Impact Assessment of Problem-Based Learning in an Engineering Science Course

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Abstract

This paper presents the development and implementation of Problem-Based Learning (PBL) in an engineering thermodynamics course at Kettering University. In this project, the thermodynamics course was restructured as modules presenting practical applications first, whereas principles were introduced just-in-time and as encountered. Theoretical information was presented to support the understanding of knowledge as students applied inquiry-based learning. These modules were carefully designed to reflect traditional concepts but made more exciting as students discover the need for the laws and principles. The classroom format was interactive, cooperative and revolves around students' needs. Formative and summative assessment tools were designed to examine the effectiveness of created modules.

Introduction

The majority of engineering professors in higher education use subject-based learning (SBL) to teach and convey course material. This method typically relies on several attributes, which include the instructor presenting facts to students, a learning structure defined by the sequence of material presented in a text book, and a discussion of questions based on "who, what, where, and when". This traditional and often successful model of knowledge transmission centers primarily on the teacher and what they want students to learn and accomplish from lectures.

Another teaching approach known as Problem-Based Learning (PBL) promotes critical thinking utilizing real-life problems as the starting point. Professors and students are expected to play non-conventional roles by engaging in this instructional and learning approach. In a PBL environment, learners practice higher order cognitive skills (analysis, synthesis and evaluation) and are constantly engaged in reflective thinking asking questions that are based on "why and how" rather than "where, when, and what".

PBL has been employed in a number of disciplines, particularly in the medical field [1-4] and in education-related professions [5-8]. Recent work, some with support from NSF, has targeted the fields of engineering and applied sciences in both course reform and complete curriculum reform [9-13]. In other studies [14-17], PBL was documented to help students' progression into the higher levels of Bloom's Taxonomy of Learning. There are six levels in Bloom's Taxonomy of learning, they are: knowledge, comprehension, application, analysis, synthesis, and evaluation. PBL helps students with activities that are focused mainly on application, analysis, and synthesis; and to significantly improve problem analysis and solution, finding and evaluating resources, cooperative teamwork, and communication.

In a number of studies, students' comments on PBL experiences were very encouraging. Many stated that the PBL approach was more interesting, provided a better learning environment, helped develop significant skills in self-directed learning, and enhanced their learning capabilities through cooperative learning [18-20]. Finally, in a white paper [21] on future thermal science education, the authors state that "perhaps the most commonly used approach for development in the higher-level domains is problem-based learning ….. Technology can be a powerful partner to assist students in developing in higher order domains" [21].

This paper draws on the lessons learned from different disciplines where PBL has been employed and documents assessment data to validate potential benefits. The motivation behind the development and implementation of PBL in an engineering thermodynamics course at Kettering University was to help students avoid memorization, to free them from being equations-driven ("pluggers and chuggers"), and to assist them in internalizing knowledge and understanding through critical thinking.

Project Approach

The objectives of this project focused on developing curricular materials that are founded on PBL and the examination of their effectiveness in enhancing students' learning. The course under consideration is a first course on Engineering Thermodynamics. A general skeleton of the module-structured Problem-Based Engineering Thermodynamics (PBET) is made up of basically five modules and has been described at length in an earlier publication [22]. The five modules are:

Module I: Spark/Compression Ignition Engines
Module II: Steam Power Plants
Module III: Power Gas Turbines
Module IV: Vapor Compression Refrigeration
Module V: Transient Problems

For each module, students tackled a practical, complex but well-designed, problem(s) to solve, employing just-in-time discovery of principles in a cooperative-learning environment. The class motto is "think better and retain more". Modules I & II are, to a large extent, the largest and most extensive as concepts encountered in these two modules are also encountered in the other modules.

Module I: The restructured course begins with this module intentionally, allowing students to recall the familiar ideal gas law, limiting the scariness of the open-ended nature of PBL, and giving them the opportunity to consult early sections of their textbook for additional help. Students face a complex practical problem on Spark Ignition (SI) engines whose solution requires them to uncover the 1st and the 2nd laws of Thermodynamics. This module addresses concepts used to analyze Otto and Diesel cycles. It requires students to model, simplify, and interpret the problem and turn an open system into a closed one. 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. In this course, the instructor first introduced the application, followed by the students setting initial desired objectives (power and efficiency) of the problem. The instructor then facilitated the modeling phase, probing students on their knowledge of engines. Students break into 3-4 person teams for five-minute brainstorming sessions, task formulation, and direction identification. Through an interactive discussion, students watched an online simulation on the operation of an automotive piston-cylinder as an engine demonstrator, assisting students in visualizing processes in a real engine. Students then described the processes amongst themselves, leading up to the need for and discovery of an energy principle, and queuing the instructor to formally introduce the 1st Law of Thermodynamics. Challenged by the instructor to raise the efficiency, students moved into the 2nd Law of Thermodynamics. In the 2nd law, reversibility and irreversibility are introduced along with isentropic relations and entropy generation. Module I concludes with a problem on Compression Ignition (CI) engines where concepts seen and utilized earlier are reconfirmed and "enthalpy" is encountered and introduced. Thus for the CI problem, the process begins anew but in a rapid manner, building on the material and concepts learned from the SI portion. A substantial part of learning and thinking is shifted onto students' shoulders since the instructor facilitates learning and presents principles as needed. Module I required sixteen hours of instructional (classroom) time.

Module II treats steam power plants and makes the jump from control mass (closed systems) to control volume (open systems). Students began with an online tour of a coal-fueled steam power plant, detailing the function of each component. The challenge lies in handling pure compressible substances and the fact that the ideal gas law does not apply to water. Students were asked to examine what happens to water as it becomes steam and identify the need for properties of a pure compressible substance, distinctly different from ideal gases. Students identified components of the plant and determined needs and objectives, discovering that the 1st law for a closed system required modification to be used for open systems, and saw the concept of "flow work" for the first time. In improving thermal efficiency, students related to the need for the isentropic efficiencies of devices. The instructor facilitated coverage of issues, concepts and topics based on students' needs and time constraints for the course. Module II required sixteen hours of instructional (classroom) time.

In Module III, students tackled gas turbines whose components are open systems and the working substance is an ideal gas. Having seen all needed fundamental principles, students revisited the ideal gas model and felt more comfortable applying the 1st and 2nd laws for open systems. Students developed their objectives (power-efficiency-thrust) and exhibited their problem-solving skills. In addition to the fact that the application was exciting (producing power, turbo-jets, turbo-props), this module boosted students' confidence in their abilities to think critically and independently. In-class instruction time for this module is a two-hour block only.

In Module IV, students realized also that this application is based on previously seen governing principles (1st and 2nd laws) and cruised through the solution to such problems. Students practiced more critical thinking skills, felt at ease dealing with compressible substances (refrigerants), and encountered coefficient of performance as a measure of systems' efficiency. They revisited Carnot principles, realized Clausius statement, and examined ways to increase the coefficient of performance (COP) of the system. This module required two hours of instructional time.

Module V (Transient Processes): The open system modules addressed steady-state, steady-flow devices and therefore a different type of a problem was needed for unsteady situations. Hence, in Module V students solved small problems of charging/discharging of tanks and applied the first law of thermodynamics. In-class instruction time for this module is two-hours.

Classroom Environment

The classroom environment was based on the philosophy of "guided discovery". This environment has been described in an earlier paper and details about it can be found in [22]. During the implementation of the above described modules, a number of tools were used to facilitate learning of engineering thermodynamics at Kettering University; these tools include:

- Concept Table: features a layout of thermodynamic concepts (terms), what they mean to the student (in his/her own words), and any supporting equations. These tables were first generated by students and later corrected by the instructor who provided feedback on any misconceptions.
- Concept Map: helps develop critical thinking skills and help students become concepts-driven as opposed to being equations or "formulae"-driven. The concept-map was drawn at the end of each module.
- Cross-Reference Table: cross-referencing discovered knowledge with sections in their own textbook [24]. This table is especially helpful to students as they link their understanding to textbook treatments and get another perspective on thermodynamic concepts.
- E-learning Platform: At the conclusion of each module, files containing slides of the concepts that are tied to that particular problem were posted online on Kettering University's website. The concepts were presented in a concise and clear format, leaving no ambiguity on what they mean and how they should be applied. The on-line platform also helped in communicating with students the grader's reflections and served as an on-line trace to all such observations.

Assessment, Evaluation, and Mastering of Disciplinary Knowledge

In a paper [25] on describing common characteristics of PBL, the authors emphasized the need for compatibility between the assessment method and the objectives of the learning process. Several studies [26, 27] offer a number of sources that focus on assessment tools and techniques but they are not compatible with the PBL instructional method. Therefore, in order to ensure that desired outcomes are being measured, a number of assessment tools (formative and summative, objective and subjective) are employed here to evaluate the impact of PBL on students' learning, problem-solving skills acquisition, and critical thinking skills. These tools are as follows:

- Professor's examination of students' homework assignments, and mid-term exams
- Professor's examination of students' concept maps
- Team project
- Senior student observer diary
- PBL-focused questionnaire
- Common final exam given to PBL-instructed students and traditional Subject-Based Learning (SBL) students

Some of these tools focus on independent learning experiences where emphasis is placed on the ability to reason through given information and identify a solution approach to the problem and on the ability to solve an unseen problem. Students must also be able to apply team-based skills to produce a solution to a project idea and be able to produce a formal report detailing their thought processes with proper documentation.

Mastering disciplinary knowledge in an engineering science course like thermodynamics is a primary objective. The tie between disciplinary knowledge and PBL environments was addressed in a recent paper [28]. The author of the paper recommends that instructors use strategies that engage students in revising existing knowledge and applying disciplinary concepts in multiple contexts.

Results and Discussion:

In order to rate the contribution of PBL in providing students with certain desired abilities, and to determine students' level of agreement with PBL descriptors, a PBL-focused questionnaire was conducted at the end of the term. The abilities ranged from Bloom's Taxonomy of Learning levels to enhancing students' creativity and technical maturity. On the questionnaire students were asked to indicate the level of contribution as being either "High", "Above Average", "Average", or "Minimum". A numerical rating factor was associated with these indicators as follows:

High = 4, Above Average = 3, Average = 2, Minimum = 1

An average rating factor for each question was obtained using:

RF = [4*(number of responses is "High") + 3*(number of responses is "Above Average") + 2* (number of responses is "Average") +1*(number of responses is "Minimum")]/ (Total number of responses)

The questionnaire was divided into two parts. In one part the students were asked to rate the contribution of PBL in enhancing their ability in: comprehension, application, analysis, synthesis, evaluation, creativity, technical maturity, and to think better and retain more knowledge of thermodynamics. The results of the questionnaire were averaged and tabulated for

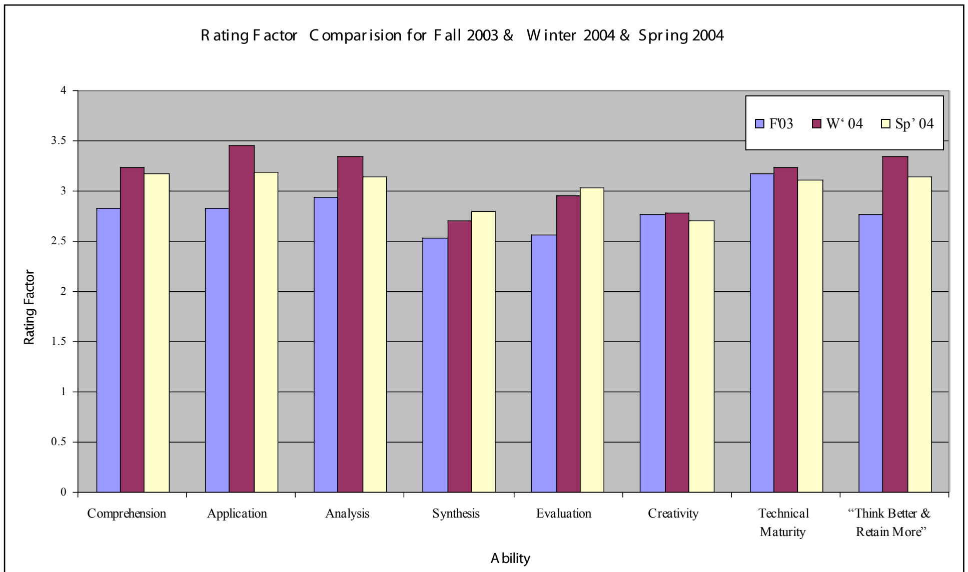

Figure 1: Rating factors for each ability.

three terms (Fall 2003, Winter 2004, and Spring 2004). The results for part one are listed in Table 1 in the form of percentages. Figure 1 shows the results using the rating factor shown above. Students reported high agreement ($RF_{avg} > 3$) with having acquired desired abilities in comprehension, application, analysis, and technical maturity. They also believed that the teaching/learning environment allowed them to "think better & retain more" with $RF_{avg} = 3.1$. In the second part of the questionnaire students were asked to rate certain features of PBL. The results of the second part were also averaged and are listed in Table 2 in the form of percentages. Figure 2 shows the same results using the rating factor. Based on these results, students agreed that the approach is student-centered, that the material as presented in five modules is relevant, that PBL combines classroom with real-life applications, and that it promotes a climate of active engagement. The rating factors for these PBL-instructed students are high and especially in some areas that are very difficult to measure through students' work. 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. The results of this question are shown in detail in Figure 3. Overall, two-third of the students reported a preference of the PBL approach over the traditional approach.

Another measure of the effect of PBL on students' learning is students' performance on a common final exam with Subject-Based Learning (SBL) students. The SBL students were 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. The exam was designed to have twenty questions. These questions were tied directly to educational outcomes previously agreed upon by all instructors of thermodynamics. Figure 4 exhibits, on a question by question basis, the difference in students' performances on the final exam for the Spring'04 term. Gathered data indicated that PBL-instructed students outperformed, on the majority of questions, their classmates who were taught in a traditional way (SBL-instructed students). These findings are also consistent with earlier findings when the same comparison was done on another set of students in previous terms.

It is believed that the student-generated concept tables, concept maps, and cross-refer-

	Unable to Assess (%)			Minimum (%)			Average (%)			Above Average (%)			High (%)		
Ability	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04
Comprehension	0	0	0	0	0	0	29	15	12	58	48	58	13	38	30
Application	0	0	0	6	0	0	19	5	13	60	45	56	15	50	31
Analysis	0	0	0	2	0	0	23	18	20	54	30	45	21	53	34
Synthesis	0	3	0	10	5	3	31	38	28	52	30	55	6	25	14
Evaluation	0	0	0	6	5	0	46	25	19	33	40	57	15	30	23
Creativity	0	3	0	13	5	8	19	35	31	48	28	37	21	30	22
Technical Maturity	0	5	0	0	0	3	21	13	18	42	33	43	38	50	36
"Think Better & Retain More"	0	0	0	6	3	9	31	13	7	42	33	44	21	53	40

Percentages were obtained by dividing the total number of similar responses by the total number of responses. For example % "High" was obtained by dividing the total number of responses is "High" to the total number of responses on the questionnaire. Other percentages listed in the table were obtained in a similar way.

A number of "0" indicates zero responses.

Table 1: Students' reflections on the contribution of PBL to stated abilities.

Feature	Unable to Assess (%)			Strongly Disagree (%)			Disagree (%)			Agree (%)			Strongly Agree (%)		
	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04	F' 03	W' 04	Sp' 04
Student-Centered	0	3	3	4	0	0	19	8	11	64	53	38	13	38	48
Enjoyable Class	2	0	2	8	3	4	38	18	18	44	50	59	8	30	17
Increased Understanding	4	5	0	8	3	4	19	13	9	60	48	51	8	33	36
Active Engagement	0	5	0	2	3	2	25	5	6	67	55	60	6	33	32
Confident Problem-Solver	2	3	0	10	3	4	38	10	19	40	53	57	10	33	20
Stimulated Interest	4	3	5	4	3	2	25	10	12	58	50	48	8	35	33
Combined Classroom & Real-Life	0	5	2	0	0	2	8	3	4	69	42	42	23	50	51
Reflective Thinking	6	8	6	2	0	0	17	10	6	60	58	66	15	25	22
Material Relevance	2	3	0	0	0	0	10	3	4	58	48	49	29	48	47
Helped Motivation	8	5	4	10	0	4	27	30	14	42	43	60	13	23	18

Table 2: Students' reflections on PBL features

encing tables help students in revising knowledge, and that authentic homework problems, examinations, and team-projects provide them with opportunities to apply disciplinary knowledge in multiple contexts.

Conclusions

This paper presented PBL modules developed for teaching engineering thermodynamics at Kettering University. In addition, the challenges that were encountered, assessment tools used, and responses to questionnaires, were

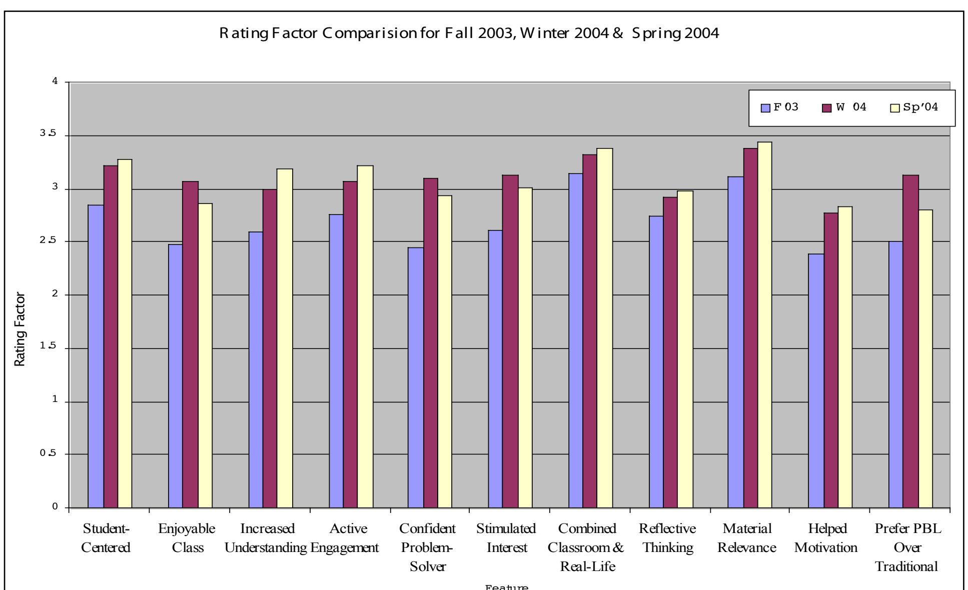

Figure 2: Rating factors for PBL features.

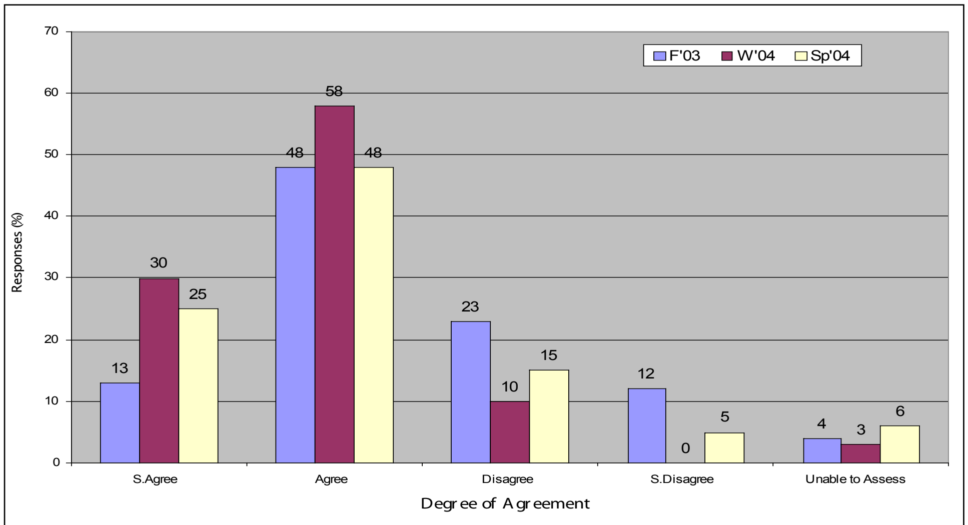

Figure 3: Students' level of agreement for preferring PBL.

presented. Based on the results of the questionnaire, final exam results, and instructors' experiences in implementing PBL, the following conclusions and observations can be made:

- PBL-instructed students outperformed, on the majority of questions in a common final exam, the SBL-instructed students.
- The results of the students questionnaire show that students were supportive of PBL.

A number of issues need to be recognized using this approach:

- Professors need to have practical experience in the area of instruction to facilitate learning.
- Instructor/students are expected to play roles that are different from traditional ones.
- The available time for instruction is key to the success of PBL. The interactive and cooperative aspects of PBL consume a substantial amount of time.
- PBL-type homework assignments need to be carefully designed to match instructional approach.
- As compared to Subject-Based teaching, the professor spends more time interacting with students.
- Creating "good problems" that are PBL-founded and do not compromise disciplinary

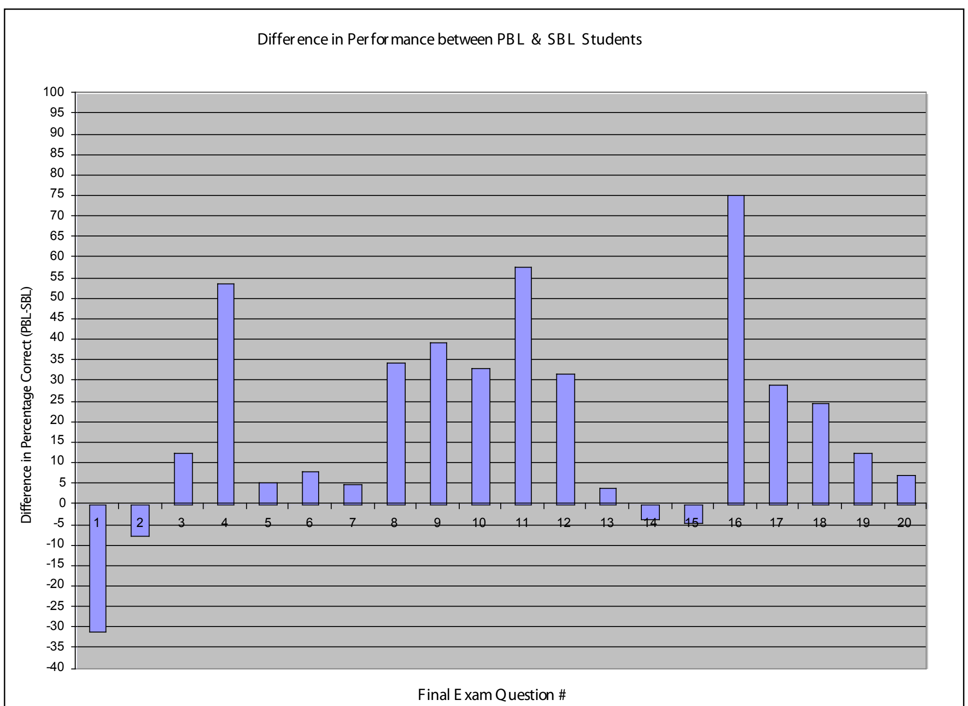

Figure 4: Difference in final exam performance for PBL and SBL-instructed students

knowledge is a challenge.

- Carrying out proper assessment and monitoring students' acquisition of skills is also a challenge.
- Finally, the authors believe that successful demonstration of PBL in Thermodynamics opens the door for its implementation into practically any course in the engineering curriculum.

In addition, students' tendencies to memorize material and generalize application of equations should also be controlled. Extra care should be taken in helping students internalize information and be self-conscious about their learning. Using multiple assessment tools with target measurement of specific characteristics, PBL has the potential for overcoming many of the challenges and as a result, students experience deep understanding and master the use of important concepts.

Challenges Encountered

Engineering Thermodynamics is an engineering science course where disciplinary knowledge forms its foundation. While implementing PBL in this course a number of challenges were encountered. Some of these challenges are:

- The majority of students are formulae-driven. Effective methods need to be employed to discourage students from reaching out for quick equations to plug and chug in.
- A new classroom environment needs to be created by the instructor that is based on understanding and synthesis rather than memorization.
- A role adjustment with regards to students' problem-solving approach needs to be played as they solve real-life problems.
- Further practice is needed as students get engaged in independent learning and life-long learning activities.
- Requiring students to seek knowledge/concepts on their own can be frustrating to some of them.
- Authenticity and open-ended nature of thermodynamics problems maybe overwhelming to some students.
- Assessment of what students are able to do and attributing those abilities/skills to PBL is, and will continue to be, a challenge.
- With disciplinary knowledge and fundamentals forming the foundation of a course like thermodynamics, real-life aspects must not overshadow the instructional time spent on basic principles and needed theoretical treatments.

The instructor of the course carries the burden of handling these challenges properly. Mainly, the instructor needs to have practical experience in the area he teaches in order to use PBL effectively. Moreover, he needs to be able to steer students away from the conventional way of learning without overwhelming students with new knowledge.

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Prof. Nasr acted as a member of SAE, ASEE, ASME, ASHRAE, the World Energy Council, and EC2000 Evaluator. Prof. Nasr served as a reviewer for McGraw-Hill, refereed engineering journals (Journal of Heat Transfer) and the National Science Foundation (CCLI). He is a recipient of SAE's Ralph Teetor Educational Award (1998), Kettering University's Outstanding Teacher Award (2000), Outstanding Applied Reseracher Award (2000), CETL's Best Poster Award on Educational Research (2002), and TRW/CETL Educational Scholar Award (2003).

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Professor Ramadan joined Kettering University on July 1, 1998. He teaches undergraduate courses in thermodynamics, fluid mechanics, heat transfer, and graduate courses in the thermal sciences area. Dr. Ramadan's expertise is in Computational Fluid Dynamics (CFD), Heat Transfer, and Combustion. He has received several research grants from industry and government to perform numerical simulations of IC engine processes including, intake, compression, fuel injection, combustion, exhaust, and engine cooling. He has worked on engine research involving PFI, DI and IDI, methanol, ethanol, diesel, and gasoline. He has extensive experience in the development and use of CFD and computational tools and knowledge of experimental methods to analyze and solve complicated engineering systems. He has also worked with Delphi Corporation in Flint, Michigan on the design of engine exhaust systems to reduce emissions. He received the "Outstanding New Researcher Award", the "Outstanding Applied Researcher Award", and the Outstanding Teacher Award. He has developed several undergraduate and graduate courses in the thermal sciences area which he also teach. Moreover, he has also developed specialized courses in combustion and HVAC for Delphi Corporation and General Motors. He has published in AIAA, the Combustion Institute, APS, ASME, SAE, ASHRAE and is an active member of ACS, SAE, ASME, and ASEE. He has also acted as a reviewer for ASME, SAE, and the Journal of Energy and Fuels.