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CHALLENGES OF ENGINEERING THERMODYNAMICS EDUCATION

Tamer Ceylan

University of Wisconsin-Platteville, Platteville, Wisconsin; Email: ceylan@uwplatt.edu

1. ABSTRACT

Thermodynamics, a fascinating branch of engineering sciences, is either a required course in some engineering programs or an elective in others. In the author's experience, more than any other undergraduate engineering class, students struggle in introductory thermodynamics. This paper takes a look at the challenges of thermodynamics education and effective methods to deal with them.

Basic thermodynamics is not mathematically complex or heavy in theory. In most cases, computational aspects in this class are limited to simple arithmetic operations. Yet, despite numerous practical applications of thermodynamics, it tends to be an abstract and conceptual subject for most students. There are additional reasons why students have serious difficulties in thermodynamics.

After briefly reviewing the evolution of the thermodynamics education in the past fifty years, many known reasons for the challenges of thermodynamics are given together with effective methods to address them. A comprehensive and solution-oriented analysis of these issues will enable new engineering educators to tailor their teaching techniques for maximum learning effectiveness while providing insights and a useful perspective to experienced educators in this field.

2. INTRODUCTION

Albert Einstein, who is generally accepted as one of the top two geniuses of all times together with Isaac Newton, stated that "The most admirable of all engineering sciences is thermodynamics, whose laws can be simply stated in words and that only after can they be translated into mathematical formulation." (Einstein, 1949) Thermodynamics, arguably the most fascinating branch of engineering sciences, challenges students and educators alike. Teaching it well is a challenge for engineering educators and learning it is an equal challenge for students.

Certain engineering programs (e.g., mechanical, chemical, and nuclear engineering) require at least one semester of thermodynamics. It could be a technical elective in some other engineering programs (e.g., civil, industrial, and electrical engineering). Although thermodynamics can also be taught in a science department, this paper focuses on engineering thermodynamics.

Some engineering educators report that, in their experience, more than any other undergraduate engineering class, students struggle in introductory thermodynamics. This has been the case in the author's over thirty years of teaching experience. If a student takes a second or applied thermodynamics class, it tends to go much smoother than the first one.

It should be noted that basic thermodynamics does not have complex mathematical theories, heavy computing, or lengthy derivations. Students do not find themselves buried in difficult matrix theory or triple integrals. In most cases, computational aspects in this class are very straightforward and limited to simple arithmetic operations. More challenging thermodynamics problems can make use of commercial software (e.g., EES, Mathcad, MATLAB) but this is not the part that gives most difficulty to engineering students.

Similarly, one cannot argue that thermodynamics does not have any practical applications. It has numerous practical applications. One can cite heating and air-conditioning systems, power plants, heat pumps, and many devices in these systems to name a few. Yet, it is not uncommon that some students passing thermodynamics are determined to stay away from anything related to thermodynamics as much as possible.

There are other and very real reasons why many students find thermodynamics frustratingly difficult. The challenges of thermodynamics education and effective methods to deal with them deserve serious consideration and discussion.

3. BRIEF HISTORY OF THERMODYNAMICS EDUCATION

The science of thermodynamics was founded by Rankine, Clausius, and Lord Kelvin. An easy way to track the evolution of the thermodynamics education is to examine the books written in this subject. Although it is generally accepted that Rankine wrote the first thermodynamics textbook in 1859, thermodynamics textbooks of the mid-20th century and anecdotal evidence suggest that, for the large part, engineering thermodynamics was not initially taught in a well-structured and methodical manner, as we understand it today, except in a small number of engineering schools. Using class notes without a textbook was not unusual about sixty years ago. Some examples of good books from that era used at various engineering schools (i.e., Purdue University, University of Wisconsin) were written by Hawkins (1946, 1951) and Obert (1963; 1960; 1949).

In the 1960s, a major breakthrough was the textbook written by Van Wylen and Sonntag and many later editions of it in the subsequent decades (1993). Their book became the leading book and maintained this status for many years because it was viewed as a book that brought a real structure and methodology to how engineering thermodynamics should be taught. Many textbooks in the 1960s, 1970s, and 1980s maintained the same basic structure and made further modifications and improvements.

Another breakthrough came with the publication of the book by Myers (1989, 2007). This book emphasized mass-, energy-, availability- (exergy-), and entropy-balance equations early on (Chapter 1) and reinforced these balances with applications in subsequent chapters. Myers wrote, "one of the primary objectives of this book is to develop second-law concepts in parallel with those of the first law to help make the student feel as comfortable with the concept of availability as with the more familiar concept of energy" and "the concept of the general balance, Inflow + Produced = Outflow + Stored + Destroyed is introduced in the first chapter and immediately applied to the extensive properties of mass, momentum, energy, availability, and entropy." Later books made more use of entropy- and exergy-balance equations as they covered the second law of thermodynamics, but using these balance equations early in the course has not become widespread.

Although there are many thermodynamics textbooks today, two examples are sufficient to describe the current approach: the worldwide bestseller by Cengel and Boles (2011) and the book by Moran, *et al.* (2010). As one looks at the books from the past fifty years, it is easy to notice that today's textbooks are much thicker, presented in a more appealing format, and more expensive, at least if prices are not adjusted for inflation. Also, they use color and contain more problems.

4. CHALLENGES OF THERMODYNAMICS

The central question asked by many thermodynamics teachers for a long time is this: How can we make this subject easier to comprehend for students? This paper will primarily focus on the goal of increasing the student's performance in thermodynamics. One school of thought views this as the student's responsibility. However, taking steps to help them with no compromise on fundamental principles and their applications is the right thing to do.

Secondary goals such as how to engage students more in thermodynamics (Anderson, *et al.*, 2002) or how to make the course material more interesting for students can still be viewed in the context of improving students' learning and performing better on thermodynamics tests. Tebbe, *et al.* (2010; 2008; 2007a; 2007b) worked on the development of the "Engineering Scenario" concept "to combine real world scenarios, problems, and solutions in a way that promotes greater student engagement in the learning process."

Borrowing from educational psychology and cognitive science concepts, Turns and Van Meter (2011) discussed key characteristics and instructional applications of declarative, procedural, and conditional knowledge in thermodynamics. To help the student acquire them, they presented a series of tables or matrices to provide a summary and structure to problem solving in thermodynamics. Turns and Van Meter also suggest assigning "the task of writing verbal explanations for each step of the examples" to students as a learning strategy.

Although there are other ways to group the challenges of thermodynamics, the following practical approach will be taken: the challenges that are under the student's control to some extent and the challenges that stem from the subject matter. Although some educational strategies like giving announced/unannounced short quizzes or making the Rankine cycle a part of a basic thermodynamics course helps both types of challenges, it is best to discuss each type of challenge separately.

4.1 Challenges under the Student's Control

If the right steps are taken, thermodynamics has a set of challenges under the student's control at least to some extent. First, students in thermodynamics need to be made aware of the challenges. Second, they need to accept them. Finally, they need to commit themselves to overcome them by devoting more effort and time. This requires patience and determination on the part of the student.

Motivation to succeed is important. Instructors can take steps to motivate the student but the best motivation is internal. Success in a thermodynamics class should be viewed by the student in a broader picture. As a student, what are your goals in life? Since one might have too many goals, what are your priorities and why? One would think that becoming a successful engineer is one of the few priorities. Clarity on these two issues is not sufficient. Are you managing your time effectively according to your priorities? This brings us to effective time management skills. Effective time management skills can only go so far if they are not combined with effective study habits. Especially at the stage when a student takes thermodynamics, this is a major issue. It is not uncommon to find students who do not read their textbook or review their class notes. The recent trend to heavily use solution manuals, which was unthinkable a generation ago, is worrisome. It is possible to assign problems from other sources and to make better use of technology to address this problem.

Most of the difficulties in thermodynamics are the result of a lack of organized way of thinking on the student's part. The challenge is actually twofold: Thermodynamics requires thinking more than many other subjects, and this thinking process needs to be conducted in a serious and organized way. This skill needs to be nurtured and illustrated by examples in class.

Active involvement in learning thermodynamics is much more effective than passively receiving information and explanations. One useful advice for a thermodynamics student is, "Practice, practice, practice!" The lack of practice on the part of the student can cause a lot of difficulties. With practice, tasks in thermodynamics get easier and become faster (Turns and Van Meter, 2011). Without sufficient practice, a straightforward issue becomes problematic especially during tests. There are reasons why students do not take this advice to heart. Practice takes time, patience, and discipline. Students may find it boring and be unwilling to spend the time it requires. Technology can be used in resourceful ways to encourage practice but not devoting sufficient time to practice still remains a problem. Students need to be convinced that it is necessary to allocate sufficient time to thermodynamics. Underestimating the time it takes to learn thermodynamics could have disastrous consequences. It is not the current practice in most engineering schools but recitation sections in thermodynamics would alleviate this problem.

Patience and discipline need to be brought to the student's attention as useful qualities. The tendency to take shortcuts should be discouraged. This does not eliminate impatience and the tendency to take shortcuts; however, it reduces these unproductive tendencies somewhat, at least for some students.

Overconfidence is another challenge. Most students are young. Overconfidence is a built-in tendency in most young people; this natural phenomenon should be recognized and accepted for what it is. After explaining the difference between overconfidence and a healthy dose of confidence, students should be made aware of possible consequences of overconfidence in thermodynamics. Most or many will still remain overconfident, but some will benefit from this distinction.

If a student claims that poor exam performance is due to "just some silly mistakes" and otherwise he or she "understands the material pretty well", this should be viewed with caution. The problem could be deeper and, in most cases, it is. While recognizing that there were mistakes, the student should be encouraged to consider the strong possibility that perhaps the grasp of the material was not as strong as it should have been. This conversation goes better if it is engaged with the common goal of trying to prevent a similar disappointing exam performance in the future. The tendency to believe that it was just bad luck should be countered by broadening the discussion to make the student consider other aspects and face the reality squarely, however uncomfortable this might be initially.

Many engineering students have a tendency to rely on example problems. To "plug and chug" (or "plug and chuck" as some call it) does not work in thermodynamics. At the same time, "instructors could consider how to help students use these examples most effectively" (Turns and Van Meter, 2011). Cramming in the last day or so does not work either. Unrealistic expectations about these two approaches should be fought early on.

Some students' tendency to skip a class or two for whatever reason should be strongly discouraged by explaining that attendance is very important and that skipping classes can be fatal. Online availability of class discussions in some cases alleviated this problem somewhat. At the same time, online availability made regular class attendance seem less important to some.

Getting a tutor before the first test or right after a disappointing first exam should be encouraged. Many universities and engineering schools make this easy and cost free for struggling students. Finally, forming a study pair or a study group could be suggested in addition to studying alone. Results of such attempts are mixed. Success depends on who a student studies with. A committed student pair or group could indeed help. On the other hand, time spent with another student or student group could be worthless depending on the persons involved.

4.2 Challenges That Stem from the Subject Matter

The challenges in this category are related to the nature and content of thermodynamics. In a typical engineering school, it is not the most favorite and popular class. As always, a caring instructor's enthusiasm and positive attitude about the subject matter would be most helpful.

Many students find introductory thermodynamics very challenging and time consuming. Although there are pedagogical arguments against it, it is still advisable to bring this to the student's attention during the advising process or on the first class day. Students who are inclined to take advice might want to readjust their commitments, class schedules, or work hours especially if doing so will not cause financial problems or a delay in their graduation dates. Most students report that thermodynamics is unlike any other class they took before. What worked reliably before thermodynamics does not work in thermodynamics. It might be a good idea to alert the student to this in the first week of classes so that they can begin making the mental adjustment needed. In addition, in many engineering programs, thermodynamics is the first engineering class or at least the first engineering science class. One way to address this issue is, if the curriculum flexibilities permit, to make a class like, say, Calculus III a prerequisite for thermodynamics. The idea here is not that thermodynamics students need to be familiar with the content of Calculus III to succeed but to ensure that students taking thermodynamics have a higher level of academic maturity.

Although some may change their minds before graduation, in most engineering schools, students report that they find thermodynamics to be too dry, too abstract (Baker, *et al.*, 2000), and too conceptual. They are correct on the conceptual part in the sense that no other class they ever took is as conceptual as thermodynamics. More than fluid dynamics or heat transfer students, thermodynamics students report that they are not able to visualize processes, devices, or systems discussed in class. Yet, as Schmidt (1992) stated, “Airplanes and rockets don’t work without engines, and engines don’t work without thermodynamics.” Since students are very interested in real-world applications, in the beginning of a basic thermodynamics class, the instructor can provide a clear sense of how the student will be able to apply the fundamental principles to practical engineering problems at a later point. In class discussions, rather than treating thermodynamics definitions (say, power cycle efficiency) in an abstract way, it is possible to explain what even a slightly higher plant efficiency would really mean in fuel-cost savings in the long run. An extended discussion of the second law and the concept of entropy with every day examples helps the student internalize these topics.

Actually, if each thermodynamics issue is taken one at a time, most students grasp it without much difficulty. The challenge starts when, given a problem, they need to bring different things together to be able to solve a problem successfully. To address this difficulty, it is suggested that a well-structured problem-solving approach or, at a minimum, a checklist be used routinely especially as the complexity level increases later in the course. Turns and Van Meter (2011) emphasized “the ability to recognize the deep structure of a problem, determine the key features that distinguish problem types from one another, and consequently, select the correct principle to apply.”

In thermodynamics, the course material keeps on building on the earlier material. Falling behind is dangerous because the new material will require a solid knowledge of the earlier material. This aspect of thermodynamics is especially problematic for someone who fails on the first test. In this sense, thermodynamics is quite different from, say, studying the geography of China first and then the geography of Japan. An example from an engineering discipline is this: In heat transfer, someone who does not grasp conduction heat transfer sufficiently might do well later when the other two modes of heat transfer and heat exchangers are discussed.

For students, another problem in thermodynamics is units and unit systems, especially the English system of units. Early emphasis on units and unit systems combined with a no-tolerance attitude on unit mistakes helps but still falls short of resolving the issue completely.

Some students struggle with the proper use of property tables in thermodynamics during the greater part of the course. Once again, practice is highly recommended. An online program that provides them with opportunities to practice looking up properties is helpful. A commercial software program can be used to easily find the properties needed in a problem and to use them in the solution but it is common to emphasize manual solutions first.

Missing a word or two (e.g., isothermal, saturated vapor, polytropic, adiabatic, constant volume, isentropic, ideal gas) in a thermodynamics problem statement may result in no solution. This is much more true in thermodynamics than other engineering classes. It should be emphasized that words have meanings and that missing them may make a solution impossible.

5. CONCLUSIONS

To successfully deal with the challenges of thermodynamics, the ideas presented in this paper are helpful. Sometimes they contribute to a successful strategy but do not completely resolve the issue. In some situations in life, if a perfect solution is not within reach, a partial solution is better than the alternative.

Thermodynamics instructors are encouraged to always keep an open mind to new approaches and ideas to increase the student's learning. While the main course objective should remain emphasizing the fundamental principles of thermodynamics and their applications to idealized problems, the tips presented here and effective use of technology as a tool can be combined to achieve best possible results.

In the interest of continuous improvement, the author would be grateful to anyone who would suggest additional ideas or paradigm shifts on this issue. Carnot, Rankine, Clausius, Lord Kelvin, and Gibbs would be pleased if we can make thermodynamics more palatable and understandable.

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