Redesigning the First Course of Thermodynamics to Improve Student Conceptualization and Application of Entropy and Second Law Concepts

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Abstract

The first course on thermodynamics (FTC), as taught in most mechanical engineering disciplines, typically follows a standard topical progression: properties of substances, first law concepts of closed systems, first law concepts of open systems, second law concepts, and cycles. Students often struggle with some concepts in courses that follow such a presentation. First, introduction of second law concepts late in the course leaves less time for students to apply second law concepts; student understanding of such likely suffers. Second, the flow of material goes from “specific” (closed system analysis) to “general” (open system analysis), which delays opportunities for students to use assumptions to develop simplified models that can be analyzed. Third, disconnects between entropy and energy prevent students from recognizing the “value” or quality of energy and why energy has different “forms” (e.g., thermal, mechanical, and chemical). This paper describes a course redesign with the following objective: improve student knowledge and application of entropy and second law concepts, and the role second law concepts have on energy conversion, by integrating second law concepts and entropy throughout the course. The redesigned course was first taught in Fall 2012 and has been taught three times. In addition to describing the course redesign, the paper uses a newly designed concept inventory to assess conceptual growth of students in the redesigned course. The concept inventory reveals that students in the redesigned FTC capture some second law concepts better than students in the conventional FTC; these concepts mostly include those related to exergy (the availability of energy to do useful work). On average, however, students in the redesigned FTC score about the same on the second law concept inventory as those students in the conventional FTC.

Introduction

The first course on thermodynamics (FTC) is perhaps for many engineering students a rite of passage to achieve their end goal of an engineering degree. Perhaps a reason why students anecdotally deplore thermodynamics is because they struggle with the second law of thermodynamics. It seems many students have a harder time grasping concepts related to the second law (reversibility, impossibility, entropy, and exergy) than those to the first law. For example, a Delphi study \(^1\) identified thermodynamic concepts of high importance but with little student-understanding \(^2\); the study reveals a second law concept (reversibility) to be ranked 7\(^{th}\) among 28 concepts because very few students understand it but experts generally consider it important. During the development of second-law oriented tutorials, Cochran and Heron observed severe deficiencies of students’ second-law understanding \(^3\).

To address issues about students’ challenges in mastering the second law, it is necessary to articulate second law concepts and describe how they differ from first law concepts. In general, the second law suggests natural processes will proceed in a given direction: one which ultimately
increases the net entropy of the combined system and surroundings. A process may proceed in a different direction, but this will require some other interaction to occur between the system and surroundings; no process can proceed in a fashion that decreases net entropy of the isolated system/surroundings. These truths lead to many corollary statements that are often alternative versions of the same second law.

First law concepts are, of course, those related to the first law of thermodynamics. Unlike the second law, the first law does seem to have a simple statement; it’s the conservation of energy principle and states that energy is neither created nor destroyed. Thus, first law concepts center on those that mandate energy be conserved. The first and second laws are related to each other. In fact, combining second law concepts with first law concepts reveals the effect that entropy has on energy. That is, the second law recognizes, by virtue of the increase in net entropy principle, the ability of energy to do useful work (exergy) necessarily decreases. Engineers must apply this principle analyzing alternative designs, but, to do this, the FTC must be taught to help engineers develop the ability to apply the principle in many different contexts.

Engineers need to have as strong of an understanding of second law as they do first law. First law concepts ensure engineering analysis is done correctly. It ensures energy is balanced properly, control systems are chosen wisely when doing analysis, and proper decisions are made when sizing systems or ensuring highest efficiency of a given design. Second law concepts, however, constrain the parameter space within which they work because of limitations imposed by the second law. These concepts allow engineers to recognize that various types of energy have better uses in different applications. Second law concepts enable engineers to make decisions about how to allocate resources for developing and advancing various energy-related technology likely to result in better designs.

The objective of the course described in this article is to improve student conceptualization and application of entropy and second law concepts and their role on energy conversion. This objective is met by redesigning the FTC to elevate the discussions and use of entropy and second law concepts throughout the semester. In the redesign, course topics must be reorganized to focus on the challenges that students find most difficult. To increase a student’s ability to apply entropy in novel contexts (because all contexts cannot be addressed in the first course), some elements of entropy and second law concepts are discussed in the context of microscale behavior. (As an aside, the above referenced Delphi study additionally identified conceptual misunderstandings since students fail to recognize connections, or lack thereof between macroscale and microscale behavior). This also enables a smooth discussion of the relationship between energy and entropy, namely exergy. This article will highlight the modifications to the redesigned FTC, in the context of the conventional FTC, and provide preliminary evidence of its impact on student learning. Throughout the article, it may be helpful to know the general composition of engineering students taking this course is all majors, with about 63% from non-mechanical engineering majors including civil engineering, industrial engineering, nuclear engineering, and petroleum engineering. The remaining 37% are mechanical engineers.
Conventional FTC

The conventional FTC is organized very similarly to the prevailing engineering thermodynamic textbooks (e.g.,\textsuperscript{5-7}) used by most mechanical engineering thermodynamic courses; it most closely mirrors Cengel and Boles’ text\textsuperscript{6} since this is the required text for the FTC in mechanical engineering at Texas A&M University. A week-by-week summary of the major topics and concepts discussed is provided in Table 1. In the conventional topic order, the course is separated into three major conceptual groups: 1) first law concepts and supporting information (e.g., properties), 2) second law concepts and supporting information (e.g., properties), and 3) cycle analysis. The first 6.5 weeks of the semester are mostly dedicated to first law concepts. That is, knowledge of conservation of energy, heat transfer, work transfer, modes of other energy transfer, first law efficiency, different control systems (open system versus closed system), and supporting information (properties, property tables, units, and dimensions). Interestingly, subtle second law concepts such as equilibrium, states, and processes are introduced in Week 1 but are not discussed in their second-law context; they are simply defined.

Table 1: Summary of weekly topics covered in conventional FTC in Department of Mechanical Engineering at Texas A&M University.

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics Discussed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction, Conservation of energy, Units, Dimensions, States, Equilibrium, Processes</td>
</tr>
<tr>
<td>2</td>
<td>Temperature, Pressure, Energy, Heat, Work, First Law</td>
</tr>
<tr>
<td>3</td>
<td>First Law, Efficiency, Phases, Phase changes, Property data / tables</td>
</tr>
<tr>
<td>4</td>
<td>Ideal gases, Real gases, Equations of state, Boundary work, Energy balance, Specific heats</td>
</tr>
<tr>
<td>5</td>
<td>Internal energy and enthalpy of ideal gases, Conservation of mass, Flow work, Energy transport by mass</td>
</tr>
<tr>
<td>6</td>
<td>Exam #1, Steady flow systems, Steady flow devices</td>
</tr>
<tr>
<td>7</td>
<td>Steady flow devices, transient analysis, second law, thermal reservoirs, heat engines</td>
</tr>
<tr>
<td>8</td>
<td>Heat pumps / refrigerators, reversibility, Carnot principles, Entropy</td>
</tr>
<tr>
<td>9</td>
<td>Entropy, Ts equations, Entropy changes for ideal gases, Reversible work, Isentropic efficiencies</td>
</tr>
<tr>
<td>10</td>
<td>Isentropic efficiencies, Entropy balance, Carnot cycle, Air cycles (Otto)</td>
</tr>
<tr>
<td>11</td>
<td>Exam #2, Air cycles (Otto and Diesel), Brayton cycle</td>
</tr>
<tr>
<td>12</td>
<td>Rankine, with reheat, and with feedwater heater cycles, Ranking cycle efficiency increases, Rankine cycle real losses</td>
</tr>
<tr>
<td>13</td>
<td>Refrigerator and heat pump cycles</td>
</tr>
<tr>
<td>14</td>
<td>Instructor choice, Conclusion</td>
</tr>
</tbody>
</table>

Second law discussions rigorously appear starting mid-way through Week 6. Second law is introduced in the classical fashion of a heat engine (and heat pump) interacting with thermal reservoirs. Kelvin-Planck and Clausius Statements are defined and provide the “spring-board” for developing the idea of reversibility and Carnot postulates. Combining reversible heat transfer with one of Carnot postulates (efficiency of a reversible heat engine / heat pump depends only on the temperatures between which the cyclic device interacts) leads to Kelvin’s temperature scale and the relationship between heat transfers and temperatures of the thermal reservoirs. This,
when combined with irreversibility, eventually leads to the Clausius Inequality which then serves as the classical mathematical basis for defining entropy.

Once entropy is defined, the first 1/3 of the semester is essentially repeated in a condensed fashion by going through similar analysis for closed and open systems with second law concepts now available (i.e., determining entropy at states using property tables / relationships, restricting processes to ideal constraints such as constant entropy). Also, new concepts are introduced including entropy generation and isentropic efficiency of processes. The remainder of the semester integrates most of these concepts with cycle analysis.

Data on Student Learning in a Conventional FTC

Anecdotally, students often suggest that they understood thermodynamics up to the point of the second law, after which they lose confidence in the subject since the second law seems to them ungraspable. Data using a preliminarily-designed concept inventory ⁸ may support the anecdotal evidence. Figure 1 shows the percentage of questions answered correctly (averaged among all students in a given class) for five different courses to which the concept inventory was administered. A summary of the classes is provided in Table 2. The concept inventory was administered to two sections of the conventional FTC at the conclusion of the semester (post test), two sections of the second thermodynamics course (STC) at the start of the semester where students have had at least the FTC (pre test), and one section of the graduate thermodynamics course (GTC) at the start of the semester where presumably the students have had at least one thermodynamics course. The uncertainty of the data is represented by one standard deviation of the population scatter. There are two critical observations: 1) students that have just completed their FTC are failing to grasp second law concepts (evidenced by the less-than-60% percentile average of the two FTC sections), and 2) students are not retaining important second law concepts (as evidenced by the less-than 65% average of the two STC sections and one GTC section, although it is recognized that roughly 40% of the students in some of these courses are scoring higher than 70%). Such data suggest that a new approach to how the second law is taught in the FTC is needed to improve conceptual understanding and retention.

Opportunities to Improve the FTC

The authors believe there are several opportunities to improve the conventional approach:

1) **Separation of first and second law discussions:** Since they are two separate, but major laws, it may appear instructionally sound to separate discussions of first and second laws. They are two different laws and capture two unique universal features of our physical world (hence, their existence as two separate laws). However, productive analysis of any engineering system – particularly a new, unexplored, or undiscovered engineering system – in the context of just one of the laws is not possible. It seems conventionally engineers always think about system analysis in the context of the first law. This may result from the simple outcome that the second law has already been imposed implicitly in the system design (i.e., unwittingly to the engineer analyzing the system). Regardless, if one holds the need to understand the second law to the same level of that of the first law, then clearly engineers need to think of both laws seamlessly. Thus, combining discussions of first and second laws in the FTC creates the expectation that students and future engineers must
coincidentally consider both first and second law consequences when designing engineering systems.

2) **Presentation of entropy and second law concepts strictly from macroscopic perspectives.** As described above, students often fail to recognize connections between microscale and macroscale behavior; this may also be true in the conventional presentation of the FTC where entropy is mathematically derived from Carnot principles and Clausius Inequality. That is, entropy is defined as a macroscopic parameter rather than its microscopic behavior (i.e., Boltzmann approach). Without diving deeply into the details of statistical thermodynamics, students can appreciate the improbability of precisely defining a system’s particle behavior since they already gain these mental images from high school and early college physics courses. Once students understand what entropy is, they can better appreciate the definition of the second law.

3) **Lack of connections between energy and entropy.** In the conventional approach, insufficient linkages are made between energy and entropy; that is, exergy is not rigorously discussed. Students in the conventional FTC learn to use entropy as another property to fix a state, or to decide if a process / cycle is possible. These are important and necessary skills, but they do not fully offer the completeness of entropy’s importance in an engineering setting: the degradation of energy’s ability to do useful work. There is, of course, a property that links entropy’s effect on energy: exergy. When students understand entropy on a microscale basis, they can visualize how entropy degrades energy’s ability to do useful work and appreciate the full context of the second law on engineering systems. It’s more intuitive for an engineer to think of the second law as a statement of lost work opportunity rather than entropy generation and entropy as a means to lower the quality of energy than just some arbitrary property.

Table 2: Summary of identifiers used in Figure 1. “Post course” means the concept inventory was administered at the end of the semester. “Pre course” means the concept inventory was administered at the start of the semester.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Class</th>
<th>Semester Administered</th>
</tr>
</thead>
<tbody>
<tr>
<td>cFTC 13b 1</td>
<td>First section of FTC (conventional), post course</td>
<td>Summer 2013</td>
</tr>
<tr>
<td>cFTC 13b 2</td>
<td>Second section of FTC (conventional), post course</td>
<td>Summer 2013</td>
</tr>
<tr>
<td>STC 13c 1</td>
<td>First section of second thermodynamics course, pre course</td>
<td>Fall 2013</td>
</tr>
<tr>
<td>STC 13c 2</td>
<td>Second section of second thermodynamics course, pre course</td>
<td>Fall 2013</td>
</tr>
<tr>
<td>GTC 13c</td>
<td>Graduate thermodynamics course, pre course</td>
<td>Fall 2013</td>
</tr>
</tbody>
</table>
A redesigned FTC that attempts to rectify what the authors believe to be three critical flaws in the conventional FTC (as described above) is described next.

**Redesigned FTC**

The redesigned FTC involves four major deviations from the conventional FTC:

1. Second law and entropy are defined and discussed in parallel with first law.
2. Entropy is described, qualitatively, as improbability to precisely define particle behavior (microscopic terms) rather than mathematically derived from Carnot principles and Clausius Inequality (macroscopic terms).
3. Exergy is defined and discussed in parallel with energy and entropy, to create an awareness and appreciation of the effect of entropy on energy’s ability to do useful work.
4. Open system analysis is presented before closed system analysis.

Reasons for #1, #2, and #3 are described in the above section. The fourth deviation (moving open system analysis ahead of closed system analysis) is made possible by the relocation of second law definition and analysis to be coincident with first law definition and analysis. That is, the open system is presented as the most general simple thermodynamic system available to engineers with all applicable thermodynamic laws for that general system (i.e., first law, second law, and third law).
law, and conservation of mass). As this is done early in the semester (i.e., by the fourth lecture, as described below), students are presented with all properties (i.e., temperature, pressure, specific volume, internal energy, enthalpy, entropy, velocity, potential elevation, mass, and volume) they will need and use through the whole semester. The general system and corresponding equations are then modified as appropriate by the constraints of a closed system (i.e., no mass exchange with the surroundings).

There is a fifth deviation between the conventional FTC and the redesigned FTC: integration of engineering design and a team-oriented open-ended design project. This particular deviation is independent of the general effort to redesign the FTC to elevate student understanding and retention of second law concepts, therefore it is not highlighted in this discussion. It is mentioned, however, as it appears in the week-by-week summary of topics, provided in Table 3.

### Table 3: Summary of weekly topics covered in redesigned FTC in Department of Mechanical Engineering at Texas A&M University.

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics Discussed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction, Overview of thermodynamics (example of steam power plant).</td>
</tr>
<tr>
<td>2</td>
<td>Definition and description of functional decomposition (engineering design), definition of systems (open and closed) and corresponding laws (conservation of mass, first law, second law), definition of steady-state and transient processes.</td>
</tr>
<tr>
<td>3</td>
<td>Definition and discussion of energy, entropy and exergy, definition and relevance of reversible / irreversible processes.</td>
</tr>
<tr>
<td>4</td>
<td>Properties and relationships (temperature, pressure, specific volume, internal energy, enthalpy, entropy, and specific heats) of phase changing substances (e.g., water and R-134a).</td>
</tr>
<tr>
<td>5</td>
<td>Properties and relationships (temperature, pressure, specific volume, internal energy, enthalpy, entropy, and specific heats) of ideal gases. Distinguishing real gases from ideal gases.</td>
</tr>
<tr>
<td>6</td>
<td>Exam #1, Open system analysis (introduction)</td>
</tr>
<tr>
<td>7</td>
<td>Open system analysis, work-related steady-state devices (i.e., turbines, compressors / pumps), isentropic efficiency, reversible work transfer (shaft work).</td>
</tr>
<tr>
<td>8</td>
<td>Open system analysis, non-work steady-state devices (i.e., nozzles / diffusers, heaters / chillers, heat exchangers, mixers, and throttles).</td>
</tr>
<tr>
<td>9</td>
<td>Closed system analysis, introduction, piston/cylinder arrangements, boundary work</td>
</tr>
<tr>
<td>10</td>
<td>Closed system analysis energy and entropy balances, entropy generation, system / surrounding interactions, net increase in entropy principle.</td>
</tr>
<tr>
<td>11</td>
<td>Exam #2, heat engine / heat pump cycles.</td>
</tr>
<tr>
<td>12</td>
<td>Definition of Kelvin-Planck / Clausius Statements, Carnot principles, reversible heat engine / heat pump cycles, Carnot cycle.</td>
</tr>
<tr>
<td>13</td>
<td>Rankine cycle, Rankine with reheat, air standard power cycles (Otto, Diesel, and Brayton)</td>
</tr>
<tr>
<td>14</td>
<td>Air standard power cycles (Otto, Diesel, and Brayton), Vapor Refrigeration Cycle, conclusion.</td>
</tr>
</tbody>
</table>
In comparing to the weekly summary of the conventional FTC (reference Table 1), there are several departures in the weekly schedule. They are summarized thus:

1. Week 1 in the redesigned FTC provides a general overview of thermodynamics by walking students through a general discussion of power plants, exposing them to terms such as cycles, processes, steady-state, and certain thermodynamic devices (such as turbines, pumps, boilers, and condensers). Students are exposed to both first law and second law principles (i.e., energy must be conserved, but low quality heat rejection must occur for the heat engine cycle). This approach could be interpreted as “top-down”. Week 1 in the conventional FTC moves immediately into first law definitions and laying the foundation for a “bottom-up” approach.

2. Week 2 in the redesigned FTC exposes students to functional decomposition (a method to identify a need and the requirements that must be considered to satisfy the need), a first step in the engineering design process. This addition to the redesigned FTC is independent of the effort to improve student understanding and retention of second law concepts. Week 2 also exposes students to the general simple thermodynamic system and the three major thermodynamic laws used to analyze a simple thermodynamic system. Week 2 in the conventional FTC provides definitions and analysis techniques for some properties and the first law.

3. Week 3 in the redesigned FTC exposes students to definitions and analysis techniques of energy, entropy, and exergy. Further, students are exposed to microscale descriptions of energy and entropy, and the relationship between energy and entropy. Exergy is introduced to give students an applicable sense of entropy in engineering context. Finally, the basis for the second law, in terms of reversibility / irreversibility, is introduced. Students are provided the basic definition of the second law of thermodynamics in the context of entropy generation, lost work potential (exergy destruction), and irreversibility. Week 3 in the conventional FTC provides deeper discussions of first law analysis and property behavior of typical substances changing phase during engineering processes (e.g., water and R-134a).

4. Week 4 in the redesigned FTC provides property behavior of typical substances changing phase during engineering processes (e.g., water and R-134a), including entropy. Week 4 in the conventional FTC provides property behavior of typical substances that can be modeled as ideal gases during engineering processes (excluding internal energy, enthalpy, and entropy). Also, students learn closed system analysis and boundary work.

5. Week 5 in the redesigned FTC provides property behavior of typical substances that can be modeled as ideal gases during engineering processes (including internal energy, enthalpy, and entropy). Week 5 in the conventional FTC teaches students additional information about property changes for ideal gases (i.e., internal energy and enthalpy, but not entropy). Further, students begin to learn open system analysis principles such as conservation of mass, flow work, and energy transport by mass (enthalpy).

6. Week 6 in the redesigned FTC begins to expose students to open system analysis. Week 6 in the conventional FTC exposes students to steady-state principles and steady-state devices.

7. Week 7 in the redesigned FTC continues open system analysis with particular emphasis on work-related devices (i.e., turbines, and compressors/pumps), including second law analysis of such devices (i.e., isentropic efficiency analysis). Week 7 in the conventional FTC continues open system analysis with continued discussions on steady-state devices.
(without entropy or second law discussions). Further, the conventional FTC begins discussions on second law concepts with introduction to thermal reservoirs and heat engines / heat pumps.

8. Week 8 in the redesigned FTC continues open system analysis with emphasis on non-work steady-state devices (i.e., nozzles / diffusers, heaters / chillers, heat exchangers, mixers, and throttles). Week 8 in the conventional FTC continues second law discussions including Kelvin-Planck / Clausius Statements, reversibility, Carnot principles, and the classical development of entropy.

9. Week 9 in the redesigned FTC continues the top-down approach by constraining the general system with no mass transfer (closed system analysis) and boundary work. Week 9 in the conventional FTC teaches the details on using entropy in engineering analysis (i.e., determining entropy for substances including ideal gases, entropy generation, and isentropic efficiency).

10. Week 10 in the redesigned FTC continues closed system analysis by teaching energy and entropy balances, entropy generation, the interaction of systems and surroundings, and the net increase in entropy principle. The conventional FTC also discusses system / surrounding interactions, entropy balance, and net increase in entropy principle. The conventional FTC also begins cycle analysis with Carnot Cycle and Air Standard Power Cycles.

11. Week 11 in the redesigned FTC begins discussions heat engines / heat pumps while the conventional FTC continues discussions of air standard power cycles.

12. Week 12 in the redesigned FTC provides deeper discussions on heat engine / heat pumps with presentation of Kelvin-Planck / Clausius Statements, Carnot principles, reversible cycles, and the Carnot Cycle. Week 12 in the conventional FTC teaches vapor power cycles including Rankine, Rankine with Reheat, and Rankine with Feedwater Heater cycles.

13. Week 13 in the redesigned FTC provides more discussions on cycle analysis including vapor power cycles (Rankine Cycle and Rankine Cycle with Reheat) and air standard power cycles. Week 13 in the conventional FTC teaches the vapor refrigeration cycle and allows some cushion for instructor topics.

14. Week 14 in the redesigned FTC concludes the semester with continued discussions of air standard power cycles and vapor refrigeration cycles. Week 14 in the conventional FTC concludes the semester with cushion for instructor topics.

Nearly all the topics covered in the conventional FTC are covered in the redesigned FTC. The redesign, with increased emphasis on second law concepts and introduction of design principles, requires some topics to be diminished in discussion. Specifically, these include:

1. The redesigned FTC spends considerably less time teaching students about compressibility of real gases. Students in the redesign FTC do learn about real gases (i.e., not all gases can or should be modeled as ideal) and how to judge a substance to be reasonably modeled as an ideal gas (i.e., compressibility factor).

2. The redesigned FTC spends considerably less time teaching students about the subtle details of the Rankine Cycle. For example, Rankine with Feedwater Heater analysis and real Rankine Cycle analysis are not covered.
3. The redesigned FTC spends less time teaching students about the Brayton Cycle. Specifically, this cycle is not explicitly discussed in class, but it is included as a study topic for students as part of homework.

Evidence of Changes to Student Learning

Some effort has been initiated to quantitatively determine if the redesigned FTC improves student understanding and retention of second law concepts. It’s too early in the project to assess student retention. Student understanding of second law concepts is done via a second law concept inventory that is designed and developed in parallel with the present study. The concept inventory was administered on the last day of class in four courses: two conventional FTCs and two redesigned FTCs. The average results for the four courses are shown in Figure 2 with question-by-question responses for each class shown in Figure 3; a summary of the four classes and the identifiers used in Figure 2 is provided in Table 4. There are two interesting, albeit discouraging, results apparent in Figure 2: First, as noted in the discussion on Figure 1, the average percentage of questions answered correctly by the students is low (on the order of 56% with a 10 percentage-point standard deviation. The second observation is that the redesigned course does not offer much improvement in the average percentage of questions answered correctly. In the first semester the redesigned FTC was offered (“rFTC 13a” in Figure 2), the average percent of correctly answered questions was 67%, but with a 20 percentage-point standard deviation. In the second semester the redesigned FTC was offered (“rFTC 13c” in Figure 2), the average percent of correctly answered questions was the same as the conventional FTC scores (56% with 10 percentage point standard deviation). On the one hand, it can be argued that the redesigned FTC is not harming student learning of second law concepts. On the other hand, there does not yet appear to be a clear improvement in average results.

Table 4: Summary of identifiers used in Figure 2 and Figure 3.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Class</th>
<th>Semester Administered</th>
</tr>
</thead>
<tbody>
<tr>
<td>cFTC 13b 1</td>
<td>First section of conventional FTC</td>
<td>Summer 2013</td>
</tr>
<tr>
<td>cFTC 13b 2</td>
<td>Second section of conventional FTC</td>
<td>Summer 2013</td>
</tr>
<tr>
<td>rFTC 13a</td>
<td>First section of redesigned FTC</td>
<td>Spring 2013</td>
</tr>
<tr>
<td>rFTC 13c</td>
<td>Second section of redesigned FTC</td>
<td>Fall 2013</td>
</tr>
</tbody>
</table>
Although improvements in average results are not clear, there may be some sign of improved understanding of certain core second law concepts, as observed in Figure 3 which shows the % of students answering a given question correctly. For simplicity of the graph, only questions of interest for discussion are included. In general, the correct-response-percent is nearly the same among class groups for those questions not shown. The data in Figure 3 are organized in the same fashion as Figure 2 and Table 4; the first data bar for each question is cFTC 13b 1, the second is cFTC 13b 2, the third is rFTC 13a, and the fourth is rFTC 13c. To aid in interpreting the data of Figure 3, the discussed questions that are asked on the concept inventory are included herewith in the appendix.
Students in the redesigned FTC on average scored better than those in the conventional FTC in 11 questions (the remaining 8 were answered correctly by more students in the conventional FTC, and Question #4 was poorly answered by all students in all classes). Most of these differences are rather small and un-noteworthy (e.g., questions 3 and 5). There are some questions where the redesigned FTC students score significantly better than the conventional FTC students. These questions include #6, #11, #13, and #16. Questions #6 and #11 both assess students’ understanding of the relationship between entropy and energy, and the degradation of useful work that entropy imposes on energy. The property that quantifies this idea, exergy, is parenthetically included in both questions. The improvement in student understanding of this concept with the redesigned courses is reassuring, as it’s one of the major objectives of the redesign effort. Question #13 is similar in concept to Question #4; the difference with Question #13, however, is that students are alerted to the idea of cyclic behavior of properties with the inclusion of other properties (such as temperature and pressure). When Question #13 is asked,
Students realize or remember that a cycle requires all properties to be the same after the final process as their respective values at the start of the first process. The inclusion of the cycle being irreversible is irrelevant (which simply means entropy is generated and, in the case of the cycle, is transferred to the surroundings). It seems relatively more students in the redesigned FTC detected this subtlety compared to those in the conventional FTC. Finally, Question #16 addresses the concept of using earth’s reservoirs, such as the atmosphere, land, and oceans, as thermal reservoirs to produce work. Students in the redesigned FTC did substantially better on this question than students in the conventional FTC. A similar question (Question #19), was also scored more correctly by students in the redesigned FTC, although with a much smaller difference in percent of correct responses. Thus, it’s not clear if there is conceptual improvement with students in the redesigned FTC or a wording issue with Question #16.

There are qualitative measures of improved student success with the redesigned FTC that can be mentioned with the caveat that there is some bias in these measures. The first is the instructor’s perceptions of the course organization. The flow of the course has a more natural feel to the instructor where discussions tend to be more integrated and less discretized. There is much to cover in the beginning and there could be a concern of overwhelming the students. But, given their strong background knowledge from physics and chemistry courses, this does not seem to be an issue; in fact, the redesigned course organization seems to build more appropriately on the students’ a priori knowledge. The second is feedback from members of an advisory panel, composed of five thermodynamic experts from industry, academia, and governmental research laboratories. Their comments were generally positive during a review of the redesigned course organization; at least one requested the syllabus for use in industry-based instruction. The third is feedback from students. In the three semesters of offering the course in redesigned fashion (approximately 250 students) there has only been one comment that complained entropy and second law were being taught simultaneously with first law concepts; actually, the comment was really directed at the lecture material being out of phase with the textbook (as an aside, students are given the relevant textbook sections that lecture and homework material cover during a week). Otherwise, student comments have been typical of those of thermodynamic courses; students are generally positive about the course organization.

Work will continue to collect data from both the conventional FTC and the redesigned FTC. Further, students in follow-on thermodynamic courses will be assessed on their retention of second law concepts; an effort will be made to correlate, if appropriate, concept retention to the FTC students had.

Conclusions

This article describes a redesign of the FTC to improve student understanding and application of second law concepts as well as analysis of some data about student understanding of the concepts. The major objective of the study is to improve student conceptualization and application of entropy and second law concepts and their role on energy conversion. This objective is met by redesigning the FTC to elevate the discussions and use of entropy and second law concepts throughout the semester. In doing so, reorganization of the course material is necessary that moves discussions around relative to their presentation in a conventional FTC. Further, in an effort to increase student’s ideas of entropy, some elements of entropy and second
law concepts are discussed in the context of microscale behavior. This also enables a smooth
discussion of the relationship between energy and entropy, namely exergy. The article describes
the modifications to the redesigned FTC, in the context of the conventional FTC, and provides
preliminary evidence based on a second law concept inventory (developed in parallel with the
current study) of its impact on student learning.

A question-by-question analysis reveals that students in the FTC score better on certain second
law conceptual questions; these mostly include questions about the availability (exergy) of
energy. In general, however, students in the redesigned FTC score the same on average on the
second law concept inventory than students in the conventional FTC. This is, as might be
expected, disappointing as it had been hoped students in the redesigned FTC would score better.
Data collection will continue in future offerings of the redesigned FTC to assess potential
improvements to student knowledge and retention of second law concepts.

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Appendix

The following are the questions asked in the second law concept inventory \(^8\) used to provide some quantitative assessment of student understanding and retention of second law concepts as part of the redesign effort of the FTC. Comments are also provided for those questions that may be vague or possess confusing subtleties; modifications to the second law concept inventory are ongoing.

Please select the “best” choice:

3. In thermodynamics, the idea of a “reversible” process is most closely associated with
   a. The first law of thermodynamics
   b. The second law of thermodynamics
   c. The state principle of thermodynamics
   d. Work interactions
   e. a & b
   Correct answer = b.

4. For an irreversible cycle, the ending value of the system entropy
   a. is less than the starting value
   b. is equal to the starting value
   c. is greater than the starting value
   d. depends on the type of process
   e. depends on the working fluid
   Correct answer = b.

5. Entropy is a thermodynamic property most closely associated with
   a. The first law of thermodynamics
   b. The second law of thermodynamics
   c. The state principle of thermodynamics
   d. Work interactions
   e. a & b
   Correct answer = b.

6. Consider all the energy associated with an irreversible process:
   a. energy is conserved and its potential to do work (i.e., exergy) has increased
   b. energy is conserved and its potential to do work (i.e., exergy) has not changed
   c. energy is conserved and its potential to do work (i.e., exergy) has decreased
   d. energy is not conserved and its potential to do work (i.e., exergy) has not changed
   e. energy is not conserved and its potential to do work (i.e., exergy) has decreased
   Correct answer = c.
11. On a global basis,
   a. energy is conserved and its potential to do work (i.e., exergy) has not changed
   b. energy is conserved and its potential to do work (i.e., exergy) has increased
   c. energy is conserved and its potential to do work (i.e., exergy) has decreased
   d. energy is not conserved and its potential to do work (i.e., exergy) has not changed
   e. energy is not conserved and its potential to do work (i.e., exergy) has decreased
   Correct answer = c.

13. Consider a gas that undergoes an irreversible cyclic process which consists of a series of changes in pressure and temperature. For each complete cycle,
   a. The beginning and ending temperatures are the same, but the beginning and ending entropy values are different.
   b. The beginning and ending temperatures and the beginning and ending pressures are the same, but the beginning and ending entropy values are different.
   c. The beginning and ending temperatures are the same and the beginning and ending entropy values are the same.
   d. The beginning and ending temperatures are different and the beginning and ending entropy values are different.
   e. The beginning and ending temperatures and the beginning and ending pressures are different and the beginning and ending entropy values are different.
   Correct answer = c.
   Comment: The responses for this question are too long. The goal of this question is to assess students’ understanding that what makes a cyclic heat engine / heat pump necessarily less than 100% efficient is the requirement that unusable entropy must be rejected from the system (hence, the cyclic nature of the device); therefore, entropy of the system cannot increase and the starting value of entropy must always be the same (if the device is to operate cyclically). The responses can be simplified by removing the pressure property, and making the responses more concise.

16. Assume that the environment is available as a high temperature reservoir. To use this source and produce work, a device would need
   a. At least one other thermal reservoir at any temperature
   b. At least one other thermal reservoir at a higher temperature
   c. At least one other thermal reservoir at a lower temperature
   d. At least one other thermal reservoir at the environment temperature
   e. This source can never produce work.
   Correct answer = c.
   Comment: The responses make it clear the “device” in the question is meant to be cyclic. Regardless, it would be clearer to specify the device is a cyclic device, so as to avoid confusion with the subtlety that a device could interact with just one reservoir and produce work non-cyclically. Further, technically response “b” could be true (even though the question states “as a high temperature” reservoir, implying $T_H$); it is suggested that the question and responses be reworded appropriately.