DIFFICULTIES IN LEARNING THERMODYNAMICS, THAT HAVE THEIR ORIGIN IN THE SUBJECT MATTER


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Abstract

Thermodynamics is hard, according to a widely extended opinion of students that major in engineering, chemistry or science, and of many instructors, around the world. The difficulties in learning the subject have different sources pertaining to the contents, the textbooks, the students, the instructors, the academic institutions, etc. This paper particularly addresses those difficulties in learning the subject that can be traced back to the features of the content matter itself. The study is part of a program of research that investigates in an integral manner the main factors of the problem. A review of pertinent literature, a critical analysis of programs of study with their learning objectives, and many technical debates by a group of experts in physics teaching, pedagogy and psychology, led to the identification of the following set of difficulties directly linked to the content matter of thermodynamics. a) Some of the principles of this subject can be stated in various ways, whose equivalence is not always easy to see. Yet, the student is expected to get a thorough understanding of them all, from the beginning, and use them in problem solving. b) The classical approach to the subject is macroscopic. Looking into the microscopic structure of matter, in the hope of getting a better understanding of the concepts, is a debatable strategy. It can even prove misleading in some cases, if it is not properly used. c) As thermodynamics is traditionally taught through its applications to particular physical systems, the student simply cannot learn the subject if he/she does not acquire, at the same time, a working knowledge of the physics of those systems (e.g. fluid mechanics in many cases). d) Problem solving in this subject frequently needs the use of experimental information, e.g. some physical properties of substances. The retrieval of that information from tables and charts usually requires from the user special skills that the student needs to acquire along the way, to be able to deal with the problems. e) The kind of problems that the student must be able to solve require maturity of judgement. The student will have to make simplifying assumptions and other considerations and decisions, to get to solve the problem with the information provided. f) It is quite common in undergraduate engineering programs that the first formal course on thermodynamics is not a true introductory course to this subject. Instead, it is a first course on thermal engineering. This poses a challenge for the student, who will get confronted with topics and problems from real-life engineering while still striving to understand the concepts and principles of thermodynamics itself. The paper includes some preliminary suggestions aimed to help the students and the instructors to contend with the kind of difficulties here described.

Keywords: thermodynamics teaching, difficulties in learning.

1 INTRODUCTION

The opinion that thermodynamics is a difficult subject in the curricula of science, chemistry and engineering programs is frequently expressed by students and instructors at different institutions all over the world. Not only one finds it repeatedly in blogs where students share their experiences and thoughts, but it is, and has been for long time, also the topic of technical articles and many papers presented in conferences about science and engineering education [1]-[8].

To show this, many authors have cited a quote attributed to Arnold Sommerfeld (1868-1951). They say that when he was asked why he did not write a book on thermodynamics, having written books on most areas of physics, he replied [9]-[12]:

“Thermodynamics is a funny subject. The first time you go through it, you don’t understand it at all. The second time you go through it, you think you understand it, except for one or two points. The third time you go through it, you know you don’t understand it, but by that time you are so used to that subject, it doesn’t bother you anymore”.
By the way, Sommerfeld did write a book on thermodynamics and statistical mechanics, but it was the last volume of his series on theoretical physics.

In 1949, Max Born wrote a very precise criticism of the way classical thermodynamics was structured and taught [13]:

“.. (by) introducing the conception of idealized thermal machines which transform heat into work and vice versa (William Thomson Lord Kelvin), or which pump heat from one reservoir into another (Clausius). The second law of thermodynamics is then derived from the assumption that not all processes of this kind are possible: you cannot transform heat completely into work, nor bring it from a state of lower temperature to one of higher ‘without compensation’. These are new and strange conceptions, obviously borrowed from engineering. (It is true that) [...] the steam-engine existed before thermodynamics; it was a matter of course at that time to use the notions and experiences of the engineer to obtain the laws of heat transformation; and the establishment of the abstract concepts of entropy and absolute temperature by this method is a wonderful achievement. It would be ridiculous to feel anything but admiration for the men who invented these methods. But even as a student, I thought that they deviated too much from the ordinary methods of physics; I discussed the problem with my mathematical friend, Caratheodory, with the result that he analyzed it and produced a much more satisfactory solution. This was about forty years ago, but still all textbooks reproduce the ‘classical’ method, and I am almost certain that the same holds for the great majority of lectures. [...] This state of affairs seems to me one of unhealthy conservatism”.

We can state nowadays (2019) that the approach criticized by Born keeps being commonly used in most courses of thermodynamics at an undergraduate level.

But aside from the usual approach of the subject, complications in learning thermodynamics arise from the fact that thermodynamics is of itself very different from other branches of physics, as has been pointed out by Herbert Callen, incidentally the author of one of the few alternative approaches that have been developed. In the introduction to the second edition (1985) of his book on thermodynamics [14], he states that:

“In contrast to the specificity of mechanics and electromagnetism, the hallmark of thermodynamics is generality [...] it applies to all types of systems in macroscopic aggregation, and [...] (it) does not predict specific numerical values for observable quantities. Instead, thermodynamics sets limits (inequalities) on permissible physical processes, and it establishes relationships among apparently unrelated properties. In brief, thermodynamics is the study of the restrictions on the possible properties of matter that follow from the symmetry properties of the fundamental laws of physics. The connection between the symmetry of fundamental laws and the macroscopic properties of matter is not trivially evident [...]. But even the preliminary assertion of this basis of thermodynamics may help to prepare the reader for the somewhat uncommon form of thermodynamic theory”.

Given that learning is a process that involves different factors: the student, the instructor, the course content, the academic institution, etc., any education researcher seriously trying to find out the reasons for the difficulties that instructors and students face when teaching or learning a subject, will need to consider all of those factors. The work that we report here is concerned only with one of them: the content material. The purpose of the study is to identify those difficulties in learning thermodynamics, whose origin comes from the course content itself. This makes sense in this case because the study is part of a wider program of research that investigates, in an integral manner, all the main factors of the problem.

2 METHODOLOGY

Many of the problems associated with the teaching and learning of thermodynamics have been discussed for decades, and a rich literature has emerged on the topic: articles in journals and conference records, as well as the classical and contemporary textbooks for the subject. A careful review of that literature was made, paying special attention to review articles that comprise a wealth of ideas, proposals and experiences from specialists and instructors at different countries, at different times.

The core part of our study comprised a large series of analytical debates about the teaching and learning of thermodynamics, carried out by a group of specialists in physics teaching, pedagogy and psychology, which led us to a deeper understanding of the problem, and eventually to the set of conclusions that this paper presents.
To estimate the relative difficulty of a typical course on thermodynamics, a comparison was made between the learning objectives of that course and those of other physics courses that occupy similar positions in the programs of study at our own institution, the School of Engineering of the National Autonomous University of Mexico.

3 RESULTS

Among the various learning difficulties reported by students and instructors of thermodynamics at the undergraduate level, six of them were identified by our research, which relate directly to the features of the subject, that is, to its technical content.

a) The multiplicity of statements for one same principle

Some of the principles of this subject can be stated in various ways, whose equivalence is not always easy to see. Yet, the student is expected to get a thorough understanding of them all, from the beginning, and use them in problem solving. A few new approaches to classical thermodynamics have been proposed that avoid, among other undesirable features of the traditional approach, the multiplicity of statements for the same principle.

b) Disregard of the microscopic nature of matter

The classical approach to the subject is macroscopic. Looking into the microscopic structure of matter in the hope of getting a better understanding of the concepts is a debatable strategy. It will not always help. It can even prove misleading in some cases, if it is not properly used.

c) Introduction of the subject through particular applications

As thermodynamics is traditionally taught through its applications to particular physical systems, the student simply cannot learn the subject if he/she does not acquire, at the same time, a working knowledge of the physics of those systems (typically, fluid mechanics).

d) Technical-information retrieval

Problem solving in this subject frequently needs the use of experimental information, e.g. some physical properties of substances. The retrieval of technical information from tables and charts usually requires from the user special skills that the student needs to acquire along the way, to be able to deal with application problems.

e) The requirement of maturity of judgement for students in the introductory course

The kind of problems that the student must be able to solve require maturity of judgement. The student will have to make simplifying assumptions and other considerations and decisions, to get to solve the problem with the information provided. Table 1 compares the (published) learning objectives for problem-solving goals of two second-year courses in the program of mechanical engineering, at the academic institution of the authors (translated from the official curricula, published in Spanish) http://www.ingenieria.unam.mx/programas_academicos/licenciatura/Mecanica/2016/asignaturas_mecanica_2016.pdf.

<table>
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<tr>
<th>Course</th>
<th>Learning objectives</th>
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<tbody>
<tr>
<td>Thermodynamics</td>
<td>The student will [...] develop observation- and logical reasoning skills, and use them to make decisions when solving problems that require balances of mass, energy and entropy ..</td>
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<tr>
<td>Kinematics and Dynamics</td>
<td>The student will [...] analyze and solve problems on kinematics and kinetics.</td>
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The ability to make decisions, which is required in Thermodynamics, sets the skills required in this course at a higher level in Bloom’s taxonomy of learning objectives, than those of Kinematics and Dynamics. This can explain, at least to some extent, the higher level of difficulty which the course on thermodynamics has.
f) Focus on thermal engineering, not on introductory thermodynamics

It is quite common in undergraduate engineering programs that the first formal course on thermodynamics is not a true introductory course to this subject. Instead, it is the first course on thermal engineering. This poses a challenge for the student, who will get confronted with topics and problems from real-life engineering while still striving to understand the concepts and principles of basic thermodynamics itself. Table 2 shows a comparison between some of the learning objectives for the course of Thermodynamics and those for Acoustics and Optics. Both courses are part of the Electrical Engineering program at the academic institution of the authors. (Translated from the official curricula, published in Spanish) http://www.ingenieria.unam.mx/programas_academicos/licenciatura/Electrica_Electronica/2016/asignaturas_electrica_2016.pdf.

<table>
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<th>Course</th>
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<tbody>
<tr>
<td>Thermodynamics</td>
<td>The student will make mathematical models for typical application problems of engineering, and will use mass and energy balance equations to solve those problems quantitatively.</td>
</tr>
<tr>
<td>Acoustics and Optics</td>
<td>The student will understand fundamental aspects of the behavior of light and sound, and will get familiarity with the mathematical models that describe them, to be able to undertake, in subsequent courses, problems related to the generation, transmission, detection and processing of optical and acoustical signals.</td>
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As shown, in Thermodynamics the student is confronted with problems of engineering right away, within the course. In Acoustics and Optics, by contrast, he/she only has to understand fundamental aspects of the discipline, to be prepared for problems to come in subsequent courses, related to engineering applications. Once again, the requirements in Thermodynamics are higher than those in the other course. Incidentally, this is so, even though in this program, Acoustics and Optics comes in the third year, one year later than Thermodynamics.

The (many) abstract concepts that are used in thermodynamics, like temperature, heat, entropy, enthalpy, etc. can certainly be another source of difficulty for the beginner in the field. This aspect was not included, however, in the list above, because the use of that kind of concepts is not an exclusive characteristic of this discipline. For other areas of physics, abstract concepts like time, instant velocity, electric charge, electric field, etc. play a very important role. It is an essential feature of physics and science. Familiarity with the resource to abstract concepts in any systematic study of nature must necessarily be one of the achievements of scientific education, which starts early in the life of any educated person of our time.

4 CONCLUSIONS

The student of thermodynamics at the undergraduate level faces true difficulties in learning the subject and, even though the problem is admittedly multifactorial, some of the most important difficulties are clearly associated with the content matter itself.

It is clear that the classical approach of thermodynamics is inadequate, at least for teaching and learning purposes. Various alternative approaches have been developed that would be worth trying, in search for better instructional results [2], [14], [15], [16].

Formal education research is needed to produce evidence-based technical guidelines that effectively help to improve the teaching and learning of this subject. New approaches based on alternative theories must be tested under rigorous criteria, to make sure that they meet the didactic requirements that the traditional approach does not meet.

An introductory course on thermodynamics should precede the first course on engineering thermodynamics in undergraduate programs of study.

While evidence-based teaching strategies start to appear for the subject, students and instructors are strongly advised to take advantage of the many teaching aids that technology provides, like videos, interactive simulators, discussion forums, etc.
ACKNOWLEDGEMENTS

Project “Factores que intervienen en la docencia de la termodinámica en ingeniería causando dificultad en su enseñanza y aprendizaje; propuestas de solución”, which is the framework for the study reported in this paper, has been funded by the PAPIME grant program of the National Autonomous University of Mexico under grant number: PE106518.

REFERENCES


