Workshop Exercises for Connecting Fundamentals to Equipment in the First Thermodynamics Course

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Abstract

Using balance equations for mass, energy and entropy and property diagrams for analysis, design and intuition about thermodynamic processes is a basic skill which many students find difficult to master. The abstractness of these fundamental relationships and graphs requires students to have moved from concrete to abstract thinking, but this often has not occurred by the second year. Further, many students lack essential connections between scientific/technological descriptions and physical behavior of real systems. We believe that a successful first course in engineering thermodynamics must address these issues by careful and comprehensive pedagogy and assessment. This paper describes our approach that involves laboratory workshops.

In our course is taken principally by mechanical and chemical engineering majors. For it, we have developed nearly a dozen 1-hour laboratory sessions to augment classroom activities and to facilitate student growth in connecting descriptions to behavior. These include 1) simple custom devices such as piston/cylinder systems and instrumented spray bottles of refrigerant, 2) "familiar" household devices such as bicycle generators, refrigerators and room air conditioners, and 3) university steam generator and chiller facilities. The goal is to engage learners and then lead them through directed exploration, schematic representation and thermodynamic calculation to establish a comprehensive view.

In addition to the developments and workshop exercises we currently use, we discuss our mixed success in this effort. It seems that for students to achieve any level of mastery, we are limited by the time it takes to overcome their deficiencies in certain very basic knowledge and skills. It is likely that teachers often overlook such impediments to deep learning when preparing foundational courses. We are continuing to refine our techniques to achieve the highest possible level of success.

1. Introduction

Thermodynamics is a discipline that deals with energy utilization as constrained by Natural Laws that are expressed in fundamental properties and with its applications via mathematical models. Its study is basic to science and engineering and it is a core subject in many engineering curricula.

Thermodynamics challenges students in several ways[1,2]. First, to get to the stage of making reliable and efficient applications requires knowing the fundamental principles and using procedures that are abstract and mathematical. Next, teaching styles and structures based on problem-solving methodologies or on deductive reasoning can require students to discover for the first time a need for strategies of learning that are more sophisticated than what is their usual previous experience of memorization and working of many example problems without generalization.

Finally, the devices and system concepts most commonly treated in an initial engineering course, such as engines, power generation, refrigeration and energy conversion are unfamiliar and appear complex to students who have limited experience with the real world. They have not personally tinkered with mechanical and chemical devices, and they can have serious misconceptions about the behavior of Natural and engineered systems. As a result, teachers cannot now rely on experiential background for students to build connections between book material and engineering reality.

For these reasons, we have initiated pedagogy to augment the traditional introductory thermodynamics course in the School of Engineering and Applied Science (SEAS) at the University of Virginia[2]. Our course complements its classroom settings with weekly workshops intended to illustrate principles by hands-on experiments, computer-assisted modeling and study of energy systems, visits to full-scale sites, and team problem-solving activities. We created most of these exercises ourselves since, except for some expensive commercial apparatuses, there can be found very few laboratory/workshop exercises in the thermodynamics education literature. For example, among the publications and web sites of the several NSF Engineering Coalitions, there are only a few computer-oriented materials and no experiments in this subject. While web searches uncover a variety of thermodynamics learning aids, essentially all are typical textbook or computer descriptions. Some have animated phenomena, but no real devices or systems.

This paper focuses on our experiences of the past 2 years when our workshop schedule, content, philosophy, and execution have been fully established. We describe our approach and then illustrate some of the laboratory activities and related classroom exercises. The results we find demonstrate how difficult it is to help students achieve deep understanding so they can give immediate and correct responses when questioned about fundamental phenomena and behaviors. We believe that repetition of the basics and carefully directed experience in a variety of forms can promote learning. However, justifying the time and effort needed may be difficult in current curricula.

2. Structures of Thermodynamics

There are many strategies for presenting the material of thermodynamics. These are illustrated by the plethora of textbooks and the fact that many longtime instructors of undergraduate courses - and their students - are dissatisfied with whatever text material they use (including personally generated notes). We have also discussed these issues elsewhere.[1,3]

It is apparent that accomplishing the desired degree of learning depends on many factors besides the subject’s structure, including a student’s background and motivation. Among the ways to characterize the learning process, the analysis by Haile[4] may be particularly useful for thermodynamics. He describes successive levels of growth and understanding as well as the transitions from one to the next. The elementary levels begin with "making conversation" followed by "identifying elements", "recognizing patterns" and finally "solving problems". Haile’s advanced levels go from "posing problems" to "making connections" to "creating extensions". In the first thermodynamics course, the advanced levels are definitely unreachable. What we have found most surprising, challenging and frustrating, is that many students do not have adequate experience even to "make conversation" about some of the phenomena that thermodynamics is intended to describe, so even getting to "solving problems" could be unrealistic.

A traditional course structure (see, *e.g.*, Sonntag, et al.[5]) is given in Figure 1A. *Properties* of real and ideal gas substances come first, followed by *processes* for the First Law of Thermodynamics with applications to closed and open systems including cycles, followed by the Second Law for individual heat and work machines, and then analyses of multiple process units. The apparent advantage of this approach is that "real" examples and problems can be immediately done with a large range of substances, suggesting that learners are ready to connect processes to real and familiar systems. This assumes that students are not only familiar with, but have actually considered in depth, the behavior and consequences of fluid flow, phase changes, measurement devices and materials of construction on their own or in prior schooling. However, it is both our experience and that of the literature[6-9] that such assumptions may not be warranted. There are many "counterintuitive" behaviors that teachers and learners must deal with; an example is that children generally think in Aristotelian, rather than Newtonian, fashion when considering moving bodies[9]. In addition, erroneous understandings of phenomena require extra effort to overcome[4]. Without careful attention to these deficiencies, learning in such situations will consist of merely memorizing formulae. While teachers know that specific relations are usually only for certain cases, students will unhesitatingly use them wrongly because they lack basic understanding of both the phenomena and the approximations made in deriving the relations from fundamentals.

As a result, we have adopted a blend of alternative structures[1,4,10] shown in Figure 1B which first develops the primitives of measurables and processes, including balances followed by the Laws with closed and open single unit applications using ideal gases. We feel that only after much practice on problems where process and property analysis is simplest, can the complexity of multiphase and multiunit and cyclic systems be treated. While this approach can have the appearance of abstractness to many students, success can be achieved when the lecture material is accompanied by demonstrations and team activities of the classroom and guided laboratory workshop experiences. We believe that when our students finish our course they have a more general, integrated set of skills and approaches to the complex problems of real systems, even if they have not memorized many formulae. In addition to direct assessment evidence, this may be demonstrated by our ability to successfully, and without much difficulty, introduce how properties are obtained from equations of state, which is beyond typical treatments.

Even with this approach, we still encounter levels of misconception much greater than we may have anticipated. We find student misunderstandings reminiscent of Aristotelian errors persist even after many and varied class and workshop attempts to overcome them.

3. Classroom and Workshop Activities

We introduce the subject material in terms of "Primitives" such as suggested by Fenn[11] with his character "Charlie the Caveman" who recognized Natural phenomena even in the absence of modern devices and terminology. This includes hotness/coldness (temperature), force, mass and length in one to three dimensions. This is followed by considering changes in properties by processes, especially work and heat and the evidence of the asymmetry of their interconversion. Each aspect has workshop experiences and in-class demonstrations that accompany the text,

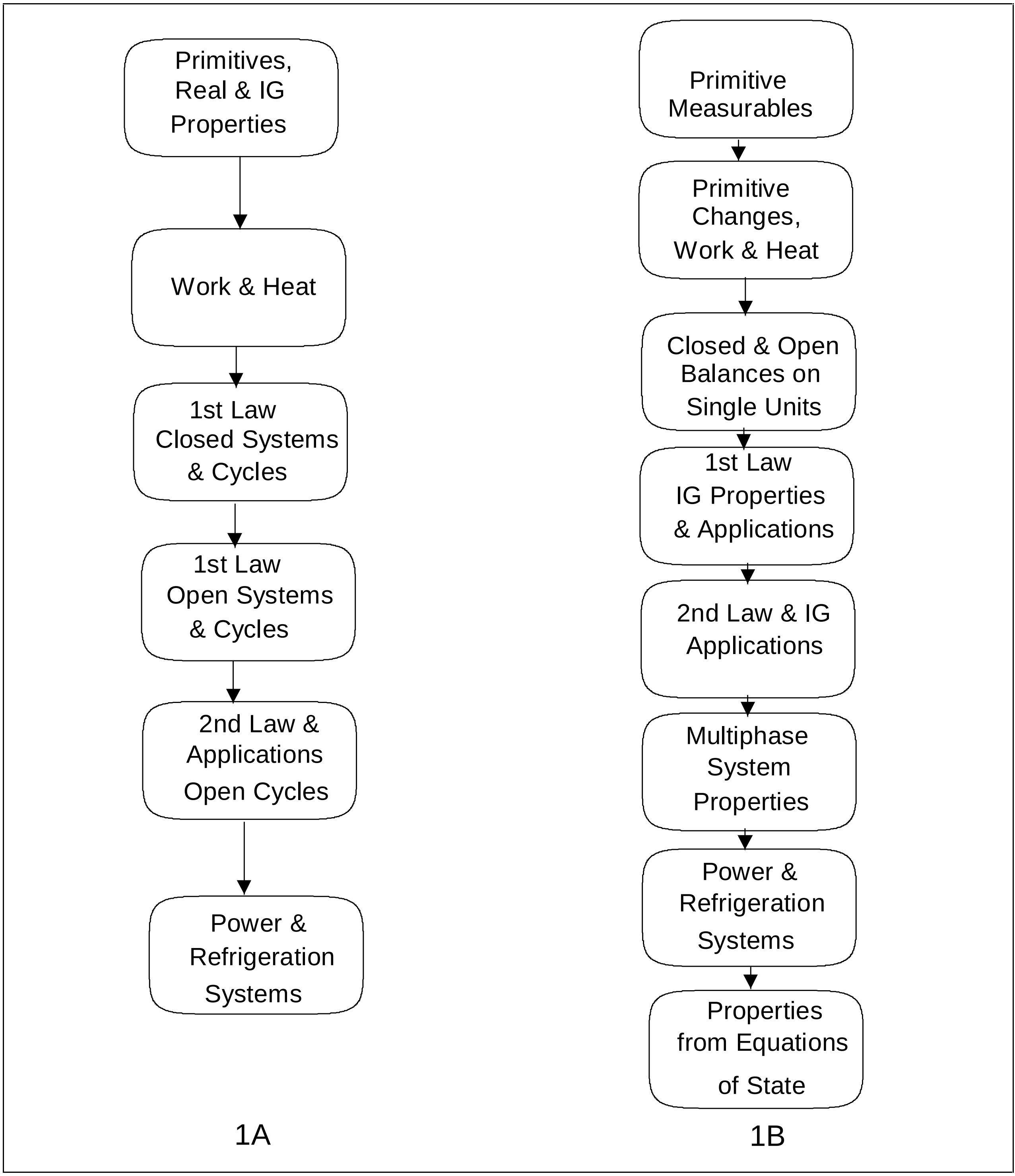

Figure 1. Structures of Beginning Engineering Thermodynamics Courses

lectures and assigned problems (in-class and homework). The workshop assignments are either handed out in hard copy or are put on the course web page (via the University of Virginia Toolkit: http://toolkit.virginia.edu) 2-4 days ahead of the sessions. These consist of graded "advance question" assignments for individual students to submit at the workshop, step-by-step detailed instructions for manipulating the equipment, data sheets for logging information and answering immediate questions, and home assignments to be done in 2-4 member teams and turned in as a report 4 or 5 days later. Finally there is an individual short quiz the day after the report is due. This assignment pattern is followed essentially every week for the whole semester. To foster student acquaintanceship, for the first few weeks, teams are composed of students who do not know each other. Later, permanent teams are formed by student choice. There seems to be little difference in team effectiveness between these modes of organization.

The initial workshop subjects are:

A. Force, pressure and work involving 1) a "dead-weight" pressure tester and 2) masses placed on a transparent plate over an inner tube. These show different levels of accuracy and try to unify the relationship of mass, gravity, area of contact, and pressure.

B. Aspects of work and heat interconversion with 1) a bicycle-wheel generator attached to lights and to resistors hand-held in air and placed in water in an insulated flask and 2) a piston-cylinder system containing air with different applied masses that can be immersed in water of different temperatures. Some sense of energy proportions can be gained by the effort required to turn the bicycle wheel to obtain a little light and changes of piston/cylinder volume with added masses and from transfer between ice water and boiling water.

The in-class demonstrations include student manipulation of the piston-cylinder system, touching cold and hot surfaces for heat conduction, feeling forced and natural convection as well as radiative heat transfer associated with an ice-covered metal cookie sheet and a light bulb fixture. While many of these phenomena may have been experienced in prior physics classes, we find students unable to discuss the behavior and relationships with coherence or generality. Common errors are to mix up properties with other entities (a system "has heat") and to expect particular property changes regardless of the process ("temperature always goes up if the volume decreases", "if the temperature of a fluid goes up when flowing through a pipe, the pressure must also go up because the volume doesn't").

At this point, students are taught in class and in a workshop session a thermodynamics-oriented problem-solving method[3]. Then we do general and particular treatments of the balance equations ultimately used for mass/material, energy and entropy. We do not attempt to make physical connections to the thermodynamic properties in these balances; rather, the definitions and balances of energy and entropy are made plausible mathematically with the hope that ultimate familiarity with their behavior will lead to acceptance and predictive ability. Students usually have confused concepts about the relationships of these properties and processes; getting them to distinguish in an orderly fashion the various boundary-crossing terms and to account for accumulation takes considerable effort and repetition.

After the balance equations are developed, classes and workshops focus on changes of state of ideal gases and the relationships of changes in measurable properties such as temperature, pressure, and volume, to changes in the conceptual properties of energy, enthalpy, and entropy. Closed-system cycles are done using the same piston-cylinder systems as before. With care, the workshop experiments with air do follow the proper ideal gas behavior, so credibility is gained while the distinction of properties (temperature, energy) and process quantities (work, heat) is reinforced. These equipment-oriented workshops are followed by a series of spreadsheet workshops on closed-system ideal gas cycles similar to the workshop setups. Our goal is to get students comfortable with organizing multistep and multiple equation calculations. We find that other classes do not adequately prepare students to structure their own spreadsheets; only if we take the time to guide them thoroughly, can they can ultimately establish effective templates.

At this point in the course, the goal is for students to appreciate and treat full thermodynamics problems. They need to determine what quantities are sought given specified constraints (the unknowns and the knowns), to know how to select the optimum system and boundaries for most efficient analysis, to make particular for the case at hand the "always true" principles (the specific balance equations and property relations to give the correct number of correct equations), and to adopt simple strategies for finding the unknown values (via sequential or simultaneous methods).

Emphasis is placed on repetition of the *procedure* (not the answer) and on *precision* in thought, expression and calculation. Student unwillingness to consistently organize the basic relations and sloppiness in definitions and equations is common. For example, we allow students to bring to quizzes a single page "cheat sheet" with whatever information they wish to use for the quiz; we unexpectedly require them turn it in with their quiz paper. Our examination of these papers shows an appalling range of mistakes and lack of distinction between "always true" and "occasionally true". Many papers are filled with redundant and excessive numbers of equations, but very little commentary on how to approach problems. A disappointing behavior is that students will list similar equations from other courses, such as from physics where different notation and unknown approximations are used, right along with those from our course, as if they are either different or more useful.

Further, consistent with the experience of others[12], we must give several repetitive assignments and quizzes before most students can accurately and consistently draw schematics of systems, make graphs of properties and their changes for various steps, and correctly write basic equations that are consistent in form and accurate in content. It cannot be assumed that they are able to do these activities. We know that if they cannot do them, they will not attain real understanding, so time must be spent in developing these rudimentary skills.

Much student frustration occurs during this part of the course because the learning is neither fast nor "easy". They are much more used to being told "what to do" rather than required to "figure it out" or to express it "in their own terms". We demand that they articulate the possible interpretations and procedures and then decide the most effective way to arrive at an answer. This is a great challenge to them because they are much more used to, and have been successful with, single method/single solution approaches. Their expectations that this should continue can be a great stumbling block to achieving a real professional education.

Even more debilitating, students at this level usually cannot phrase questions that will assist them in making progress. The desired approach would be for them to say something like, "I have tried . . ., and what happened was . . . . This seems wrong. Did I make an error here . . ., here . . ., or here . . .?". Instead, students will commonly say, "I do not understand anything; do the problem for me.", and then not internalize the learning. Under these circumstances, the teaching team (faculty and assistants) must be fully consistent in their responses to such student demands by recognizing that one’s ability to think and understand can not be "taught", it can only be "figured out". The path to independence is initially slow and frustrating[4].

Before these efforts to get student skills and habits to the appropriate level are fully completed, our course moves on to multiphase systems where we find other misconceptions and inexperience. While the level of naiveté is not as great as described in the literature of lower schooling[7], our students often *guess*, and usually are wrong about, fundamentals. For example, they will insist that the material in the bubbles of vapor in steadily boiling room-temperature water "must be air", they will forget that vapor pressure and temperature have a fixed relationship, especially in flowing systems, and they do not have instincts about evaporative cooling.

Here, we present most of the problems in the same form as previously with ideal gases to demonstrate that the dramatic differences among systems is not in the setup of the fundamental equations but in the behavior of the substances as given by their thermodynamic properties. Thus, water and refrigerant information is obtained from graphs and computer programs. Since this turns out to be easier than for ideal gases, we can often reinforce the desired generality. Interestingly, however, student resistance to even this kind of simplification can persist.

We also do workshops that deal with single process units having multiphase fluids:

A. We show 1) water boiling at room temperature in a glass vacuum flask and 2) emptying of part of the contents of an insulated can of refrigerant. The first experiment demonstrates the nature of boiling. The second is run with measurements of T and mass until no more refrigerant comes out because evaporation has caused the T to fall to the point where the vapor pressure is atmospheric (usually within 2 minutes). These are intended to connect T and P in multiphase systems and they do seem to make some impact.

B. Taking steam from a line through an expansion valve and then into a weighed container of water while measuring appropriate T and P. This confirms that the energy balance holds in a Joule-Thomson expansion as well as for the mixing of hot and cold water including when changes of phase occur.

We find that most students do not really know the correct property connections and behavior in multiphase systems and have great difficulty learning them. Example 1 shows one kind of quiz/homework exercise we give. Less than 1/2 of the class will get more than one item correct the first time; they will respond with "temperature is not connected to pressure", "heat flow into a fluid lowers its quality", etc. Only after three or more repetitions of the same kind of question with the answers displayed and discussed each time will more than 3/4 of the class get the questions correct. Many students will apologize about "getting it wrong again", but they seem helpless to replace their incorrect image with the proper one.

We conclude that some of the deficiency is an inability to read for comprehension, but most of it is students' lack of consistent application of principles and procedures. This persists even when shown reliable ways to approach what should be a familiar situation. For example, few students draw their own figures to do the problem of Example 1, but when the solution is revealed by starting with a figure, many can immediately jump to the correct results. They often are embarrassed by their inability to "do it for themselves" even in later tries when they cannot seem to adjust their thinking procedures. Old habits die hard.

Example 1. A Quiz Problem on Multiphase Systems

One kg s^{-1} steam containing 50 mass % vapor steadily & slowly enters a countercurrent heat exchanger with large diameter tubes. The steam leaving the exchanger has both vapor and liquid. The other stream of the exchanger has 1000 kg s^{-1} water entering at 80 ^{o}C, 0.1 MPa. Put an **X** in the boxes below that most closely describe the changes. If there is only a small change in a characteristic, put ~ in the box of the direction. If your answer is "depends", explain the options below. Use your usual Mollier Diagram for the properties of steam.

a. The steam is at 0.02 MPa. Its characteristics at the outlet compared to those at the inlet are:

Value\Characteristic	*T*	*P*	Quality, *x*	$\hat{V}$	$\hat{H}$	$\hat{S}$	Linear Velocity
Higher							
Lower							
Same							
Depends							

b. The characteristics for the water at its outlet compared to its inlet for this case are:

Value\Characteristic	*T*	*P*	Quality, *x*	$\hat{V}$	$\hat{H}$	$\hat{S}$	Linear Velocity
Higher							
Lower							
Same							
Depends							

Our course then moves on to multiple unit systems with multiple phases. The class work covers diagrams and various analysis and design problems especially with nonisentropic compressors and turbines.

The workshops focus on refrigeration.

A. There is a laboratory with both a refrigerator and a window air conditioner that have most of their covers removed. The students can see the refrigeration systems and many of their parts are labeled with numbered tags. Teams of 3 to 4 members are to write the tag numbers on appropriate locations of the system's schematic diagram. The air conditioning unit is then turned on so that the power usage is monitored and temperatures can be measured at up to 10 places along the refrigerant flow path. Students are asked to trace the refrigerant path and identify from touch what is hot and cold as well as what they hear as the unit's functions (high and low cool, fan only, etc.) are changed.

B. The next workshop is at one of the university's chilled water facilities so that another dimension of the similarities and differences in refrigeration can be encountered. The same activity of identifying tagged equipment is used along with analyses for overall and subsystem energy balances. Here, in addition to being exposed to large-scale equipment, noise and power units - often for the first time ever - students can deal directly with the roles of the circulating chilled water, condenser water and the evaporative cooling system. The comparison with air exchange household systems often makes a significant impact. We also have a similar workshop at the university's steam generation plant.

Initial responses to questions like "where is the pressure the highest?", "how many phases are in this cold part?", "what would you see if you could crawl inside this tube?" are often disappointing. Unless coached, few connections are made to the boiling water flask, the emptying of the refrigerant can, and the condensing of steam. Ultimately, most students can connect the physical units to a schematic and even to trace out the path on a thermodynamic diagram such as ln P vs. H. Further, the similarities and differences between the refrigerator and the air conditioner refrigerant units and cycles are commonly recognized (though we have found that students can be confused by nonessential refrigerator parts such as the cooling coil for the drinking water and ice maker dispensers). In the end, some of the team reports successfully plot the refrigeration process on several property diagrams and perform appropriate calculations on software to verify their interrelatedness. But the rate of learning and performing is slowed by student unfamiliarity with phase transitions and fluid flow; gaps in relating the physical behavior to paper problems can still remain.

4. Discussion

We teach our class ambitiously. We seek to have our students go from a low level of comprehension and performance to semiprofessional proficiency and thought. This involves major improvements in their basic skills, dramatic reorientation of their objectives and views about learning and producing, and significant expansion of their personal experience with Natural behavior, especially in man-made systems. To do this takes major commitments of time and energy of the teaching team and the students. We have found much of this can be successful only if the teaching team is sensitive, consistent and available.

On the other hand, our accomplishments have been limited in unanticipated ways. Many of our students cannot visualize or articulate the behavior of simple processes like boiling or condensing in a tube or the changes in the liquid and vapor inside the refrigerant can when the valve is open. Our hope was that as we built up student experience by dealing with the thermodynamics of simpler processes from ideal gases to the can drainage and the steam tank, their transition to the air conditioning unit with its combination of units, phases and processes would be straightforward. As we examine our students' lack of growth in spite of everyone's good efforts, it seems that it was not the thermodynamic analysis of the A/C unit that needed prerequisite knowledge from the simpler processes. It is its relation with rest of the physical world that is lacking.

We now believe that learners must have made real connections between the scientific descriptions and the physical reality in all of the simple processes before they can be successful in analyzing cyclic processes. Further, the definition of "simple" is at a lower level than we expected. We start with "Charlie the Caveman" primitives, assuming that their consequences are readily appreciated, but even this may not be true for many students. Like most instructors, we thought our students had already made the connections. We found out differently only with direct conversations, special "on-their-own" summaries and carefully designed quizzes. One might ask why we have not realized this before. We suspect it is because the analysis of the simplest processes is mathematically easy and most students can memorize and manipulate them adequately to get enough of the right answer on typical thermodynamics quizzes and homework to earn a "good grade". Only if we carefully craft questions that probe the desired objectives do we find that these connections are not made.

To the degree this assessment is true, it means that to overcome these gaps, the ability to repeat and reinforce the more slowly learned concepts, and the need to concentrate adequately on the knowledge and skills will require both teachers and students to put in much more time and effort than for other courses of the same number of hours. Further, the growth can best be done only in small classes where individuals can be introduced to the best level and kind of fundamentals at optimal times to eliminate their individual barriers. Such commitment may not be justifiable in today's educational climate.

Our advice to colleagues is that it is easy to overestimate and overlook the limits of students' capabilities to utilize "common" engineering tools, insights and intuitions. One must seek information outside the usual testing schemes to learn where misconceptions exist and how to correct them in each individual. Of course, the easiest path for both faculty and students is for classes to consist of lectures, and for homework and tests to require quite limited mastery of narrowly focused knowledge that is unconnected to physical reality. But the results of this approach are predictably circumscribed and we will not settle for them.

5. Conclusions

We believe that the first thermodynamics course can achieve high-level objectives only by overcoming students' fundamental deficiencies. Our integrative approach combines 1) realistic initial assessment of students, 2) assignments that uncover basic misconceptions about physical processes, 3) laboratory workshops and classroom techniques, exercises and experiences that reinforce procedure and generalization. In this way, we hope to better prepare our students for the variety of problems and phenomena they will encounter as engineers.

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