Identifying common problems in the determination of the thermodynamic properties of pure substances by Mechanical Engineering undergraduate students

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Introduction

Thermodynamics, the science of energy, represents one of the core areas of technical competency that undergraduate mechanical engineering students are typically expected to master. However, it has been frequently observed that the field is one in which students struggle.

To underscore this point, Dukhan (2014) noted that between 2002 and 2012 in the USA's Fundamentals of Engineering Exam (administered by the National Council of Examiners for Engineering and Surveyors) typically a third to half of mechanical engineering students failed the thermodynamics component. That said, the apparent difficulties posed by thermodynamics are not limited to students in the USA, with the situation having been noted in Europe (Partanen, 2016), Malaysia (Abdullah et al, 2013), India (Kulkarni and Tambade, 2013), New Zealand (Anderson et al, 2016) and Australia (Capra, 2015).

Given the widespread nature of the issue, numerous researchers have hypothesised as to the cause of this and proposed strategies for countering it. At perhaps the most basic level, Anderson et al (2016) noted a positive correlation between student attendance at face-to-face lectures and tutorials with their overall grade and a strong positive correlation between a student's performance in the pre-requisite course in dynamics and their result in thermodynamics. This highlighted two potential factors at play in determining student success in thermodynamics: student engagement and entry preparation.

In a similar vein, Ugursal and Cruikshank (2015) undertook an extensive survey of student perceptions of thermodynamics that showed students found thermodynamics "boring" or "not-so-interesting". This was compounded by the fact that students who felt they had a demanding professor found thermodynamics more difficult.

Dukhan (2014) argued that perhaps the sequence of "typical" instruction in thermodynamics: starting with abstract concepts, moving to energy, properties of pure substances, first law in a closed system, open steady flow, the Carnot cycle and second law and entropy though logical may be to blame for poor student performance. Dukhan suggests that this can lead students to "fall under heavy cognitive load", to not see the real context of thermodynamics or for them to receive their knowledge in a fragmented form.

At a more specific level, Loverude et al (2002) noted the difficulties students encountered around concepts such as heat, work, temperature and internal energy. They suggested that some of the problems students encounter when linking work with heat may be related to difficulties with mechanics. These issues were also encountered by Prince et al (2009), who noted the difficulties students had with rates versus quantity and the misconception of temperature as a measure of the quantity of energy/heat. This recurring misconception, frequented in the literature, is that of the difference between a path function (e.g. work or heat transfer) and a state function (e.g. temperature, volume, enthalpy).

The confusion between states and paths is a persistent misconception and in part may be due to the use of thermodynamic terms in the everyday vernacular, and the treatment of thermal science in pre-university education. For example, it is common to hear mention of "heat" tied to temperature, for example: 'it's hot today', similarly everyone 'knows' that water boils at 100°C (although this is only true at standard atmospheric pressure); several of these issues were discussed by Alwan (2011). This confusion leads to significant challenges, particularly in attempting to equip students with an understanding of the thermodynamic properties of pure substances.

As noted earlier, the determination of the thermodynamic properties of pure substances tends to be one of the earliest topics addressed in thermodynamics. This is because it allows engineers to determine the states that define the start and finish of a path. One of the issues that this presents is that if students fail to grasp this early concept, they will be unable to progress to latter concepts (Ceylan, 2012).

In a typical treatment of the properties of pure substances, a textbook (e.g. Cengel and Boles, 2015) will often start by discussing solids, liquids and gases before proceeding through the transition from a compressed liquid to superheated vapour with reference to temperature-volume diagrams, pressure-volume diagrams, pressure-volume-temperature surfaces and finishing with ideal gas relationships. Along the way it will typically introduce several thermodynamic properties such as specific volume and quality and introduce the use of property tables and the ideal gas law.

Dixon (2001) however argues vigorously for the elimination of property tables in favour of computer-based property calculations. He suggests that mastery of tabulated data serves as an impediment to a student's understanding of the thermodynamic processes and the need to (potentially) interpolate may lead to unnecessary confusion. Bakrania (2017) and Bakrania and Mallouk (2017) take a more measured view of property data, instead advocating for the use of computational tools in the form of temperature-entropy and pressure-enthalpy diagrams. Such diagrams have historically been a mainstay of thermodynamics calculations in industries such as heating, ventilation and air-conditioning and are frequently used as visual illustrations of phase change processes in many thermodynamics courses.

Despite the calls for alternatives, the use of the ideal gas law and property tables (which may appear archaic) is quite ingrained in thermodynamics education. This is most likely due to tables being readily available (in most undergraduate textbooks), easily reproduced and avoids equity issues (Dixon, 2001) relating to students who do not have access to a programmable calculator. Given the ubiquity of the ideal gas law and thermodynamic property tables, it then raises the need to understand the common mistakes students make in the determination of the thermodynamic properties of pure substances to better inform how students are introduced to the use of these tools.

Method

In order to gain an understanding of the most common errors students make in determining the thermodynamic properties of pure substances, this study categorised the mistakes made by students in a test on the subject and analysed their frequency.

The test was undertaken by two consecutive cohorts (84 students in Cohort 1 and 87 in Cohort 2) of second year Bachelor of Engineering Technology (Mechanical) students studying "Thermodynamics and Heat Transfer" at Auckland University of Technology. This course examines basic thermodynamic principles, such as the ideal gas law, property tables, mass and energy conservation and follows on from an introductory course entitled "Introduction to Thermofluids and Energy". As such, "Thermodynamics and Heat Transfer" is not the first encounter students have with thermodynamics, or the ideal gas law, but does represent a notable increase in their expected outcome.

In conducting the test, worth 5% of their overall grade, students were given 20 minutes to answer two questions involving the use of the ideal gas law and thermodynamic property tables. To achieve this, students were supplied with a formula sheet containing some general thermodynamics relationships and an abridged set of the property tables from Cengel and Boles (2015). Although the test questions were changed between the two cohorts, the style and level of difficulty in the questions was similar, as shown in Appendix A. In these tests, the first question involves a student manipulating the ideal gas relationship and the second involves completing a table of missing property data for water as a compressed liquid, saturated mixture of superheated vapour using the tabulated data provided.

During marking, any incorrect answers were noted, and an attempt was made to categorise the nature of the most significant error. Subsequently, the frequency of occurrence was determined, with a view to determining any common mistakes.

Results and Discussion

From the results of the tests, both cohorts performed similarly, with the average mark being 63% and 66% respectively. That said, in the marking of the two tests it was apparent that there were several common mistakes that students made when dealing with the ideal gas equation: simple arithmetic errors, incorrectly manipulating the equation, poor handling of units and more fundamentally, misunderstanding the concept of/terms - volume, specific volume and density. Table 1 shows the frequency of mistakes made by category for the two cohorts.

Table 1: Nature of mistake when using the ideal gas equation and number of occurrences

Application of Ideal Gas Equation Errors		
Common error	No. of Instances	
	Cohort 1 (n=84)	Cohort 2 (n=87)
Misidentified Variable	29	7
Unit Omission	20	6
Unit Conversion	8	2
Mathematical Manipulation	4	6
Computational	3	2

Although data was not gathered formally, it became apparent from discussions with students, that many had made “some silly mistakes”. Ceylan (2012) notes that this reason is often provided by students (perhaps as a denial coping mechanism) but can be an indicator of a deeper lack of understanding. This lack of understanding may explain the frequency with which volume, specific volume and density were confused.

A similar result was highlighted in de Berg’s (1995) study which found that over 1/3 of 17 and 18-year-old college students did not understand the concepts of volume and mass of a gas as it related to a gas in different states of compression. That said, it should be noted that the greatest number of mistakes occurred in the determination of the specific volume, which reflects the apparent difficulty students have in understanding ‘specific’ properties.

In addition, and again its occurrence was not formally recorded, it was apparent that many students’ test strategy consisted of removing the formula sheet at the beginning of the test and staring intently at it, perhaps awaiting divine intervention, and somewhat like going to a smorgasbord restaurant. This also suggests a lack of understanding or a propensity by students to “plug and chug” variables into formulae, as Ceylan (2012) puts it. This approach, which may work in other areas of engineering, but can cause students to fall-down in thermodynamics where concepts are built up over time.

Similarly, in dealing with the property tables, there were several common mistakes that were observed, as noted in Table 2. The most obvious of these relates to students being unable to determine the phase (i.e. compressed liquid, saturated liquid/vapour, saturated mixture or superheated vapour). Saturated mixtures present a particular challenge, as many students have failed to develop a systematic approach to determining whether they are on the saturation line, in the mixture region or have a superheated vapour (Abdullah, 2013, includes a nice flow chart illustrating the process for reading tables). Similarly, quality represents a challenge, and often falls victim to the “plug and chug”, leading students to obtain quality values greater than 1 for superheated vapours.

Table 2: Nature of mistakes when using property tables, and number of occurrences

Application of Steam Tables		
Common errors by state	No. of Instances	
	Cohort 1 (n=84)	Cohort 2 (n=87)
Compressed Liquid		
Defined Quality x	19	29
Used Saturated Gas Properties	11	22
Used Saturated Pressure Value	10	10
No response	22	42
Superheated		
Defined Quality x	19	31
Used saturated properties	29	49
No response	20	12
Saturated Mixture		
Ignored Quality x	18	22
Incorrect Quality x provided	50	26
Incorrect Pressure units	28	-
No response	10	22

One observation, that is not immediately apparent from the tabulated results, is for students to favour the Saturated Water – Temperature Table over the Saturated Water – Pressure Table, perhaps because students feel more comfortable with temperature than pressure. This approach can lead to issues in determining a substances state, as it requires a student to understand that at a mixture at a given saturation temperature subject to a reduction in pressure will lead to a superheated vapour. However, many students struggle with this idea, and the assertion that water can boil at room temperature, if the pressure is low enough, is often met with disbelief or the question ‘is it hot’? Contrary to this, at a given saturation pressure an increase in temperature will lead to a superheated vapour, which is perhaps a more accessible explanation and starting point.

Conclusion

The observations made in this study broadly reflect those encountered by numerous authors in the field, which generally highlight the poor performance of students in the field of thermodynamics. Overall, this work has noted that there are perhaps several factors at play in the broader picture. Principally it highlights the fact that many students struggle in determining thermodynamic properties (i.e. state variables), which can lead to ongoing problems once these begin to be applied to higher level problems.

It appears that part of student difficulties stems from their experience and everyday vernacular, and a naïve/low level approach to problem framing and appreciation of understanding (over-reliance on formulae). Further, underlying this is an implicit need to instil a more systematic approach to determining property data, and an appreciation for the meaning of terminology relating to thermodynamic properties, into students.

Appendix A

Cohort 1:

Question 1 - What is the specific volume of air (R=287J/kgK) at 5MPa (absolute) and 227°C. (1 mark)

Question 2 - Fill in the missing property data for water (4 marks)

T (°C)	P (kPa)	u (kJ/kg)	Quality
	100		0.5
125		2534.6	
55	1000		
	500	3129	

Cohort 2:

Question 1 - What is the density of argon (R=208.1J/kgK) at 27°C and 500kPa (absolute) (1 mark)

Question 2 - Fill in the missing property data for water (4 marks)

T (°C)	P (kPa)	u (kJ/kg)	Quality
	150		0.5
100	1000		
	200	2967.2	
55		230.24	

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Acknowledgements

Smitesh Bakrania would like to thank the Fulbright Program for supporting the author's visit to Auckland University of Technology to undertake this research.

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