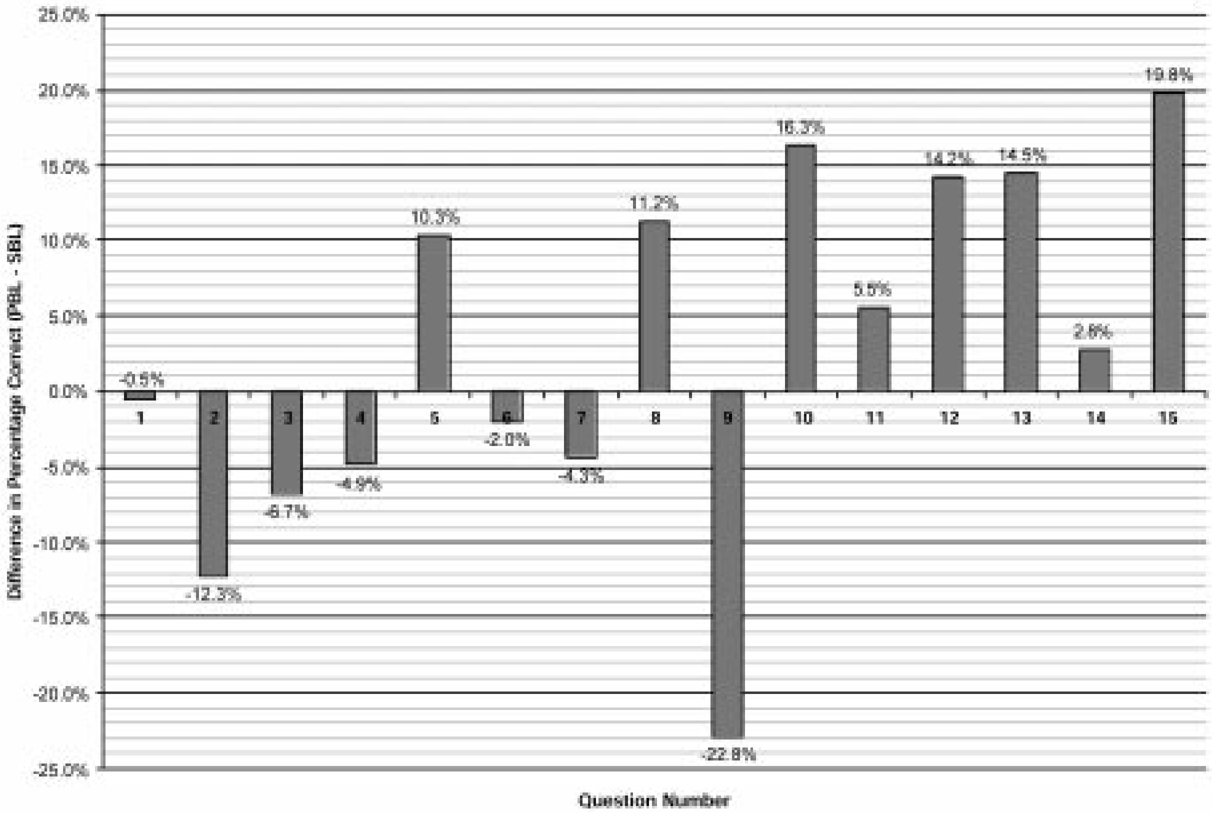

Fig. 6. Difference in final exam performance of Spring '02 PBL students and Summer '02 SBL students for a common instructor; (PBL: 23 students, SBL: 33 students).

- Professor/students need to play roles that are different from traditional ones.
- Available time for instruction is key to the success of PBL. Having little time limits the interactive and cooperative aspects of PBL.
- Homework is a significant source of frustration for students. Homework assignments need to be carefully designed so that students' motivation is sustained.
- Students are noticeably engaged in the learning process via PBL as they kept on working during breaks.
- Professors must 'even-out' students' load to avoid reaching frustration threshold.
- For the first time PBL is introduced, the professor is anticipated to work harder on designing suitable problems. But as the course is taught over, professors retrieve their comfort level and the load would be comparable to that if the course was taught traditionally.
- Creating 'good problems' that are PBL-founded is a challenge.
- Students seem to have performed better when compared to their SBL counterparts.

Further study is needed to eliminate factors that might bias assessment results and examine the impact of PBL on students. Finally, although PBL was applied here to thermodynamics, it seems to offer many benefits to our students and may be applied to practically any course in the engineering curriculum.

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