Improvement in Second-Law Concept Retention in Students Taking Redesigned Entropy-Centered FTC

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Abstract

Thermodynamics remains an important subject for mechanical engineers. Likewise, second law concepts such as entropy, reversibility, and exergy can remain confusing and abstract for mechanical engineering students; an outcome that may result in mechanical engineers losing opportunities to improve energy utilization and conversion due to poor understanding of all important laws of thermodynamics. Realizing the possible deficiency in students' conceptual understanding of second law, and the perceived importance of having conceptual understanding of second law, an effort was undertaken to redesign the first thermodynamics course (FTC) to improve student understanding and retention of second law concepts. The results of this effort are reported elsewhere. The present follow-on study describes the possible improved retention of second law concepts among students who had the redesigned FTC by assessing their second law conceptual understanding in an important follow-on course, the second thermodynamics course (STC). This paper describes the redesigned FTC, relative to the conventional FTC, the STC, and the approach taken to assess possible improvement in student retention of second law concepts. Further, the study quantifies the impact of the redesigned FTC on students' ability to be successful in the STC.

Introduction

The current study evaluates the impact of a redesign of the first course on thermodynamics, (FTC) as reported in Jacobs, et al.[1], on retention of important second law concepts. The redesign of the FTC occurred during 2011 – 2014; some students who had both the conventional and redesigned FTC have taken the second thermodynamics course (STC). One way to assess the possible improvement of the redesigned FTC is by quantifying concept retention of FTC concepts. As the redesigned FTC is meant to improve understanding and retention of second law concepts, this study attempts to quantify the possible improvement in second law concept retention of those students having had the redesigned FTC relative to those students having had the conventional FTC.

The original motivation for redesigning the FTC is centered on an anecdote that students 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 [2] identified thermodynamic concepts of high importance but with little student-understanding [3]; the study reveals a second law concept (reversibility) to be ranked 7th 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 [4]. Indeed, in a coincident study to the present FTC redesign resulting in a second law concept inventory[5], it was observed that graduate-level students struggle to fully understand and retain basic second law concepts.

It is further believed that engineers need to have as strong of an understanding of second law as they do first law[3, 4, 6]. 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 [6] likely to result in better designs.

Based on the above noted deficiencies in, and importance of, second law concepts, the study endeavored to drastically redesign the FTC. As noted above, this redesign took place in 2011 and the initial results reported elsewhere[1]. At the time of the initial results, students had just completed the FTC. Now, many of these students have taken a second course on thermodynamics (STC) – a time separation that typically spans no less than 2 semester (one year) from their FTC. In an effort to quantify the impact that the redesigned FTC may have had on students in their retention of second law concepts, the same concept inventory[5] administered to them in their FTC was administered to them again at the start of their STC. Further, to ensure that the redesign does not in some way damage or hurt the students' abilities to succeed in all elements of thermodynamics, the students' STC grades are compared against those students who did not have the redesigned FTC. The objectives of this study are to quantify the potential improvements in second law concept retention between first exposure in the FTC and the start of the STC and to ensure students are not disadvantaged in being successful in their STC by having had the redesigned FTC.

The article proceeds to describe the conventional FTC, the redesigned FTC, and the STC courses taught at the institution where the study takes place. Following these descriptions, results are shown that illustrate potential improvement in second law concept retention between the FTC and STC for those students who had the redesigned FTC. Further, results show that students in the redesigned FTC are likely not disadvantaged by having had the redesigned FTC in their subsequent STC. Finally, the article provides conclusions and suggestions for future study.

Conventional FTC

As reported elsewhere[1], the conventional FTC is organized very similarly to the prevailing engineering thermodynamic textbooks (e.g.,[7-9]) used by most mechanical engineering thermodynamic courses; it most closely mirrors Cengel and Boles' text [8] since this is the required text for the FTC in Department of Mechanical Engineering at Texas A&M University. 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.

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.

Opportunities to Improve the FTC

As described elsewhere[1], the study identified several opportunities to improve the conventional approach:

1) *Combine 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 practiced. 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) *Introduce micro-scale concepts in the presentation of entropy and second law concepts*: As described above, students often fail to recognize connections between microscale and macroscale behavior [2]; 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) *Reveal the connection 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.

The redesigned FTC that attempts to accomplish the above stated opportunities is described next.

Redesigned FTC

As described elsewhere[1], 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 a general simple thermodynamic system available to engineers with all applicable thermodynamic laws for that general system (i.e., first law, second law, and conservation of mass). As this is done early in the semester (i.e., by the fourth lecture), 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). A comparison between the conventional FTC and redesigned FTC is tabulated in Table 1 for convenience. It is noted that the "cost" of teaching the redesigned FTC is minimal, as it mostly entails a reorganization of existing material. New concepts to the FTC, such as exergy, are usually covered in existing thermodynamic textbooks. Thus, the most significant cost (which is not trivial) is instructor preparation and the need to go outside one’s comfort zone. It is not expected that ABET accreditation would be jeopardized by the Redesigned FTC.

The STC

It is fairly common among mechanical engineering curricula that a second course on thermodynamics was removed as a degree requirement. Many curricula, however, still offer the STC. The STC at Texas A&M encompasses an integration of advanced thermodynamic, heat transfer, and fluid mechanics concepts in a design-oriented structure. Such an approach is believed to enable students to integrate the “thermal-fluid sciences” concepts and apply them in open-ended situations, such as those encountered during design. Although the STC is not explicitly required, it is one of three “stem” courses of which students must choose two to complete degree requirements. Thus, roughly 2/3 of the department’s students take the STC. Heat transfer is a pre-requisite (which has fluid mechanics as a pre-requisite), thus senior-level students take the course. Since the FTC is a pre-requisite to fluid mechanics, there can be no less than 2 semesters between when a student finishes the FTC and takes the STC.

The technical content of the STC includes review of thermodynamic concepts from the FTC, review of basic fluid equations, review of basic heat transfer analysis, and then conveyance of advanced thermodynamic subjects such as mixtures, psychometrics, combustion, and advanced cycle analysis. It is clear that students must have a solid foundation in the essential components of thermodynamics learned in the FTC. Thus, while the redesigned FTC may improve students’ conceptual understanding of second law concepts, it may not do so at the expense of providing the same foundational basis that the conventional FTC provides. It is presumed that a failure to do so would be most obvious in the STC, where FTC concepts are inherently prerequisite to success in the STC. One element of this study is to evaluate the effectiveness of the redesigned FTC in enabling students to be successful in the STC.

Table 1: Weekly comparison of topic organization between conventional FTC and redesigned FTC.

Week	Conventional FTC	Redesigned FTC
1	Introduction, Conservation of energy, Units, Dimensions, States, Equilibrium, Processes	Introduction, Overview of thermodynamics (example of steam power plant).
2	Temperature, Pressure, Energy, Heat, Work, First Law	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.
3	First Law, Efficiency, Phases, Phase changes, Property data / tables	Definition and discussion of energy, entropy and exergy, definition and relevance of reversible / irreversible processes.
4	Ideal gases, Real gases, Equations of state, Boundary work, Energy balance, Specific heats	Properties and relationships (temperature, pressure, specific volume, internal energy, enthalpy, entropy, and specific heats) of phase changing substances (e.g., water and R-134a).
5	Internal energy and enthalpy of ideal gases, Conservation of mass, Flow work, Energy transport by mass	Properties and relationships (temperature, pressure, specific volume, internal energy, enthalpy, entropy, and specific heats) of ideal gases. Distinguishing real gases from ideal gases.
6	Exam #1, Steady flow systems, Steady flow devices	Exam #1, Open system analysis (introduction)
7	Steady flow devices, transient analysis, second law, thermal reservoirs, heat engines	Open system analysis, work-related steady-state devices (i.e., turbines, compressors / pumps), isentropic efficiency, reversible work transfer (shaft work).
8	Heat pumps / refrigerators, reversibility, Carnot principles, Entropy	Open system analysis, non-work steady-state devices (i.e., nozzles / diffusers, heaters / chillers, heat exchangers, mixers, and throttles).
9	Entropy, Tds equations, Entropy changes for ideal gases, Reversible work, Isentropic efficiencies	Closed system analysis, introduction, piston/cylinder arrangements, boundary work
10	Isentropic efficiencies, Entropy balance, Carnot cycle, Air cycles (Otto)	Closed system analysis energy and entropy balances, entropy generation, system / surrounding interactions, net increase in entropy principle.

11	Exam #2, Air cycles (Otto and Diesel), Brayton cycle	Exam #2, heat engine / heat pump cycles.
12	Rankine, with reheat, and with feedwater heater cycles, Ranking cycle efficiency increases, Rankine cycle real losses	Definition of Kelvin-Planck / Clausius Statements, Carnot principles, reversible heat engine / heat pump cycles, Carnot cycle.
13	Refrigerator and heat pump cycles	Rankine cycle, Rankine with reheat, air standard power cycles (Otto, Diesel, and Brayton)
14	Instructor choice, Conclusion	Air standard power cycles (Otto, Diesel, and Brayton), Vapor Refrigeration Cycle, conclusion.

Evidence of Improved Student Retention of Second Law Concepts

The initial study provided some evidence of student improvement in second law concepts via the administration of a coincidently-developed second law concept inventory[5]. The concept inventory was administered on the last day of class in four courses: two conventional FTCs and two redesigned FTCs. The average results[1] show that the percentage of questions answered correctly by the students is low (on the order of 56% with a 10 percentage-point standard deviation). Further, on average, it is shown[1] 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, 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, 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, a clear improvement in average results was not shown.

Although the first study[1] does not show improvements in average results, there may be some sign of improved understanding of certain core second law concepts. Specifically, students in the redesigned FTC on average scored better than those in the conventional FTC in 11 out of 20 questions (the remaining 8 were answered correctly by more students in the conventional FTC, and one question was poorly answered by all students in all classes[1]). Most of the observed differences are rather small and un-noteworthy. There are some questions where the redesigned FTC students score significantly better than the conventional FTC students. These questions 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.

The same second law concept inventory[5] developed with the first study was administered to students (some being the same students as those who had the redesigned FTC) in the STC several semesters after the redesigned FTC was first taught. Because the FTC is taught in multiple sections, only about 15 – 20% of the students taking the FTC were exposed to the redesigned section. Further, because only about 35% of the students taking the FTC are mechanical engineers, the STC is mostly only available to mechanical engineers (due to pre-requisites), and not all mechanical engineers are required to take the STC, the percentage of students taking the second law concept inventory at the start of the STC who had the redesigned FTC is 11%. Regardless, some useful information may be observed by evaluating the performance of redesigned FTC students relative to conventional FTC students on the second law concept inventory at the start of the STC semester. The idea with this evaluation is to quantify if students retained their second law conceptual understanding between the end of the FTC and the start of the STC (a span of no less than 2 semesters, due to pre-requisites).

Figure 1, along with the identifier descriptors provided in Table 2, provide a statistical sense of how students who had the redesigned FTC performed on the second-law concept inventory at the start of their STC, relative to those cohort students who had the conventional FTC. Some key observations stand out:

1. The average and median scores of the redesign FTC students are higher than their cohorts who had the conventional FTC,
2. the minimum scores of the redesign FTC students are higher than their cohorts who had the conventional FTC, and
3. the maximum scores of the redesign FTC students are the same as their cohorts who had the conventional FTC, which is to say the maximum scores were not lower.

Table 2: Descriptions of the identifiers used in Figure 1.

Identifier	Description
2014a	All STC students in spring 2014 semester. Students had FTC as early as fall 2011 and as late as fall 2012.
2014a R	STC students in spring 2014 semester who had the redesigned FTC. Students had redesigned FTC as early as fall 2011 and as late as fall 2012.
2014c	All STC students in fall 2014 semester. Students had FTC as early as spring 2012 and as late as spring 2013.
2014c R	STC students in spring 2014 semester who had the redesigned FTC. Students had redesigned FTC as early as spring 2012 and as late as spring 2013.

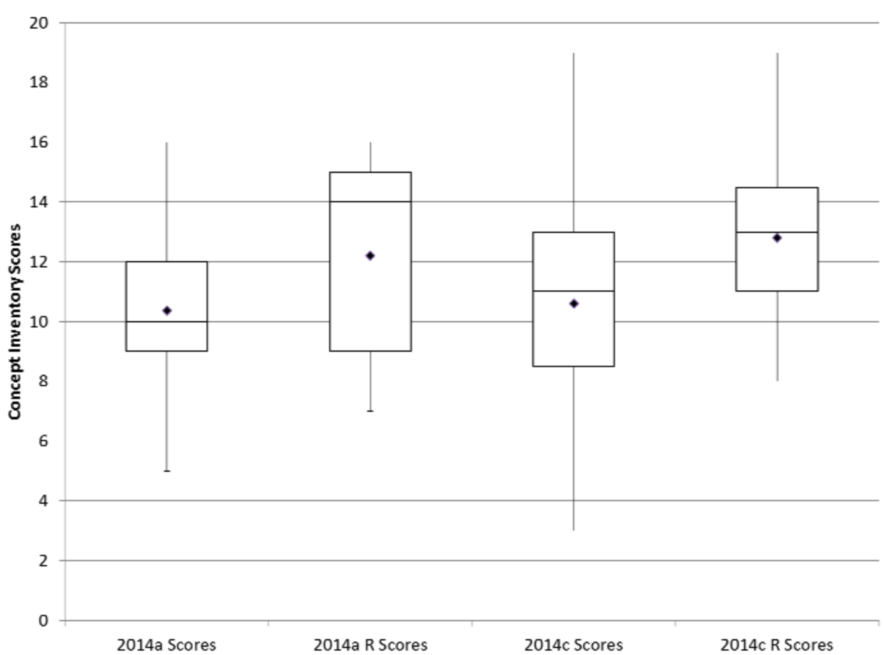

Figure 1: Concept inventory scores (out of 20 maximum possible points) of various student populations, as described in Table 2.

While these three observations are true, it should also be noted that the differences between the conventional FTC and redesign FTC students are small. The student-t test would show low probability of statistical differences between the populations.

The slight improvement in student retention between the redesigned FTC and conventional FTC students, based on their STC second law concept inventory performance, is encouraging. But it’s also important to ensure that students who had the redesigned FTC are able to be as successful as students in the conventional FTC in their follow-on courses, such as the STC. Figure 2, along with Table 3, show the grade point distributions for several semesters of the STC for all students in the STC and those students who had the redesigned FTC (indicated with an “R”) in the STC. If the redesigned FTC were failing students in other areas of preparation, then this would possibly be apparent by severe GPA deficiencies in the STC.

Table 3: Descriptions of the identifiers used in Figure 2.

Identifier	Description
2014a	All students in the spring 2014 semester STC.
2014aR	Students in the spring 2014 semester STC who had the redesigned FTC.
2014c	All students in the fall 2014 semester STC.
2014cR	Students in the fall 2014 semester STC who had the redesigned FTC.
2015a	All students in the spring 2015 semester STC.
2015aR	Students in the spring 2015 semester STC who had the redesigned FTC.
2015c	All students in the fall 2015 semester STC.
2015cR	Students in the fall 2015 semester STC who had the redesigned FTC.

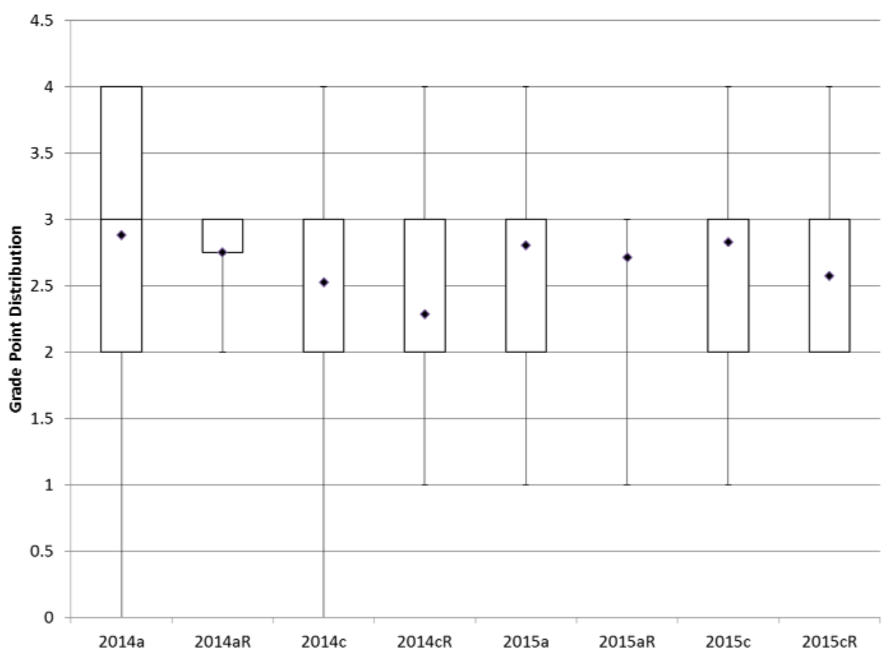

Figure 2: Grade point distribution of students of various populations (see Table 3) in the STC.

Figure 2 instead shows reasonable alignment in STC grades between all students and those who had the redesigned FTC. The average grades tend to drop for those students who had the redesigned FTC; this feature is not easily explained. The median scores, however, are always the same and the minimum scores are never as low for the students who had the redesigned FTC as the whole class. Thus, it seems compelling that the redesigned FTC does not harm students in at least their preparation for being successful in the STC.

Conclusions

This article describes a follow-on study to an original which endeavored to redesign the FTC to improve student understanding and application of second law concepts. The major objectives of the current study are to quantify the potential improvements in second law concept retention between first exposure in the FTC and the start of the STC and to ensure students are not disadvantaged in being successful in their STC by having had the redesigned FTC. These objectives are met by administering a second law concept inventory (developed along with the first study) to students at the start of their STC; some of the students in the STC were students in the redesigned FTC. Performance on the second law concept inventory is compared between the two populations of STC students (i.e., those who had the redesigned FTC and those who had the conventional FTC). It is shown that, although the differences are small, students who had the redesigned FTC performed better on the second law concept inventory at the start of their STC. This suggests these students had a strong understanding and retention of the second law concepts that are expected to be known by mechanical engineers.

Further, to ensure students are not disadvantaged in their follow-on courses that require thermodynamic prerequisite knowledge, the grade distributions of the two populations are compared at the end of the STC. It is shown that, although the students who had the redesigned FTC had slightly lower average STC GPAs, their median scores were the same as those students who had the conventional FTC. Thus, it is argued that the redesigned FTC is not hurting students in their ability to be successful in the follow-on STC.

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References

1. T. J. Jacobs, J. A. Caton, J. Froyd and K. Rajagopal. *Redesigning the first course of thermodynamics to improve student conceptualization and application of entropy and second law concepts*. in *ASEE Annual Conference*. 2014. Indianapolis, Indiana.
2. R. A. Streveler, B. M. Olds, R. L. Miller and M. A. Nelson. *Using a delphi study to identify the most difficult concepts for students to master in thermal and transport science*. in *American Society for Engineering Education Annual Conference & Exposition*. 2003. Nashville, TN.
3. B. M. Olds, R. A. Streveler, R. L. Miller and M. A. Nelson. *Preliminary results from the development of a concept inventory in thermal and transport science*. in *American Society of Engineering Education Annual Conference & Exposition*. 2004. Salt Lake City, Utah.
4. M. J. Cochran and P. R. L. Heron, *Development and assessment of research-based tutorials on heat engines and the second law of thermodynamics.* American Journal of Physics, 2006. **74**(8): p. 734 - 741.
5. T. J. Jacobs and J. A. Caton. *An inventory to assess students' knowledge of second law concepts*. in *ASEE Annual Conference*. 2014. Indianapolis, Indiana.
6. R. A. Gaggioli and P. J. Petit, *Use the second law, first.* CHEMTECH, 1977(August): p. 496 - 506.
7. C. Borgnakke and R. E. Sonntag, *Fundamentals of Thermodynamics*. 8th ed. 2012, New York: Wiley.
8. Y. Cengel and M. Boles, *Thermodynamics: An Engineering Approach*. 7th ed. 2010, New York: McGraw-Hill.
9. M. J. Moran, H. N. Shapiro, D. D. Boettner and M. B. Bailey, *Fundamentals of Engineering Thermodynamics*. 7th ed. 2010, New York: Wiley.