Framing Students’ Learning Problems of Thermodynamics

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Abstract

Firm understanding of thermodynamics by graduating engineers is critical for addressing key current and future global issues, e.g. the looming energy crisis, pollution and global warming. Forms of alternative energy, and the efficiency of their conversion processes, are all governed by the laws of thermodynamics. Despite this immense importance, engineering students has been having difficulties in building good knowledge of thermodynamics, and in applying this knowledge in problem solving and thermal design. Through a careful reading of the pertinent literature, this paper explains the difficulties students have and provides classifications of the difficulties in order to better understand them. The difficulties are grouped under major headings in order to give an easy-to-see view of them. A thorough understanding of these difficulties, and their root causes, is vital for any instructional design aimed at mitigating these problems, and for enabling better learning of thermodynamics. The paper also summarizes the techniques that have been tried to solve these problems and the degree of success achieved. Generally speaking, there are two major classes of thermodynamic learning problems. First, students do not properly learn thermodynamic concepts and principles; second, students do not seem to recognize relevant concepts and principles, and combine them in order to solve thermodynamic problems. This paper argues that in order to design an edifying approach to improve students’ learning of thermodynamics, the root causes must be addressed.

1. Introduction

Thermodynamics is the science that deals with all types of energy- renewable and non-renewable- in terms of availability, conversion, transmission, efficiency and destruction (of free energy). Thermodynamics also governs chemical reactions such as combustion of fossil fuels in automobiles and for steam generation in steam power plants, as well as nuclear reactions in nuclear power plants. The field of heating, cooling and air-conditioning is also studied using principles of thermodynamics.

Thermodynamics is taken by students in the majority of engineering majors- mechanical, chemical, civil and electrical, as well as by students majoring in physics and chemistry with some variation in the topics covered. In engineering, the first course in thermodynamics is taken early on by students, and is considered a difficult course by students, and as a filtering course by some instructors in some engineering programs. In mechanical engineering, thermodynamics has been described as the gateway course, meaning students’ performance in thermodynamics correlates well with how students do in the rest of the courses in the curriculum. Fuchs stated that thermodynamics is considered to be one of the most difficult and abstract disciplines of the physical sciences. Students’ dissatisfaction and frustration with thermodynamics are very common.
The general poor performance of US engineering students in thermodynamics is documented by the National Council of Examiners for Engineering and Surveying (NCEES), who administers the Fundamentals of Engineering Exam (FEE). For the past several years, students’ performance falls in the band from 40% to 65%. Student’s performance shows no clear improvement during the past several years.

2. Conceptual Difficulties

Meltzer reported that students have difficulties with the concepts of heat, work, cyclic processes. Misconceptions related to temperature, heat and energy; as well as ‘rate’ versus ‘amount’ were reported by Prince et al. One of the common misconceptions was to think of temperature as a measure of the amount of energy contained in an object. In addition to these, students’ misconceptions include work and internal energy. Students have been reported to confuse quantities associated with thermodynamic processes with those associated with states, Loverude et al.

Hamby described students’ problems with using the first law in solving problems. Other documented misconceptions related to the meaning of isothermal and spontaneous processes, Granville. The idea that for a system going through a cyclic process, the net work done by the system or the net heat transferred to the system must be zero, proved to be difficult for students to grasp, Meltzer.

3. Difficulties with, and Inability to, Recognize Relevant Thermodynamic Basic Principles

Meltzer reported that students have difficulties with the first and second laws. Recognizing the relevance of the first law and properly applying the ideal gas equation proved to be a challenge for students in the study of Loverude et al. Engineering students were also uncomfortable and unfamiliar with the need to provide explanations and reasoning in problem solving, Meltzer. In thermodynamics, students may still give incorrect answers to conceptual questions, even if they could solve textbook problems, as noted by Abulencia et al.

4. Persistence of Thermodynamic Learning Problems

Several articles indicated that thermodynamics misconceptions are persistent and resistant to change. Prince et al. indicated that thermodynamic misconceptions did not change through standard instructions. One out of eight students was able to apply the first law even after having studied the first law and related topics, Meltzer. In a different study, Meltzer indicated that only 20% or fewer of 653 students were able to effectively use the first law even after instructions. Regarding the persistence of the misconception concerning temperature and heat, Arnold and Millar pointed out that students regressed after showing some improvement.
5. Problems at the Pre-college Level

Pre-college students thought that temperature and heat were synonymous, Arnold and Millar.\textsuperscript{13} Misconceptions regarding thermal equilibrium by a 120 eighth-grade students were reported by Clark and Jorde.\textsuperscript{14} Senior high school students were shown to confuse the quality and quantity of energy, Ben-Zvi,\textsuperscript{15} while adolescents experienced difficulties in dealing with the temperature and heat concepts, Viennot.\textsuperscript{16} It was documented, de Berg,\textsuperscript{17} that up to 38\% of students 17- to 18-years old from two colleges in England did not understand the concepts of volume and mass. Lack of understanding of entropy by school students was presented by Johnstone et al.\textsuperscript{18} A sample of 15- to 16-years old students in Germany had severe difficulty in learning the energy concept and the distinction between heat and temperature.\textsuperscript{19}

Pre-college misconceptions are likely to remain through college.\textsuperscript{19,20} Kaper et al.\textsuperscript{21} indicated that assuming that college students have no misconceptions of some thermodynamic concepts may cause learning difficulties and impede the process of conceptual change in college.

6. Worldwide Problem

In addition to the US, student’s difficulties with thermodynamics have been reported in different parts of the world. Meltzer\textsuperscript{11} reported on students difficulties in Europe. French students’ difficulties were talked about by Viennot\textsuperscript{16}, while misconceptions carried by German students were described by Kesidou and Duit.\textsuperscript{19} Roberts and Watts\textsuperscript{22} presented problems with teaching thermodynamics in England and Kaper et al.\textsuperscript{20,21} and Mettes et al.\textsuperscript{23} discussed issues with thermodynamics learning in the Netherlands. Reports regarding thermodynamics poor competency of entering students into the University of Queensland in Australia were presented in de Berg\textsuperscript{17} and Kavanagh et al.\textsuperscript{24} Banerjee\textsuperscript{25} discussed conceptual difficulties in thermodynamics of some undergraduate students in India. It is very likely that difficulties with thermodynamics are existent in other parts of the world, but have not been reported in the open literature.

7. Attempts and Techniques for Mitigating Students’ Difficulties

Concept inventories have been very popular in probing students’ conceptual understanding in engineering education. In thermodynamics, concept inventories that targeted properties and behavior of matter, work, heat and the first and second laws were described by Midkiff et al.\textsuperscript{26} An inventory that included the concepts of thermal equilibrium, mechanical energy, heat capacity and steady state, among others was presented by Olds et al.\textsuperscript{27} The Heat and Energy Concept Inventory (HECI) was developed by Prince et al.\textsuperscript{12} to assess prevalent misconceptions related to temperature vs. energy, rate vs. amount of heat transfer and others. Using HECI on
373 undergraduate students from 10 different universities, the authors demonstrated that student misconceptions are both prevalent and resistant to change.

Real-life examples, hands-on experiments and projects have been used to help students in tackling thermodynamics abstract ideas, and to connect them to actual hardware. Flotterud et al. described a micro-combined heat and power system, sized for residential distributed power generation, that was used as a laboratory experiments to apply the first and second laws. The real-life experiments enhanced students learning of some thermodynamics principles. In a class project, students were asked to select a commercial thermal cycle, analyze its performance and discuss the difference between the actual device and the theoretical model, Li and Zhou.

Toro et al. presented a desktop scale Rankine cycle with a solar-powered boiler for use as a hands-on laboratory experiment. Patterson collected real-life thermodynamic examples in a booklet to enhance teaching of thermodynamics. The examples were designed using parts of the constructivist learning theory. Hands-on demonstrations built from common laboratory components to enhance the learning in introductory thermodynamics were presented in Plumley et al.

Inquiry-based learning has been employed to enhance thermodynamics learning. In this kind of learning, students predict the outcome of an event or a process, conduct an experiment, watch a simulation, read or engage in discussion, and then critically compare their predictions to the correct results. Inquiry-based activities are known to cause conceptual change. Prince et al. presented results that showed the effectiveness of inquiry-based activities in addressing some thermodynamic misconceptions held by engineering students, i.e., heat, energy, temperature and entropy. Field had anecdotal evidence that pointed at improved learning by students.

Problem-based learning has been implemented in thermodynamics instructions by some researchers. This method trains students to tackle ill-defined, ill-structured problems as found in the real world. Studies have shown that this learning method results in more positive students’ attitudes, a deeper conceptual understanding and improved retention of knowledge. The success of problem-based learning depends to some extent on students’ self-efficacy and the degree of collaboration among peers. In problem-based environments, learners practice higher order cognitive skills (analysis, synthesis and evaluation), and constantly engage in reflective thinking. Lape presented tiered scaffolding techniques to bridge the gaps in high-cognitive-load problem-based learning in thermodynamics. In a problem-based activity, students were asked to design an experiment based on a thermodynamics device, Alvarado. The activity improved self-confidence of students. Some problem-based thermodynamic curricular modules introduced practical applications first, whereas thermodynamic principles were introduced as encountered, Nasr and Ramadan. The authors highlighted some challenges in the implementation of their technique, but stated that students benefitted from it.
Some workers applied project-based learning in their thermodynamics course. Projects were found to be beneficial in terms of students’ motivation and learning, and effective tools for introducing some of the abstract concepts of thermodynamics.

8. Use of Electronic Media

On-line delivery, web-based instructions and software- sometimes with the use of multimedia (hypertext, sound, animation and simulation) have been widely used to facilitate thermodynamics learning. Cobourn and Lindauer and Ngo and Lai stated that students have responded favorably to their use of electronic media. Web-based modules, when interactive and visually appealing with animations and simulations, captured the attention of the wire generation, Ngo and Lai.

The use of various communication technologies for on-line offering of a thermodynamics course was described by Hall et al. Results showed that students relied heavily on the instructor to show them how to solve problems. Stanly and DiGiuseppe presented a web-based animation software for thermodynamics that was linked to homework problems in a textbook. Students considered the software to be valuable for learning thermodynamics concepts. In computer-based instruction for active-learning of thermodynamics, minor technical problems were sufficiently frustrating to discourage students from using the materials. There was no independent evidence that students comprehended the material in a deep fashion. However, in general, there was a positive correlation between time spent using the materials and test performance, Anderson et al. A model of students’ navigation in thermodynamics computer modules on a CD-ROM was developed by Taraban et al. The CD did not bring about active learning and students needed a strong incentive to use the CD.

Kumpaty introduced the so-called expert system for thermodynamics (TEST) software for enhancing students learning of thermodynamics. TEST was visual, allowed parametric studies and followed closely the textbook of Cengel and Boles. TEST received positive remarks from students. In one study, thermodynamics homework exercises that were delivered to students via the Internet, and completed by students on-line, Taraban et al. The on-line homework, along with the immediate feedback, improved students’ grades in the in-class tests. Baher described a virtual laboratory for constructing and analyzing thermodynamic cycles. Students found the software helpful in increasing their understanding.

In summary, thermodynamic learning problems are persistence and resistant to change, and for the most part, they remain intact. This strongly suggests that either a) the attempted solutions so far have not address the root causes, or b) the solutions that worked, or worked partially, have not been adapted by a sufficiently wide population of university instructors such that a clear improvement in students’ performance at the national level is achieved. In general, none of the attempts seemed to be comprehensive- each targeted certain concepts and/or principles. In
addition, engineering thermodynamics textbooks have not been affected by the attempted solutions described above.

9. The Makeup and Root Causes of Thermodynamics Learning Problems

Before proposing more solutions, it is critical to diligently attempt to a) correctly frame problems associated with thermodynamics learning, and b) identify the root causes of these problems. The literature outlined above reveals that students have three main learning issues: 1) conceptual difficulties; 2) struggle with integrating concepts and principles; and 3) not recognizing the relevance of thermodynamic principles in solving problems.

Thermodynamic principles are not impossible to understand. Shultz and Coddington\textsuperscript{52} have shown that around the age of 15, children were able to understand conservation of energy and the idea of entropy. The results were obtained using psychological investigations and physical simple apparatus. Below is an attempt to establish the root causes of the learning problems.

9.1 Conceptual difficulties are most likely due to the following:

1. The actual level of difficulty associated with thermodynamic abstract concepts is typically high (for students in second-year engineering), e.g., entropy, internal energy, enthalpy, reversible process, and the fact that temperature is related to molecular motion. Cotingnola and coworkers, for example, stated that energy is one of the most abstract ideas in physics.\textsuperscript{54} To complicate things further, students tend to exercise preferential associations between certain pairs of variables, e.g. temperature and heat.\textsuperscript{53}

2. The sheer number and interconnectivity of abstract concepts students have to struggle with is another reason for the difficulty. Students are faced with numerous new abstract ideas that they have to master in a short time. This fast bombardment does not allow students to fully understand and internalize certain concepts, before new ones are introduced. This accumulation process causes students’ frustration and dissatisfaction, if not total loss.

3. The timing at which the numerous new concepts are introduced is another contributing factor to conceptual difficulties. Typically, a high concentration of abstract concepts are jammed in the first few weeks of a first-semester course in thermodynamics. This is basically ‘starting on the wrong foot’.

4. Lack of an orienting basis. Mettes et al.\textsuperscript{23} stressed the need for an orienting basis for student to be able to absorb new knowledge for the first time, and then to apply it (in problem solving). Haber-Schaim\textsuperscript{55} stressed the importance of establishing a practical need for a new term before the term is introduced. This way the terms would have an operational meaning, and would be better integrated with the student’s natural vocabulary.
5. The connection to real-world problems and hardware is typically superficial. Manteufel\textsuperscript{1} for example reported success after implementing a spiral approach that utilized life-affecting applications in a mechanical engineering thermodynamics course.

6. While the above issues result in a heavy cognitive load, there seem to be no efforts to alleviate this load in order to enable better learning of thermodynamics. Lape\textsuperscript{36}, for example, described a tiered scaffolding technique for distributing such cognitive load by moving students up the levels of Bloom’s Taxonomy.

7. Lingering of misconceptions from the historical development of thermodynamics as a science is another source of difficulty, at least with certain concepts. The persistence of some ideas from the caloric model are found to be reinforced by some magnitude names and unit definitions.

8. Homework and classroom problems typically require students to calculate numerical values and rarely ask students to link the answer to conceptual understanding, or to reflect on the implications of such answer. Solving problems from textbooks may not indicate deep learning\textsuperscript{4,12}.

9. Some of the conceptual problems can be caused by text books:
   - Some text books fail to make clear distinction between certain concepts, e.g. internal energy and heat.\textsuperscript{56}
   - In some popular textbooks, scientific terms are confused with everyday language semantics and with common-sense knowledge.\textsuperscript{56}
   - The way in which most textbooks introduce or treat the concepts of work, energy and heat are incorrect or confusing.\textsuperscript{56}
   - Most books nowadays use a definition of heat closer to the presently accepted one: a process of energy transfer due to a temperature difference between a system and its surroundings. However, many books finally succumb to ‘heat’ is a form of ‘energy’. The term thermal energy adds to the confusion.\textsuperscript{56}

9.2 Difficulties in integrating concepts and principles, and in recognizing their relevance, are due the following:

1. Organization of thermodynamic materials is not conducive to deep learning. This is based on the fact that the learner’s cognitive structure for a given body of knowledge is likely influenced by the organization of such body of knowledge when it is taught to the learner. The cognitive structure in the brain is responsible to a large extent for the learner’s ability to solve problems.\textsuperscript{57} The process of learning is greatly influenced by how new ideas are first introduced, indexed and stored in memory so as to result in deep learning, and be available to the process of problem solving.\textsuperscript{58,59}

2. No attention to how new (thermodynamics) knowledge is indexed in memory.
Cognitive structure is a hypothetical construct that refers to the organization and relationship of concepts and ideas in memory. It represents a framework of hierarchically organized concepts. Moreira et al. found that the approach for the content of thermodynamics based on the Ausubel’s theory influenced students’ cognitive structure, in such a way that their conceptual hierarchies were more coherent with the basic laws and the conceptual structure of the subject matter of thermodynamics. This might be relevant for long-term retention of knowledge and for problem solving.

3. These issues may combine with a general (natural) tendency by students to forget relevant variables when dealing with multivariable problems.

Certainly a comprehensive robust solution must address the above issues. This requires more effort. At this time one may pose the following questions related to such solution:

- What ‘logical’ arrangement of the materials in the first course in thermodynamics should be implemented in order to affect deep learning?
- Is there one comprehensive solution that targets all the learning problems, or a series of partial solutions targeting specific problems?
- How does a solution deal with the interconnectedness of some of the leaning issues?
- What kind of reliable assessment methods should be devised to prove beyond doubt the effectiveness of a solution?
- How should electronic media be employed within a solution? How can an instructor ensure that thermodynamic learning problems do not simply move over to electronic media and stay intact?
- Are there meaningful tiered scaffolding ways to alleviate heavy cognitive load associated with thermodynamics? Is there a way of distributing the abstract concepts so that they are not all (or most) introduced early in a first course in thermodynamics?
- What orienting basis or bases should be used in the first thermodynamics course? And is this possible without changing the first course to what is covered in a second course?
- How and should engineering educators in the 21st Century prevent the historical development of thermodynamics, which is responsible for causing some of the misconceptions and confusions, from dictating how this science is taught?
- What should be done to make the solution easy to implement, and easy to embrace by instructors on a large scale?

10. Closing Remarks

It is well-established that there are learning difficulties experienced by engineering students taking a first course in thermodynamics. In this paper, an attempt was made to systematically describe these problems, and place them in general categories in order to clearly display them. This formalization was guided by the pertinent literature. Reflecting on, and analysis of, this
literature led to two major learning issues: a) conceptual difficulties and b) inability of students to recall and integrate relevant knowledge in order to solve thermodynamic problems. Reasons and root causes of these issues were listed. The literature, as well as recent statistics, pointed to the continued poor learning/performance of engineering students in thermodynamics. This indicates that the attempted solutions, which were summarized in this paper, have not worked, or have worked partially or locally. The lack of large impact and visible improvement (at the national level) of the solutions lead one to conclude that these solutions have not taken into account the nature and root causes of thermodynamic learning issues. Any envisioned solution to the poor learning of thermodynamics by engineering students would have a better chance of affecting serious change, if it addresses the root causes of the learning issues. Doing this would likely form the foundation for eradicating these problems, and can guide a didactic approach for curriculum and textbook design. It can also inform and positively influence new instructional strategies.

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