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Building a Foundation: Tools for Accentuating the First Law in an Introductory Thermodynamics Course

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Abstract

Fundamentals courses play an instrumental role in developing undergraduate students into skilled problem solvers. As such, these courses bear the responsibility of (1) instilling discipline in problem solving and (2) familiarizing students with central concepts of engineering. The two goals are inextricably linked. Success in problem solving is contingent upon understanding a remarkably few fundamental principles. Upon first introduction to new concepts, however, students usually lack the experience to understand how foundational those principles really are. In fact they can be adept at compartmentalizing information at the expense of building up a foundation of knowledge. While this tactic may present a hope for short term success, as the quantity and variety of problems increase, their ability to apply the appropriate principle suffers. This is why discipline within the problem solving method is so important; it forces the application of a very few fundamental concepts to a broad array of problems. This paper discusses the use of tools to encourage such discipline in an introductory Thermodynamics course. These include a first law classroom poster, first law student stickers, and guided in-class examples to encourage repeated application of the same principle to a myriad of problems presented to them in class, as homework, and on exams.

Introduction

Foundational engineering courses (e.g. Statics, Thermodynamics, and Circuits) aim to teach a problem solving method which involves, among other things, identifying appropriate assumptions and applying fundamental principles. In so doing, two student outcomes are pursued: the ability to apply knowledge of the fundamental principles and the ability to formulate and solve problems using these principles.[1] Though each course presents its own subset of concepts for students to master, the problem solving skills needed to employ them is fairly consistent. The first challenge is to model the system, typically requiring a system sketch (e.g. free-body diagram, circuit diagram). The model is an abstraction of the real system, and as such incorporates simplifying assumptions which make it more tractable. In some cases, these assumptions may be consistent and implicit through an entire course. For example, the assumption of non-accelerating rigid bodies in Statics. However, a student's ability to choose appropriate assumptions is an essential skill in developing the model, particularly for Thermodynamics. Subsequent to modeling, analysis requires the application of one or more fundamental principles (e.g. conservation of mass, momentum, or energy).

Again, the treatment of the assumptions is a key analysis skill developed in a Thermodynamics course which may or may not be as prevalent in other foundational courses.

This paper discusses simple tools used within an introductory Thermodynamics course, used to enforce discipline within the problem solving process. In particular, these tools aim to highlight the fundamental nature of the first law of thermodynamics and facilitate the students' treatment of modeling assumptions. The course is typically taken by first semester sophomores within a Bachelor of Science in Engineering (BSE) program. The BSE is a practice-oriented, flexible program which includes a "core" set of required foundational courses in math, science, and engineering, but also allows students flexibility in choosing 30 hours of technical electives. Faculty across engineering disciplines (civil, electrical, mechanical, and industrial) reside in a single academic department. One of the goals of the program is to build a broad, yet solid foundation from which students derive the knowledge and skill to tackle multidisciplinary problems. As such, there is a natural focus on developing consistency in problem solving.

Developing Problem Solving Skill

In an introduction to engineering text, Brockman[2] distinguishes between declarative versus procedural knowledge. The two are interdependent as an understanding of how nature works (declarative) is necessary to make predictions about how it will work for a specific problem. A general instructional approach is to provide students with a variety of specific problems in hopes to build confidence in general concepts and develop problem solving skill. However, numerous studies have shown students continue to struggle with concepts in thermodynamics even after instruction. Dukhan[3] provides a comprehensive literature survey to this effect. In particular, Meltzer[4] shows that students may even be able to solve a particular problem (or at least obtain a correct answer) without being able to articulate the principle behind his or her solution. Finally, Ghosh[5] uses a dichotomy similar to Brockman's (the "know why" and "know how") in identifying widespread prerequisite deficiencies among students taking advanced courses in the thermal-fluid sciences. These results seem to indicate an overall lack of problem solving acumen. Students may have an ability to replicate a solution to a particular problem, but lack an understanding of the broad application of the underlying principle more generally.

A brief review of textbooks for a variety foundational engineering courses reveals common elements to the problem solving process despite differences in enumeration and labeling of individual steps.[6–8] These include steps involving modeling (i.e. reducing the physical problem to one represented schematically and/or mathematically) and steps associated with analysis (applying fundamental principles to the reduced model to predict a response). Selecting and applying assumptions is a critical component for both stages. However, student attentiveness to assumptions has often been found wanting. Papadopoulos et al[9] cite treatment of assumptions as one of three key areas of concern in mechanics courses, for example. They record two areas of concern: (1) an inability to formulate assumptions when not explicitly stated in a problem and (2) a failure to apply assumptions even if explicitly given. Several papers have proposed an enhanced, systematic problem solving approach to combat these issues.[10–12] In particular, Turns et al[12] discuss the use of "matrix notes" to address assumptions associated with closed systems of ideal gases in introductory thermodynamics. The notes delineate differences in how to determine properties, construct phase diagrams, and find boundary work. A matrix summary of specific control volume components is one tool is also used here. In this case, the focus is on terms within the first law equation for control volumes. The idea is to impress upon students that the underlying principle (in this case, the first law thermodynamics) is always the same, while providing them with experience to distinguish between components by the assumptions used to model them.

For this course, the problem solving methodology adopted is that outlined by Moran et al[8] in their introductory thermal systems text. It delineates six elements: known, find, schematic, assumptions, properties, and analysis. The authors have made efforts to enforce this process through in-class examples, homework, and exams. However, student difficulties in handling assumptions persist. In some cases, the breakdown is a matter of reading comprehension. For example, understanding that ”well insulated” suggests a lack of heat transfer across a boundary or that ”rigid” usually implies zero volume change. In other cases, students resort to rote copying of an assumption from one problem to the next without assessing what makes each problem unique. In the following section, a matrix notes method is discussed as a way of presenting appropriate assumptions for modeling a variety of control volume components. This is followed by a discussion on the use of tools to enforce problem solving discipline in the analysis phase.

Assumptions for Control Volume Systems

Despite the universality of the first law of thermodynamics, textbooks often present several variants of the first law equation based on simplifying assumptions applicable for various special cases. As a case in point, the Fundamentals of Engineering Supplied-Reference Handbook includes 6 first law equations for closed systems and 11 for control-volume systems. This often leads to confusion and detracts from the students' appreciation for the fundamental nature of the principle. The authors have typically modeled problem solutions using only two first law equations: one for closed systems and one for control volumes. The form of the first law used for control volumes is provided below.

$$dE_{cv}/dt = \dot{Q}_{cv} - \dot{W}_{cv} + \Sigma\dot{m}_i(h_i + V_i^2/2 + gz_i) - \Sigma\dot{m}_e(h_e + V_e^2/2 + gz_e) \tag{1}$$

The left term is the total rate of energy change with the system or control volume. The terms on the right include the rate of heat transfer ($\dot{Q}_{cv}$) and power ($\dot{W}_{cv}$) crossing the system boundary as well as enthalpy (h), kinetic energy ($V^2/2$), and potential energy (gz) associated with inlets (indicated by the subscript 'i') and exits (indicated by subscript 'e').

The first assumption to be addressed is the ”steady state” idealization, applicable for numerous control volumes. Students are introduced to this concept early on, namely that *properties* do not change with respect to time. Since total energy of the control volume is a *property* the left hand side of the first law equation becomes zero for this idealization.

The first law then provides the basis for discussing assumptions associated with specific components. The primary thing students should learn (even memorize) about a specific component is its purpose. Understanding a component's purpose is essential in avoiding making inappropriate assumptions. For example, if the primary purpose of a nozzle is to increase velocity, kinetic energy should definitely NOT be neglected. Similarly, if the purpose of a turbine or pump is to generate work, one would expect power to be significant. Heat exchangers pose the most difficult conceptual hurdle in this regard as students are often confused when the rate of heat transfer can or cannot be neglected. The answer, of course, lies in the selection of the system which is another component of modeling. For a system insulated from its surroundings, the rate of heat transfer is usually approximated as zero. This includes heat exchangers for which the sole purpose is heat transfer *within* the system.

The second key idea for each component is how it achieves its purpose. Here it helps for students to use their own experience to the extent possible. For example, is an external source of power required (in which case, power should NOT be neglected.) In simple terms, one might ask "does it need to be plugged in?" For a pump, students should know that the answer is yes. For a garden hose nozzle, the answer is no. Thus for a nozzle, it is appropriate to assume $\dot{W}_{cv} = 0$. For a heat exchanger, students may be asked to imagine their bathroom faucet. It doesn't require power to mix hot and cold streams. Understanding a component's purpose and means of achieving that purpose also allows students to pair converse components such as nozzles and diffusers, turbines and compressors, etc. in which the pair is distinguished by reversing purpose with means. For example a nozzle's purpose is to increase velocity which it achieves through a drop in pressure (manifested as a drop in enthalpy) while a diffuser reverses this cause and effect.

Thus the purpose and primary means of achieving the purpose are the students' keys to understanding which terms within the first law equation should NOT be neglected. For other terms, students must be on guard for key phrases within a problem statement. In addition, terms can often be neglected initially, and checked for significance after analysis. It is suggested to have student's adopt this practice as a means of evaluating their assumptions whenever possible. For example, students may be asked to find a turbine's power output between a given exit and inlet state. How does their solution change depending on their assumptions regarding the rate of heat transfer?

Assumption *Device*	$\dot{m}_i = \dot{m}_e$?	Δke	Δpe	$\dot{W}_{cv}$	$\dot{Q}$	*Purpose*
Nozzles/ Diffusers	yes	Nozzle (+) Diffuser (-)	~0	0	~0	Nozzle - Increase velocity Diffuser - Decrease velocity/increase Pressure
Turbines	yes	~0	~0	+	sometimes neglected	Generate power
Compressor/pump	yes	~0	~0, depends on system boundary	—	sometimes neglected	Increase pressure
Heat Exchangers	Depends on system boundary	~0	~0	0	Depends on system boundary	Exchange heat between system and surroundings OR between streams within a system
Throttles	yes	~0	~0	0	~0	Reduce pressure

Figure 1: Assumption Matrix for Control Volume Components.

A final assumption to be considered relating to the first law is that of a single inlet and exit stream under steady state flow conditions. For this case, students should derive from the conservation of mass principle that $\dot{m}_i = \dot{m}_e$. This is less obvious to students than one might suspect as they frequently forget to expand the summation at the inlets and exits for components when this assumption does not apply. The treatment of components can thus be summarized in the form of a matrix as shown in Figure 1. The matrix is filled in with 0 for terms typically neglected and either + or - for other terms as expected for each component.

It should be noted that there are additional component assumptions not directly related to terms in the first law. Typically, these affect a relationship among properties. For example, using the one-dimensional flow simplification allows one to relate mass flow rate and velocity. Other examples include the ideal gas assumption, constant specific heats, isentropic behavior, etc. Students are encouraged to draw the implication of such idealizations within the ”assumptions” stage of the problem solution. A sample to guide students in the assumptions stage for a particular problem involving a hot air furnace is provided in Figure 2.

Assumptions:

1. Air is an___*ideal gas*___, *R* =___$0.287\ kJ/kg\,K$___, and $pv = RT$
2. Steady state, therefore $\frac{dm_{cv}}{dt} = 0$ *and* $\frac{dE_{cv}}{dt} = 0$
3. 1D Flow, therefore $\dot{m} = \frac{AV}{v}$

Figure 2: Sample ”Assumptions” Section for Guided Problem Solutions.

Tools to Accentuate the First Law

After a suitable system model is developed, complete with appropriate assumptions, the problem solving process can proceed into analysis. This starts with complete statement of the foundational principles, i.e. conservation of mass and the first and second laws of thermodynamics. A reduced form of the first law is obtained only after applying the assumptions (e.g. by crossing out neglected terms and expanding the summations at the inlet and exit). The hope is for students to embrace the full form of the foundational principle and rely on their understanding of specific components to develop a reduced equation each time rather than attempting to memorize a specific solution method for each type of component. To encourage students to adopt discipline in this approach requires leading by example and assessing their solution process.

The first tool employed is the guided solution outline. Following the six step Moran process (or any other systematic process for that matter) takes commitment and time. The authors have found that providing students a guided solution outline enables more examples to be presented within the limitations of class time without sacrificing the emphasis on process. The level of direction can be tailored to the students' experience at a given point in the semester. In every case, the guide includes the six steps (Known, Find, Schematic, Assumptions, Properties, and Analysis). In most cases, known and required items which are obvious from the problem statement are also filled in. The schematic may or may not be included or complete (for examples, students may need to draw the boundary). In some cases a place for a property diagram is given. The Assumptions and

Analysis steps may have prompts (e.g. see Figure 2) for the first few problems provided and less direction as the students gain experience.

To complement the solution outline, students were provided with stickers of Equation 1. The stickers were created on 4 inch x 1 inch address labels. The outlines provide a space at the beginning of ”Analysis” to paste the sticker. At the same time, a poster of Equation 1 was created for the classroom. The poster is framed in an inexpensive 1 ft x 3 ft frame with a plexiglass cover. The cover works well with dry-erase markers. Thus during analysis, the instructor is able to repeatedly use the poster, crossing out neglected terms to create a reduced mathematical model. Students can replicate this by crossing out terms on their sticker. Students were also allowed to use the stickers for homework. Students appreciate a rather modest accommodation of not having to write the equation by hand. What they gain is a clear understanding that there is only one first law equation that they are repeatedly applying to a wide variety of control volume systems. While reducing the number of times students write out the full equation admittedly detracts from their ability to ”memorize the formula”, many instructors already allow equation sheets. It is thought to be much preferred that they resort to a sticker of the complete equation rather than attempting a scavenger hunt for the ”nozzle” or ”turbine” equation.

It is worth noting that this tool could be replicated for any conservation law that has multiple terms that are negligible under different conditions. The stickers demonstrate that the different simplified forms of the governing equations are not unique. For example, the set of Navier-Stokes equations (which describe the conservation of mass and momentum which govern fluid motion) could be treated in the same way. However, the Conservation of Energy is one of the first conservation laws that is simplified in this manner, and so its introduction in Thermodynamics is an opportunity to demonstrate this general principle so the students will be able to apply the same principles when they come into contact with it in their future classes.

Student Assessment

The tools discussed in the previous section were adopted for three offerings of an introductory thermodynamics course: Spring, Summer, and Fall 2013. Their impact was monitored by comparing routine course metrics (final exam grades and ABET metrics), reviewing a sample of final exams, and through a post-course survey provided in January of 2014.

The tools proved to have no statistically significant impact on final exam grades (averages for the terms before and after implementation were within 1% point for the same instructor and term). In addition, a comparison was made between end of course assessment metrics for the following student outcome and performance indicator:

- Students will have an ability to identify, formulate, and solve engineering problems: Formulate statements of energy conservation for a variety of devices and systems.

The year prior to implementation of the tools discussed herein, students averaged 76% on the questions selected for assessment. For two offerings since implementation, the averages were 73% and 94% respectively. It should be noted that the 94% was for a summer offering in which most students only take one course. Based on these results, it would appear the tools do not produce an adverse effect on student learning.

In addition, a review of a comprehensive cycle problem on a recent final exam was conducted to see if (1) students were able to appropriately identify assumptions and (2) whether they started analysis with a full form of the first law equation. In the first case, six of seven students identified appropriate assumptions. The remaining student identified implications for the assumptions (for example $dE_{cv}/dt = 0$) without explaining the reason. However, none of the students produced a full form of the first law in analyzing the cycle components despite the fact that all in class problems were modeled this way. This was a bit discouraging but perhaps understandable given both the time pressures of the exam and the number of examples of specific cycles students had completed to that point. One possibility for the future is to offer a final exam problem for which the cycle and components are not explicitly named.

A web-based post-course survey was also offered to students who had completed Thermodynamics within the previous year. The survey included multiple choice questions aimed at assessing their retention of skills learned in the course, as well as Likert-style questions regarding their opinions on the effectiveness of the tools discussed herein. Fifteen students (24.5% of those attempting the course) responded. Of these, 93.3% were able to identify the control volume first law equation as a statement of conservation of energy. In addition, the survey presented students with the following reduced equation:

$$0 = h_i + \frac{V_i^2}{2} - h_e - \frac{V_e^2}{2} \tag{2}$$

Only 53.3% were able to identify this as an applicable reduction for a nozzle. However, students were 82.9% correct in identifying the individual assumptions required to arrive at this reduced equation. In addition, 80.0% were able to identify the proper reduced equation for a set of assumptions pertaining to a mixing heat exchanger. Given that students completed the survey anywhere from one to seven months after completing the course with no expected preparation, these results were mostly encouraging. Twelve and eleven of the fifteen respondents respectively, either agreed or strongly agreed with the phrases "I am comfortable applying the first law equation in the analysis of control volume systems" and "Thermodynamics improved my problem solving ability." Finally, eleven responded to the open question "Please provide any additional comments on the value of tools used in class to include 1) first law stickers, 2) first law classroom poster, and 3) guided in-class problem sets." Eight positively addressed the first law stickers. One comment particularly addressed the authors' goal with the stickers: "The stickers with the entire formula and crossing out what was unnecessary helped me catch on." Two students, however, did not like the stickers. One felt they detracted from his ability to memorize the equation. Another felt that the instructor's offer to provide additional stickers to students who performed well on one of the quizzes was using the stickers unfairly as a reward. Six students specifically mentioned appreciation for the guided problem sets, and two others felt there should be more of them. Finally, two students positively indicated that the poster was helpful. Overall, the comments reflected an appreciation for the intent of the tools to improve problem solving.

Conclusions

In summary, the struggles of students with understanding thermodynamic principles are well documented. This has a marked effect on their development as problem solvers. This paper presents an approach along with a few simple tools to improve student understanding of the development and use of assumptions associated with specific control volume components. The goal is to encourage them to adopt the general principle and use their intuition to apply it to the particular rather than memorize a set of ”solutions” to the variety of problems. Introducing specific components with a focus on their purpose and how they achieve that purpose facilitates the selection of assumptions. This is enforced with a matrix summary of all the components. In addition, discipline and repetition is developed in the problem solving process by providing guided solutions and first law stickers.

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