121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #10626

Assessment of Fundamental Concept in Thermodynamics

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Assessment of Fundamental Concepts in Thermodynamics

Abstract

Many engineering students have difficulty explaining the fundamental concepts used to solve thermodynamics problems. For example, students may be able to solve problems by neglecting kinetic and potential energies, yet struggle to explain why this is justified. Likewise, they will assume steady-state behavior, yet have difficulty to explain why. Students learn to approximate the evaluation of fluid properties, yet cannot provide a reasonable summary of the justification for these common approximations. Common areas of poor student comprehension are identified and alternative pedagogical strategies have been explored to improve student learning. A series of conceptual questions are employed in lectures, quizzes, and exams to emphasize concepts throughout the semester.

Introduction

Engineering students often develop sufficient skills to pass rigorous mathematics and physics courses before taking engineering classes. Too many students pass these courses without achieving a deep understanding of the fundamental concepts. Continued poor performance in thermodynamics is linked to students not grasping key concepts and failing to recognize how to apply relevant concepts in solving problems.(1) Many students succeed at algorithmic problem solving yet have difficulty explaining the physical systems being described by the mathematics. This is reflected in low scores on concept inventory exams which require minimal mathematical calculations, but are designed around common misconceptions.(2,3)

Poor learning has been linked to not being able to correctly assess the information provided and begins with a lack of clear understanding of the fundamental concepts. A coherent framing of problems is essential to reason through new problems.(4) To address this, teachers often reduce the complexity of introductory problems until mastery is achieved and then gradually increase the complexity of subsequent problems.

Students come to engineering classes with intuitive beliefs and in many cases these beliefs are valid and needed for learning. Yet in some cases, a student's perception is not valid and this presents a significant challenge for instructors.(4) Teachers need to help each student discover how their intuition may not be consistent with reality. Having a sound foundation, students build on prior knowledge to construct a framework for correctly solving new problems.

It has been observed that students often fall behind in thermodynamics so that instructional strategies should promote uniform engagement throughout the semester.(6) It appears student learning is improved when frequent low-stakes assessment is used throughout the semester.(7) Engagement is enhanced when the material is related to real world problems. The development of exercises that engender a positive student attitude and focus on broad conceptual underpinning is essential in helping students master the complex concepts.(8) Increasing active learning is widely recognized for improving student learning.(9,10) Inquiry based activities that focus on common thermodynamic misconceptions are continuing to be explored.(10) Having students explain difficult concepts in their own words is reported to be an active learning strategy.[11] Encouraging students to be more active and reflective in their learning is proposed in this paper.

Two Thermodynamics Courses

The mechanical engineering degree program at the author's institution requires a two-semester course sequence in thermodynamics. The first course focuses on the fundamental concepts, where students are introduced to many definitions and fundamental concepts, such as thermodynamic systems, extensive or intensive properties, forms of energies, work and heat transfer, conservation of mass and energy, and the second law of thermodynamics. Students also learn to use tables, charts, appropriate equations, and software programs to evaluate thermodynamic properties. Basic power, and refrigeration, cycles are introduced to demonstrate the application of the fundamental concepts. The second course covers exergy analysis, the analysis of more advanced power and refrigeration cycles, property relationships, gas mixtures, psychrometric applications, combustion, and chemical/phase equilibrium.

Our experiences indicate that students who have a sound understanding of the fundamental concepts in the first course do well in the second course, as well as subsequent fluid mechanics and heat transfer courses. Students who have a shallow knowledge of the concepts struggle in subsequent thermal-fluids courses. After teaching the first course for several years, it was realized that many students have difficulties in grasping some of the fundamental concepts. The range of difficulties includes definitions; selection of appropriate thermodynamic systems; distinguishing the differences between the extensive and intensive properties; evaluating properties; and applying general equations to particular systems. Many difficulties can be traced to unfamiliarity with new definitions; while others are more clearly traced to deep conceptual problems where student's intuitions about the system behavior are incorrect. In some cases, low performance on exams can be traced to the lack of student effort in the course.[12] But for many students, it is a lack of conceptual understanding that present significant challenges to the instructor.

Areas of Conceptual Difficulties

Areas of conceptual misconceptions include: open vs. closed systems, evaluation of properties, state principle, internal energy vs. enthalpy, transient vs. steady state, realizing entropy is a thermodynamic property, reversibility, and correct application of process equations vs. rate equations. A few examples are discussed here with specific strategies to promote student learning.

Students often struggle to distinguish between isothermal and adiabatic processes. Students find it counter-intuitive that a system can absorb energy by a heat transfer, Q without a change in temperature during a process. In many cases the temperature increases with heating, but if the system undergoes a phase change at constant pressure the temperature remains constant. A classic example is boiling water trapped in a piston cylinder apparatus where the piston is free to rise in a gravitational field. In this example, the concept needs to be grasped is that temperature does not rise but the internal energy and specific volume will increase due to heating. Also the temperature and pressure in the two-phase region are not independent properties. In a single-phase region, the student's intuition would lead to a correct evaluation that when there is a heat transfer into the system, the temperature of the system increases.

Students find it counter-intuitive that temperature can increase when there is no heat transfer into a closed system. This occurs when there is a work transfer into an adiabatic system. The work transfer causes an increase in the internal energy, and the internal energy of a single phase substance is dependent on temperature, so it increases. There appears to be no easy way to teach these concepts such that students easily grasp this subtly other than being explicit in highlighting when the anticipated intuition of the student will lead the student toward an incorrect response. The authors have become blunt in lectures about how students have incorrectly answered questions on previous exams because they miss this concept. Discussing assessment (final course grade) does increase the attention of many students and they appear to be more engaged in trying to understand the concepts, yet it is difficult to assess if clarity during lectures translates into correct responses at the end of the semester. This continues to be an area of active investigation, quantifying the long term impact on student learning.

To many students, it is counter-intuitive that pressure is independent of the height of a piston for a sealed vertical piston-cylinder apparatus. The students need to understand the concept that a force balance analysis on the piston shows that the gas pressure below the piston is related to the piston weight, cross-sectional area, and ambient pressure on top of piston. The height of the piston is not relevant to the force balance. A practice used by the authors is to have each student establish a free-body-diagram for the piston and then evaluate equilibrium conditions where the sum of all forces in the direction of gravity must equal zero. Instead of watching the instructor doing this, the students are asked to perform these steps until a correct free-body diagram is established. The instructor then asks if the weight of the piston changes with the elevation of the piston, or if the cross-sectional area changes with piston height. After a sequence of questions, the students realize the gas pressure below the piston is not a function of the pistons height. The instructor then may change the problem to include a spring above the piston so that it is increasingly compressed as the piston height increases. In this new case, students are asked if the gas pressure under the piston depends on the height of the piston. In the original case, the height of the piston doesn't affect the pressure of the substance trapped below the piston. Having the student actively discover these results appears to help students grasp and retain this important concept.

It is counter-intuitive to students that no work is done by a gas trapped in a piston-cylinder apparatus when the position of the piston doesn't change yet pressure does change. Students need to grasp the concept that boundary work is always zero when there is no change in volume of a closed system. This is analogous to determining the work done by a person pushing with increasing force on an immovable wall. No work is done on the wall because it doesn't move. This is physically demonstrated during lectures to appeal to the student's prior knowledge gained in the prerequisite physics class. Students should already understand how to compute mechanical displacement work as the "integral of F dx" and see how this is related to the new knowledge being acquired in thermodynamics where boundary work is the "integral P dV".

After the first few weeks in thermodynamics, students become familiar with retrieving property values from tables given values for temperature and pressure. Students begin to think of T and P as inputs, and finding other properties as the outputs. It becomes much more challenging when two different properties are used as inputs to evaluate other properties. Students often struggle to identify two properties (other than T and P), that can be determined for a given problem. One reason for this difficulty is that the tables of thermodynamic properties in the single phase regions are organized in terms pressures first, then of temperatures. It has been concluded that students need to develop a better grasp of the concept of the "state principle" and learn to identify two independent intensive properties to "fix the state" and subsequently determine other intensive properties. A successful practice used is to ask students to make a list of all the intensive properties encountered in thermodynamics. The instructor encourages students to become so familiar with this list that it comes from their memory: T, P, v, u, h, and s. The list can expand with additional properties, but this is often a sufficient list for many problems. The instructor then asks students to evaluate each property to see if it is known or unknown. Maybe the property is clearly given in the problem statement, or it may be determinable from the information given in the problem statement. Students are encouraged to find two properties that are either known or determinable. Again, students appear lost when T and P aren't the determinable properties. In some problems, T and v may be the determinable properties, then this leads to a sequence of steps to determine how to evaluate other properties such as P, given T and v. In many cases, this requires interpolation using data extracted from a property table. Overall, these problems can require a number of quantitative steps which are conceptually straightforward yet students feel overwhelmed at the onset. A successful teaching strategy is to break-down the process into manageable pieces, and require students to be able to explain why each step is taken in the process. For example when a problem provides the values for T and v for a given substance and asks for the evaluation of other properties such as P, u, h, and s; students who have just been introduced to property tables have a great difficulty to start the evaluation process. In many cases, one must first determine the correct region for the substance (compressed liquid, two-phase liquid-vapor mixture, superheated vapor). This is done by comparing know properties to the saturation properties. When students are first introduced to the property tables it is helpful to require student to first identify the phase or phases of the substance given properties pairs such as P-T, T-v, T-u, T-h. P-v, P-u, and P-h. It is particularly instructive if students correctly identify the location of the state on P-T, P-v, P-u or other appropriate diagrams, before they determine the numeric value of the unknown property from tables.

Students often are unfamiliar with the concept that there is a range of conditions where the ideal gas equation is applicable, and likewise a range of conditions where it isn't applicable. The concept needing to be grasped is that some substances are described as ideal gases (Air, O_2, N_2, He, Ar) but the same substances can also not behave as ideal gases under certain conditions. This is true at conditions near the critical point, and definitely when the substance condenses. Students should also understand that some substances rarely behave as an ideal gas (H_2O, Refrigerants), but in certain cases they can behave as ideal gases (superheated vapor at low pressures). It has been observed that some students will apply $Pv = RT$ when it is not justified, and fail to use it when it is justified.

Many students are challenged to perform analytic integration to calculate boundary work for a polytropic process. This is believed to occur because students don't retain a deep understanding of math concepts unless they have significant engagements with the math concepts at different times/semesters throughout their engineering education. Repeated exposure and frequent use of

Calculus concepts in multiple engineering classes is needed to reinforce and build a deep understanding of these concepts. It is a recommended practice that the instructor review integration concepts when they are needed in thermodynamics to emphasize both mathematical concepts as well as the specific application to thermodynamics. In addition to a purely mathematical approach, a graphical approach is frequently used to visually promote a deeper conceptual understanding of integration with an interpretation of the sign and magnitude of the boundary work transfer using a P-v diagram.

Examples of Assignments for Enhancement of Student Depth of Knowledge

In teaching the first course in thermodynamics for many years, authors have learned that there are certain areas that students struggle throughout semester. We routinely assign special problems or mini projects every semester to help students to overcome their struggle with understanding of fundamental concepts. (13,14) One area of student difficulties is the evaluation of thermodynamic properties in the compressed liquid region. Almost all thermodynamic textbooks provide compressed liquid thermodynamics property tables only for water. For other substances, students are required to approximate the properties of compressed liquids from the saturation properties using the following relationships.

$$\upsilon(T,P) \cong \upsilon_f(T) \quad \text{(subcooled liquid)} \tag{1}$$

$$u(T,P) \cong u_f(T) \quad \text{(subcooled liquid)} \tag{2}$$

$$h(T,P) \cong h_f(T) + \upsilon_f(T)[P - P_{sat}(T)] \quad \text{(subcooled liquid)} \tag{3}$$

$$u(T,P) \cong u_f(T) \quad \text{(subcooled liquid)} \tag{4}$$

When needed to evaluate the properties of fluids in the compressed liquid region, many students either cannot recall the appropriate equations given above, or they apply them incorrectly. Some students use the saturation liquid properties at a given pressure rather than those given at the saturation temperatures. One reason for students' difficulties in this area is that they do not have a full grasp of the reasoning why the saturation properties at the given temperatures are used to evaluate properties in the compressed liquid region. To improve students' understanding the authors routinely assign the following problem, or a similar problem, every semester.

Consider saturated liquid water at 100 ^{o}C undergoing an isothermal (constant temperature) compression process. For this process use steam tables to evaluate specific volume (in m^3/kg), specific internal energy (in kJ/kg), and specific enthalpy (in kJ/kg), and specific entropy (in kJ/kg.K), at pressures of 25, 50, 75, 100, 150, 200, 250, and 300 bar. At each state, evaluate the % deviation of property from its saturated liquid state. Can these properties be approximated by the liquid saturation properties? Can the approximation of specific enthalpy be improved by employing the equation: $h(T,P) \cong h_f(T) + \upsilon_f(T)[P - P_{sat}(T)]$? Discuss the results and explain what kind of conclusion can be made from the results (be specific).

By completing this assignment, students realize that the values of v, u, and s do not change very much with the increasing pressure along an isotherm. Therefore, they gain a better understanding of the reason why the properties of fluids in the compressed liquid region at a given temperature and pressure are approximated by their saturated liquid properties at the given temperature.

Students also have a difficulty to understand that the tables of thermodynamic properties for ideal gases are based on variable specific heats, where c_p and c_v are functions of temperatures. For example, they have a difficult time to comprehend that the evaluation of change of enthalpy of carbon dioxide between two given temperatures from ideal gas tables might give a significantly different number than the one is evaluated from the equation: $c_p\,(T_2-T_1)$ between the same temperatures. To gain a better understanding on how the thermodynamic tables for ideal gases are constructed, a mini project similar to the following in routinely assigned every semester

Consider the fundamental equations:

$$T d\bar{s} = d\bar{u} + P d\bar{v} \qquad (5)$$

or

$$T d\bar{s} = d\bar{h} - \bar{v} dP \qquad (6)$$

For ideal gases, we have shown

$$\bar{c}_p(T) = \bar{c}_v(T) - \bar{R} \qquad (7)$$

$$\bar{c}_p(T) = \frac{d\bar{h}}{dT} \qquad (8)$$

$$\bar{c}_v(T) = \frac{d\bar{u}}{dT} \qquad (9)$$

a) Using equations (5) and 6), show that for an ideal gas

$$\bar{s}(T_2,\bar{\upsilon}_2) - \bar{s}(T_1,\bar{\upsilon}_1) = \int_1^2 \bar{c}_\upsilon(T)\frac{dT}{T} + \bar{R}\ln\left(\frac{\bar{\upsilon}_2}{\bar{\bar{\upsilon}}_1}\right) \quad \text{(ideal gas)} \qquad (10)$$

or

$$\bar{s}(T_2, p_2) - \bar{s}(T_1, p_1) = \int_1^2 \bar{c}_p(T)\frac{dT}{T} - \bar{R}\ln\left(\frac{P_2}{P_1}\right) \quad \text{(ideal gas)} \qquad (11)$$

b) Modify equations (10) and (11), assuming constant specific heats
c) Show that for an ideal gas with constant specific heats, undergoing an isentropic between (T_1, P_1) and (T_2, P_2):

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \quad (s_1 = s_2, \text{ideal gas, constant } k), \qquad (12)$$

$$\frac{T_2}{T_1} = \left(\frac{\upsilon_1}{\upsilon_2}\right)^{(k-1)} \quad (s_1 = s_2, \text{ideal gas, constant } k), \qquad (13)$$

and

$$\frac{P_2}{P_1} = \left(\frac{\upsilon_1}{\upsilon_2}\right)^{k} \quad (s_1 = s_2, \text{ideal gas, constant } k) \qquad (14)$$

d) Given the functional relations for specific heat of carbon dioxide, CO_2

$$\bar{c}_p(T) = -55.6 + 30.5T^{1/4} - 1.96T^{1/2} \quad (15)$$

where, T is in K and $\bar{c}_p(T)$ is in kJ/kmol.K, develop a equations for $\bar{h}(T), \bar{u}(T), \bar{s}^o(T), P_r(T), v_r(T)$ in terms of constants in Eq. (15), T, and T_{ref}.

e) Develop a computer routine that evaluates the thermodynamic properties for CO_2 from the equations developed in part d. Let $T_{ref} = 10K, \bar{h}(T_{ref}) = 0, \bar{u}(T_{ref}) = 0, \bar{s}^o(T_{ref}) = 0$. You may use MS-Excel or Interactive Thermodynamics (IT) software.

e) Using your program, generate a table for properties of CO_2. Show T and the corresponding values for $\bar{h}(T), \bar{u}(T), \bar{s}^o(T), P_r(T), v_r(T)$ When possible, check the accuracy of your computations by comparing them with the data given in the textbook for CO_2.

You must submit a report that includes i) formulation of problem for property evaluation; ii) program listing; and iii) program output.

Conceptual Questions for Instruction and Assessment

The authors have been using the available concept questions in textbooks[15,16], as well as developing their own questions for a range of difficult topics. These questions have increasingly been used as both formative and summative assessment tools. Most questions are relatively straightforward and are in a true/false or multiple-choice format. It has been observed that a student may do well on solving quantitative problems yet perform poorly on conceptual questions. Figure 1 shows the results for twenty questions given to students in summer 2013 as part of the final exam. The first eight questions were true/false and the remaining 12 questions were multiple choice. The questions span the student learning outcomes in the first thermodynamics class. In some cases, nearly the exact question had been used in lecture, homework and/or mid-term exam. As part of the assessment, the goal was to have class score be 70% or greater for each question. The results are compared for all 23 students taking the final exam and for the 17 who took the final exam and passed the class. Six students took the final and didn't pass the class with a grade of "C-" or better. When all 23 students are included, 6 questions received a score of less than 70%. When only those passing the class are considered, then 3 questions received a score of less than 70%.

The results show too many students missed concepts dealing with questions 18 (Q18) regarding the pumping power association with a water pump, Q5: entropy being a property of a system, and Q16: violation of the first law of thermodynamics.

The entire class correctly answered Q11: open system identification and Q12: thermal efficiency of a power cycle. To explore the conceptual misunderstanding, the results are further analyzed with the intention of changing pedagogical strategies to improve student learning in subsequent semesters.

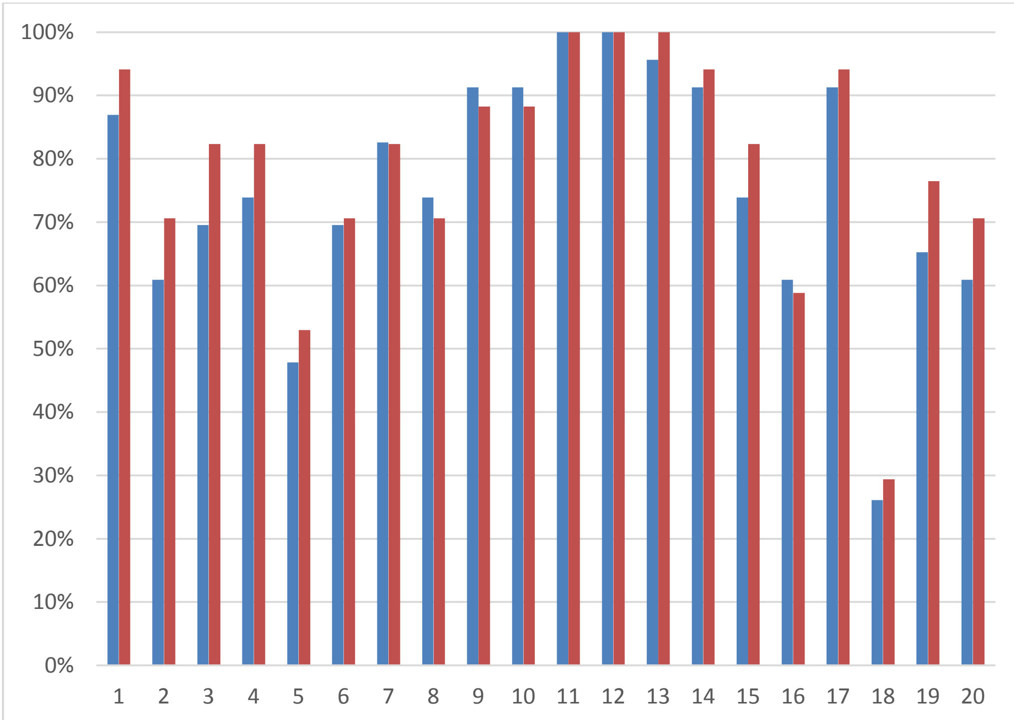

Figure 1. Percentage correct for 20 conceptual questions for all students taking the final exam n=23 (blue) and only those passing the class n=17 (red).

Q18 dwelt with the pumping power associate with a water pump. The problem required student to know that the minimum shaft power needed is the product of the pressure boost times the mass flow rate. From the distribution of student responses, there was no clear indication of a persistent conceptual misunderstanding. However, it was concluded that more emphasis needs to be devoted in covering this material in the future. The same is true for Q20 where students didn't appear too overwhelmingly select a particular wrong answer hence it is unclear if there is a specific conceptual misunderstanding that needs to be address or if students simply didn't know how to approach the problem.

Correct response rate for Q5 was 53%, which is surprising since the instructor believed these concepts had been "over-emphasized" in the class. The exact question for Q5 was:

> *True or False:* *The change in entropy of a closed system is the same for every process between two specified end states.*

The correct answer is *True* since entropy is a thermodynamic property. The change in thermodynamic properties do not depend on the path in the process. The concept needed to correctly answer this question was discussed in class, although it may have been covered early in the semester. It is believed that sufficient classroom discussion was devoted to this important concept, yet more time devoted to more active learning exercises is what is needed. It is believed that students failed to retain and apply the concepts on the final exam.

The authors now use more question-based active learning strategies during class time to improve student learning. One approach has been to present a “difficult” question to the students during lecture, such as:

True or False *The change in entropy of a closed system is the same for every process between two specified end states*.

After discussing this question and having collected student answers, the instructor admits this is a challenging question and then backtracks to simpler questions before answering the original question. After addressing simpler questions, the class then revisits the first question. Here are some of the simpler questions:

True or False *The change in* ***pressure*** *of a closed system is the same for every process between two specified end states*.

True or False *The change in* ***temperature*** *of a closed system is the same for every process between two specified end states*.

True or False *The change in* ***specific volume*** *of a closed system is the same for every process between two specified end states*.

This sequence of questions appears to be effective at improving student learning since students change their answers to the first question without being told to change their answer. They more quickly grasp how specific volume change depends on the end states, and then extend this concept to entropy. What remains an open question is the long term retention of the concept and the ability to correctly apply the concept in a new problem. For example, after using this approach early in the semester it remains uncertain if a higher percentage of students correctly answer a modified question on the final, such as:

True or False: *When a closed system undergoes a process from state “1” to “2”, the change in entropy ($s_2 - s_1$) depends on the path of the process*.

True or False *When a closed system undergoes a process from state “1” to “2”, the change in volume ($v_2 - v_1$) depends on the path of the process*.

Considering the results described above, the authors have been modifying the existing available concept questions as well as developing their own pool of questions which provide a broader spectrum of wording with the purpose of using the questions in lectures, quizzes, and exams throughout the semester. These questions are comparable to existing thermodynamic conceptual question banks, but typically are grouped in clusters which breakdown the concepts to help students process concepts in smaller pieces so the student navigates to a correct understanding. For many years, the authors engage students with questions during lectures, yet there has been a purposeful increase in the use of conceptual questions that are followed by additional conceptual questions to help clarify concepts. Using conceptual questions, the instructor has found there are more opportunities to intervene and guide students during the semester to a more solid conceptual understanding of the material.

During the fall 2013 semester, four mid semester exams and a final exam was given. Three midterm exams and the final exam included true/false and multiple choice questions on the fundamental concepts. In addition several pop quizzes were given during the semester. One pop quiz contained multiple choice questions for the identification of the state of a fluid on thermodynamic surfaces. Approximately 20% to 30% of each exam grade was based on True/False and multiple choice questions, when they were included as a part of an exam. The remaining portion of the exams required students to show detailed solution steps in solving problems. For the sections of thermodynamics courses offered by the authors, all exams and quizzes are closed book. An equation sheet containing all of the fundamental equations in the textbook is created by the authors and a copy is given to students at the beginning of each semester to be used in exams and quizzes. During exams and quizzes, students can only use the equation sheet developed by the instructors and the property tables provided in the appendices of the textbook.

The following is a list of true/false and multiple choice questions included in the first exams. Not all questions given in the two sections of the course were identical, but some were the same for both sections. The percentages of correct answers by students are also provided in the table.

a) Identify each of the following parameters as: (A)-Extensive property, (B)-Intensive property, or (C)-Not a property.

Parameter	**n**	**% Correct Answers**
Volume, V	50	73
Heat transfer, Q	50	73
Temperature, T	50	68
Work, W	50	75
Density, ρ	50	73
Internal Energy, U	50	45

The results indicate that a high percentage of students had difficulty identifying the total internal energy as an extensive property. One possible reason for this difficulty can be attributed to the fact that students did not have any previous exposure to the term "internal energy."

b) An insulated tank is divided into two compartments (A and B). Compartment (A) contains 3 kg of water at p_A and T_A and compartment (B) contains 5 kg of water at T_B and P_B. Considering the entire tank as a composite closed system, identify the equations given in the following table for the evaluation of the properties of the composite system as: (A)-true or (B)-False.

Equation	**n**	**% Correct Answer**
$V = V_A + V_B$	50	80
$v = v_A + v_B$	50	72
$P = P_A + P_B$	50	52
$U = U_A + U_B$	50	60

The results indicate that a high percentage of students had difficulty identifying the pressure as an intensive property and the total energy, U, as an extensive property.

c) Answer the following as (A)-True or (B)-False. (1 point each)

System	n	% Correct Answer
The volume of a closed system **cannot** change during a process.	50	65
When a thermodynamics system undergoes a process between two specified states, the changes in thermodynamic properties between the end states depends on the path of the process.	50	34
Heat transfer and work are thermodynamic properties.	50	67
If the value of *any* property of a system changes with time, that system cannot be at steady state.	50	69
The change in internal energy of a closed system is the same for every process between two specified end states.	50	58

The results clearly indicate that many students did not realize that thermodynamic properties are point functions and they are independent of the path of the process.

d) Identify each of the following systems as: (A)-Open System, (B)-Closed System, or (C)-Isolated System

System	n	% Correct Answer
A tank being filled with compressed air (boundary is at inner surface of tank)	50	71
Air expanding in a piston and cylinder arrangement while it is being heated	50	75
An electrical motor providing power to an air-compressor.	100	66
A tree	50	63
Hot water in a well-insulated container	50	71
A wire extended by an applied force	50	57
Air in a soccer ball in thermal equilibrium with its surroundings and assuming: no leakage, no expansion/contraction.	50	85
Water boiling in a pot placed on stove	50	85

The results indicate that the vast majority of students could identify a thermodynamic system as closed, open or isolated.

e) The first law of thermodynamics on a rate basis is expressed as $\dot{Q} - \dot{W} = \frac{dE}{dt}$. Which of the following conditions applies to each process described in the following table? (A)-$\dot{Q} = 0$, (B)-$\dot{W} = 0$, (C)-$\frac{dE}{dt} = 0$, (D)-$PV^n = constant$, and (E)-none listed

Process	n	% Correct Answer
Steady state	100	72
Adiabatic	100	75
Isobaric	50	45
Polytropic	100	62

The majority of students had a wrong answer for the isobaric process. It is not clear why students selected any answer, except E. Perhaps at the time they were not sure of the meaning of an isobaric process.

f) Each line in the following table gives information about a process of a closed system. Every entry has the same energy units.

Process	Q	W	E_1	E_2	ΔE
a	+40	+20	-20		
b		150	+20		-100

For the following items select the best answer from the following choices: (A) 50, (B) 0, (C) 20, (D) 80, (E) -80

Item	n	% Correct Answer
For process (a) E_2 = ?	50	89
For process (a) ΔE = ?	50	91
For process (b) Q = ?	50	94
For process (b) E_2 = ?	50	91

The results indicate that the vast majority of students had no problem solving this problem, using the equation for the first law of thermodynamics.

The multiple choice and true/false questions in the second exam were related to application of the first law in analysis of thermodynamic cycles, property evaluation in the compressed liquid region, and property evaluation of ideal gases. The following is a list of questions and the analysis of the results of answers by students.

a) Consider a thermodynamics cycle that operates between a low temperature region and a high temperature region. For the following questions select the best answer from the list of following options: (A) a power cycle, (B) a refrigeration cycle, (C) a heat pump cycle, (D) either a power cycle or a refrigeration cycles, (E) either a refrigeration cycle or a heat pump cycles.

Question	n	% Correct Answer
If the cycle removes heat from the lower temperature region, it is:	79	33
If the net work of the cycle is negative, it is:	79	32

If the net work of the cycle is greater than zero, it is:	79	79
If the cycle receives heat from the high temperature region	79	17
If the cycle ejects heat into the high temperature region	79	18

The results indicate that the vast majority of students did not realize that a thermodynamic cycle that removes heat from a low temperature region and ejects heat to a high temperature can be either a refrigeration cycle or a heat pump cycle. The results also show that students did not realize that work or power input is necessary for both refrigeration and power cycles. In general, the results indicated a lack of understanding of the direction of energy by heat transfer or work transfer into and out of the basic thermodynamic cycles. The results indicated that these issues need to be discussed again in the class, in order for students get a more clear understanding of the direction of specific energy transfer into and out of typical thermodynamic cycles.

b) For the following questions, select the best answers from the following list of options (A) less than 1 (100%), (B) equal to 1 (100%), (C) greater than 1 (100%), (D) both A and B, (E) all A, B, and C

Question	n	% Correct Answer
For a power cycle, the thermal efficiency is;	103	45
For a refrigeration cycle, the coefficient of performance is	103	35
For a heat pump cycle, the coefficient of performance is:	103	27

Again, the results indicate that a vast majority of students could not identify the range of acceptable values for thermal efficiency of power cycles and coefficient of performance of refrigeration or heat pump cycles. The results indicated that the meanings of thermal efficiency and coefficient performance for cycles needed to review again during class lectures.

c) Consider a refrigeration cycle which has a coefficient of performance of $\beta = 2$. The cycle removes 200 kJ of heat from the refrigerated space. For the following questions select the best answer from the following options: (A) 100 kJ, (B) 200 kJ, (C) 300 kJ, (D) 400 kJ, or (E) 500 kJ.

Question	n	% Correct Answer
Determine the network required by the cycle	79	52
The heat transfer into the space surrounding the refrigerator.	79	28

The results indicate that a vast majority of students did not have any difficulty to plug in numbers into appropriate equations to obtain correct answers for the analysis of refrigeration cycle, but the previous questions indicated the lack of understanding of the basic concepts on the direction of energy transfer into or out of the cycle and the range of acceptable values for thermal efficiency of power cycles, or coefficient of performance for refrigeration and heat pump cycles.

d) Consider a heat pump cycle which has a coefficient of performance of $\gamma = 2$. The cycle removes 200 kJ of heat from the cold region. For the following questions select the best answer from the following options: (A) 100 kJ, (B) 200 kJ, (C) 300 kJ, (D) 400 kJ, or (E) 500 kJ.

Question	n	% Correct Answer
Determine the net work required by the cycle.	103	10
The heat transfer into the e high temperature space.	103	14

The results indicate that a vast majority of students had difficulty in analyzing energy transfer into and out of a heat pump cycle. The results were surprising, since most students hand no difficulty analyzing the energy transfer for a refrigeration cycle, but had more difficulty with the analysis of energy transfer for a heat pump, even though both refrigeration and heat pump cycles work on the same principle by removing heat from a low temperature region and providing heat into a high temperature region.

e) Consider a power cycle which has a thermal efficiency of $\eta = 0.5$. The cycle receives 400 kJ of heat from the hot region. For the following questions select the best answer from the following options: (A) 100 kJ, (B) 200 kJ, (C) 300 kJ, (D) 400 kJ, or (E) 500 kJ

Question	n	% Correct Answer
Determine the net work produced by the cycle.	103	64
The heat transfer ejected by the cycle	103	60

The results reveal that most students had a good understanding of the fundamental concepts of how a power cycle works. The difficulties of analyzing the energy exchanges of a heat pump cycles were more pronounced in previous questions.

f) For the following question select the best answer from the following options: (A) 47.04 kJ/kg, (B) 48.61 kJ/kg, (C) 107.95, (D) 109.81 kJ/kg, kJ/kg, or (E) 250.64 kJ/kg

Question	n	% Correct Answer
The specific internal energy of Refrigerant 22 at 20 bar and 2 ^{o}C is	182	56
The specific enthalpy of Refrigerant 22 at 20 bar and 2 ^{o}C is	182	36

Since the state of fluid lies in the compressed liquid region and no tables are provided for the properties of refrigerant 22 in that region, students had to approximate the properties in the compressed liquid region from the properties of saturated liquid at the given temperature. The value of n presented in the above table includes the total number of students who answered these questions in fall 2012 and fall 2014. The results for the percentage of correct answers do not look to be impressive, especially when a special problem was assigned (as described in the earlier section) before the exam was given to help student gaining a better understanding of an approximation of the properties in the compressed liquid region. The main difficulty was to convince some students to attempt solving the extra problems assigned by the instructor. Some students, either did not submit any homework assignments, or only attempted the problems assigned from the textbook (since most of them have access to the textbook solution manuals or other sources available on the Internet). The authors have decided that in the future to increase the number of problems developed by them and awarding more points for submitting assignment related to those problems.

g) Carbon dioxide is heated from 300 K, 1 bar to 1000 K, 5 bar. For carbon dioxide at 300 K and 1.0 bar, c_v = 0.657 kJ/kg and c_p = 0.846 kJ/kg.K,. For the following question, select the best answers from the following choices: (A) 459.9, (B) 592.2 kJ/kg, (C) 625.2 kJ/kg, (D) 692.3, (E) 757.5 kJ/kg

Question	**n**	**% Correct Answer**
Evaluate the change in specific enthalpy of carbon dioxide between the two states, assuming constant specific heats at 300 K	182	49
Evaluate the change in specific internal energy of carbon dioxide between the two states, assuming constant specific heats at 300 K	182	51
Evaluate the change in specific internal energy of carbon dioxide between the two states, assuming variable specific heats	182	29
Evaluate the change in specific enthalpy of air between the two states, assuming variable specific heats	182	21

The results reveal students' lack of experience in the evaluation of properties of ideal gases either from equations, and especially, from ideal gas tables. In selecting their answers, many students did not realize that, in the case of variable specific heats, they could simply use the thermodynamic tables for carbon dioxide to directly evaluate the changes in specific internal energy and specific enthalpy between the two given states. Again, the results for the percentage of correct answers are surprising, especially when a special problem was assigned before the exam to help students to gain a better understanding of how the thermodynamic tables for ideal gases are constructed for ideal gases. Again, a few students had attempted to complete that assignment. Those who completed the assignment answered the questions correctly.

In fall 2013, the final exam for each section of class contained 20 true-false and multiple choice questions to assess students' knowledge of the fundamental concepts. The first portion of exam on fundamental concepts was completely closed book and closed notes. Unlike previous exams, students could not use their equation sheets or the property tables. Some of the questions on the final exam were the same or very similar to those asked in earlier quizzes and exams. The new questions were mostly related to the second law of thermodynamics or definitions requiring the knowledge of the second law of thermodynamics. The first portion of exam counted for 27% of the total points for the final exam. Students were required to complete and turn in this portion of test before receiving the questions requiring detailed solution steps. In previous exams, some of the questions on the fundamental concepts were the same for both sections of the course. But in the final exam, each section was given a completely different set of questions. The number of student who took the final exam was much lower than those who took the first or second exams. A total of 74 students took the final exam as compared to 103 students who took the second exam. The remaining students either had dropped the course earlier or did not have any hope of passing the exam. Of the 74 students who took the final exam, 17 received grades lower than C-. Therefore, only 77% of the students who attempted the final exam completed the course successfully.

The following is a list of true/false and multiple choice questions included in the final exam.

a) Answer the following statements as (A)-True or (B)-False

Statement	n	% Correct Answer
The Rankine degree is a smaller temperature unit than the Kelvin degree	41	41
In the textbook for this course, heat transfer *to* a closed system and work done *on* a closed system are each considered positive: $Q > 0$ and $W > 0$, respectively	41	71
For heat pumps, the value of the coefficient of performance is *never* greater than 1	41	59
A two-phase liquid–vapor mixture with equal volumes of saturated liquid and saturated vapor coexisting in equilibrium has a quality of 50%	41	29
All power cycles operating between the same two thermal reservoirs have the same thermal efficiency	41	44
For a gas modeled as an ideal gas, the specific internal energy, specific enthalpy, and specific entropy all functions of temperature only	41	24
Heat transfer for internally reversible processes of closed systems can be represented on a temperature–entropy diagram as an area below the path of the process	41	61
The volume of a closed system **cannot** change during a process	33	70
When a thermodynamics system undergoes a process between two specified states, the changes in thermodynamic properties between the end states depends on the path of the process	33	79
Heat transfer and work are thermodynamic properties	33	76
If the value of *any* property of a system changes with time, that system cannot be at steady state	33	76

The results for some questions with very low percentages for correct answers might be surprising at fist. However, the results might suggest that that without the aid of equation sheets, many students have more difficulty recalling the correct definition of quality or unit size of temperature scales. For the questions regarding u, h, and s for ideal gases, the rate of correct answers might have been higher, if the question was broken down into two or three separate questions, since both u and h are functions of temperature only, bus s depends on two other independent intensive properties such as pressure and temperature.

b) Identify each of the following parameters as: (A)-Extensive property, (B)-Intensive property, or (C)-Not a property.

Parameter	n	% Correct Answer
Pressure, P	41	51
Total enthalpy, H	41	49
Specific entropy, s	41	71
Density, ρ	41	47
Heat transfer, Q	41	78

Some of these questions were very similar to those asked during the first exam. The results for the correct answers in the final exam do not show any improvement over the results of the first exam. However, it is possible that some students might understand which properties of can be added together and which cannot in order to obtain the total property of the composite system, but they might be confused with meanings of words "extensive" and "intensive" properties.

c) An insulated tank is divided into two compartments (A and B). Compartment (A) contains 2 kg of water at P_A and T_A and compartment (B) contains 5 kg of water at T_B and P_B. Considering the entire tank as a composite closed system, identify equations presented in the following table for the evaluation of the properties of the composite system as: (A)-true or (B)-False.

Equation	n	% Correct Answer
$s = s_A + s_B$	33	54
$P =(P_A + P_B)/2$	33	82
$U = U_A +U_B$	33	100

Again these questions were very similar to those asked during the first exam. The results for the correct answers in the final exam show an improvement for students correctly identifying the given equations for P and U. However a good fraction of students could not realize that specific entropy is an intensive property and hence the specific entropy of the composite system cannot be determined by simply adding the specific entropies of water in compartments A and B.

d) For the followings identify each item as: (A)-Open System, (B)-Closed System, (C)-Isolated System,(D)-either A or B, (E)-none of the above.

System	n	% Correct Answer
A System the exchanges energy with is surroundings	33	30
A system that exchanges neither mass nor energy with its surroundings	33	85
A system that exchanges mass with its surroundings	33	97

The results show that a vast majority of students did not have any problem identifying a close system or an isolated system, but a large fraction of students did not realize that both closed and open systems can exchange energy with their surroundings.

e) For the blank space in each the following statements select the **best choice** from the following choices: A-(Heat), B-(Kinetic Energy), C- (Potential energy), D- (none of A, B, or C)

Statement	n	% Correct Answer
In a wind turbine ________ is converted to mechanical power	33	85
In a hydraulic turbine used in a dam, ___________ is converted to mechanical power	33	79

The results show that a vast majority of students had a good sense of the applications of kinetic and potential energies in producing mechanical work.

f) A gas flows through a one-inlet, one-exit control volume operating at steady state. Heat transfer at a rate of $\dot{Q}_{cv}$ takes place at the boundary of the control volume where the temperature is T_b. For each of the following cases, determine whether the specific entropy of the gas at the exit is: (A) greater than, (B) equal to, or (C) less than the specific entropy of the gas at the inlet

Case	n	% Correct Answer
No internal irreversibilities, $\dot{Q}_{cv} = 0.$	41	66
No internal irreversibilities, $\dot{Q}_{cv} < 0.$	41	56
No internal irreversibilities, $\dot{Q}_{cv} > 0.$	41	88
Internal irreversibilities, $\dot{Q}_{cv} \geq 0.$	41	64

The results show that a majority of students could remember the general equation for entropy balance for a control volume (through practice in homework assignments) and correctly simplify it for the given parameters.

g) For the following items select the best definition from the following list: $\frac{W_{net}}{Q_{in}}$, (B) $\frac{\dot{W}_s}{\dot{W}_a}$, (C) $\frac{\dot{W}_a}{\dot{W}_s}$, (D) $\frac{\vec{V}^2/2)_a}{\vec{V}^2/2)_s}$, (E) $\frac{Q_{in}}{W_{net}}$

Item	n	% Correct Answer
Nozzle isentropic efficiency	33	94
Thermal efficiency of a power cycle	33	64
Turbine isentropic efficiency	33	76
Pump isentropic efficiency	33	76

The results show that a good majority of students could identify the correct definitions of efficiencies of thermodynamic systems.

h) Each line in the following table gives information about a process in a thermodynamics cycle. Every entry has the same energy units.

Process	Q	W	ΔE
1-2		+20	+30

2-3	-20		
3-1		+150	-100

For the following questions, select the best answer from the following options: (A) 80, (B) 70, (C) 50, (D) -90, (E) not listed

Question	**n**	**% Correct Answer**
For process (1-2), Q =?	41	98
For process (2-3), W = ?	41	25
For process (2-3), ΔE = ?	41	42
For process (3-1), Q = ?	41	98

The results show that a good majority of students could apply the first law of thermodynamic to given processes, but they still had difficulties to extend the application of first law to cycles.

i) Consider a particular power cycle operating between hot and cold reservoirs at 1200 K and 300 K, respectively. The second law for the cycle is expressed as: $\oint \left(\frac{\delta Q}{T}\right)_b = -\sigma$. For the data presented in the following table, select the best answer from the following choices: (A) the first law of thermodynamics for cycles is not satisfied, (B) the first law of thermodynamics for cycles is satisfied, but the operation of cycle is impossible, (C) the first law of thermodynamics for cycles is satisfied and the cycle operates reversibly, (D) the first law of thermodynamics for cycles is satisfied and the cycle operates irreversibly, (E) none of the above

Data	**n**	**% Correct Answer**
Q_H = 600 kJ, W_{cycle} = 300 kJ, Q_C = 300 kJ	33	52
Q_H = 400 kJ, W_{cycle} = 280 kJ, Q_C = 120 kJ	33	70
Q_H = 700 kJ, W_{cycle} = 300 kJ, Q_C = 500 kJ	33	79
Q_H = 800 kJ, W_{cycle} = 600 kJ, Q_C = 200 kJ	33	73

The results indicate that a majority of students could correctly apply the first and second laws of thermodynamic to cycles.

Conclusions

The historical passing rate in the first thermodynamics class at the author’s institution has been about 45% to 55%, meaning that a significant number of students fail the class each semester. Some fail because they neither attend class on a regular basis nor complete assigned homework problems. It appears instructional innovations will not be effective at reaching these students. Other students appear to be engaged, yet they do poorly on exams since their efforts don’t result in significant learning. Some have a weak conceptual understanding of the material. Some pass by developing an ability to algorithmically process through anticipated exam problems with minimal thought. The size of this group of students is larger than originally anticipated by the authors since more conceptual questions have been used on exams. To improve student learning for those actively engaged in the class, the authors have purposefully developed and implemented more conceptual questions into lectures, quizzes and exams throughout the semester. In this paper, we have highlighted some of the persistent areas of poor student comprehension and specific questions being used to improve student learning. The increase in conceptual understanding is an on-going effort, yet there is a growing emphasis to increase both formative and summative assessments using more conceptual problems.

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NOMENCLATURE

c_p = constant pressure specific heat, kJ/kg.K
c_v = constant volume specific heat, kJ/kg.K
E = energy, kJ
$\dot{E}$ = rate of energy transfer, kW
g = gravitational acceleration, m/s^2
H = enthalpy, kJ
h = specific enthalpy, kJ/kg
k = c_p/c_v, dimensionless
M = Molecular weight, kg/kmol
m = mass, kg
$\dot{m}$ = mass flow rate, kg/s
P = pressure, kPa
Q = heat transfer, kJ
$\dot{Q}$ = rate of heat transfer, kW
$\overline{R}$ = 8.314 kJ/kmol.K, Universal gas constant
R = $\overline{R}$/M, gas constant, kJ/kg.K
S = entropy, kJ/K
s = specific entropy, kJ/kg.K
U = internal energy, kJ
u = specific internal energy, kJ/kg
V = velocity, m/s
V= volume, m^3
v = specific volume, m^3/kg
W = work, kJ
$\dot{W}$ = power, kW
Z = pv/RT, compressibility factor, dimensionless
z = elevation, m

Greek letters

β = coefficient of performance for cooling, dimensionless
γ = coefficient of performance for heating, dimensionless
η = isentropic efficiency, dimensionless
η_{th} = thermal efficiency, dimensionless
σ = entropy production, kJ/K
$\dot{\sigma}$ = rate of entropy production, kW/K

Subscripts

cv = control volume
e = exit port
gen = generated
i = inlet port
r relative
sto= stored