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Assessing Misconceptions of Undergraduate Engineering Students in the Thermal Sciences*

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This study presents preliminary results of a multi-year research project to identify persistent misconceptions held by undergraduate engineering students in the core engineering sciences of thermodynamics and heat transfer. This report lays out the phased development of valid and reliable concept inventories to assess the prevalence and persistence of these misconceptions. The inventories exhibit reliability and validity levels that allow them to be used for research purposes. Student performance on the instrument from several undergraduate engineering programs demonstrates the existence of two specific misconceptions: (1) students frequently confound factors which determine the rate of heat transfer and the amount of heat transfer and (2) students often misconstrue the impact of entropy on the efficiency of real systems, specifically believing that the only barrier to 100% thermal efficiency is friction and heat losses. Prelpost measures of students' conceptual understanding demonstrate that significant misconceptions persist after instruction in the relevant undergraduate thermodynamics and transport courses.

Keywords: heat transfer; thermodynamics; misconceptions

1. INTRODUCTION

Meaningful learning in science and engineering requires that students master fundamental concepts rather than simply memorizing facts and formulas [1–4]. Of three key findings in the National Research Council study of How People Learn [2], the first is the need to draw out and engage student preconceptions and the second highlights the need for students to understand facts and ideas in the context of a conceptual framework. What may be surprising, however, is the extent to which students can fail to grasp important concepts even after relevant instruction [1, 3, 5]. Extensive educational research in the sciences, especially physics, demonstrates both the limitations of traditional instruction for correcting many misconceptions and the success of inquiry-based instructional methods for more effectively promoting conceptual change [6–11].

What has slowed engineering education from capitalizing on the successful educational research in physics and adopting similar methods for addressing students' misconceptions has been (1) in some cases, a lack of knowledge of the relevant literature (2) the lack of valid and reliable concept inventories to assess conceptual understanding in core engineering disciplines and (3) the lack of inquiry-based educational materials similar to those shown to be effective in physics. This report is part of a larger study aimed at addressing all three issues. The objectives of this report are to develop valid and reliable instruments to assess students' conceptual understanding and to document the prevalence and persistence of related misconceptions through the use of such instruments.

This report shares preliminary work identifying one specific misconception held by engineering students in both heat transfer and thermodynamics. It expands our own and other earlier work [12–19] by presenting the phased development of valid and reliable concept inventories for one targeted misconception in both heat transfer and thermodynamics. Further, this report documents the use of these inventories to assess the extent of the targeted misconceptions among engineering students at several universities both before and after instruction in the relevant undergraduate courses. The development of these assessment tools and documentation of persistent student misconceptions lays the groundwork for future research efforts to repair them.

2. BACKGROUND

It is important to differentiate preconceptions that are easily repaired through instruction from

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robust misconceptions that are resistant to change [20]. New information consistent with one's existing mental framework might be learned easily through direct instruction, while concepts that require significant accommodation may require an instructional method deliberately designed to foster and support conceptual change [21, 22]. Misconceptions resistant to change through traditional teaching methods may be labeled 'robust' and are obviously of particular interest to educators, especially when the misconception concerns a critically important concept related to core engineering courses. This study seeks to identify such misconceptions related to the engineering thermal sciences.

There is an extensive literature on the prevalence of misconceptions related to heat, energy, and temperature among both adults and students at all academic levels [11, 23, 24]. There is less work documenting specific thermal science misconceptions held by engineering students. Streveler et al. [19] conducted a Delphi study in which educational experts within engineering identified concepts which they considered to be both important to their discipline and difficult for students to master. That study identified several important but difficult concepts related to heat transfer, including (1) heat vs. energy (2) heat vs. temperature (3) thermal radiation and (4) steady-state vs. equilibrium processes. While the experts identified areas of common misconceptions widely recognized in the broader literature [11, 19, 23, 25–27], the study provided no supporting empirical evidence collected from engineering students nor clarification of specific misconceptions within these broader areas. This work attempts to address that issue, focusing on misconceptions that appear to be both prevalent to persist even after traditional instruction.

A similarly large literature documents widespread confusion about entropy and the second law of thermodynamics [28–35]. Misconceptions on this area have been documented among high school students [36], pre-service teachers [37], and among college science-majors [35]. The Delphi study of Streveler et al. [19] further suggested that these concepts were both difficult and important for engineering students to understand. While the Delphi study pointed to the second law as a general area of concern, this study attempts to directly measure the extent and persistence of misconceptions in this area and to identify the nature of specific misconceptions held by engineering students. In order to do so, valid and reliable assessment tools such as concept inventories are required.

Concept inventories are multiple choice instruments designed to assess conceptual understanding rather than students' ability to solve problems or recall factual information [38]. Previous research [39] has indicated that concept inventories have a number of advantages including easy administration, objective scoring, and lend themselves to statistical analysis. In addition, Treagust [40] states, 'The development of multiple choice tests on students' misconceptions has the potential to make a valuable contribution, not only to the body of work in the area of misconceptions, but also to assist in the process of helping science teachers use the findings of research in this area' (p. 160).

In recent years there have been significant efforts to develop concept inventories for engineering fields [12, 13, 38, 41–49]. However, concept inventories with high reliability in the area of thermal science have not been developed and tested with a population of undergraduate engineering students. This study focused on developing such instruments as part of a larger effort to both identify and repair robust misconceptions held by engineering students [16–18].

Instrument development is typically an iterative process. Determining where students have misconceptions requires a valid and reliable assessment tool. At the same time, the focus of the concept inventory should be guided by knowledge of the nature and prevalence of student misconceptions so that the final instrument assesses those misconceptions of interest to educators. Instrument development tends to therefore start with drafting initial questions to elicit students' conceptual understanding. Student responses are used to suggest possible areas where significant misconceptions exist and instrument development then focuses on refining and expanding the initial questions to probe the suspected misconception. The work presented here reflects this phased development process.

3. EXPERIMENTAL METHODS

The initial instrument development drew extensively from parallel efforts to develop a Thermal and Transport Concept Inventory (TTCI) [14, 15, 19]. This work was successively expanded in the development our own instrument, with a focus on both identifying specific misconceptions and developing acceptable levels of validity and internal reliability for a research instrument. Each phase of instrument testing generally involved successively larger cohorts of undergraduate students drawn from a larger pool of undergraduate institutions. The instruments assess multiple concepts, of which those discussed here are a sub-set.

A conventional item analysis was completed, guided by Classical Test Theory [50, 51]. According to this theory, it is the information about recognizable factors of each test question that '. . . guide . . . the improvement of the test, and thus maximize the ultimate reliability of the total score' (p. 71). Two characteristics of the individual test items were examined to improve the reliability of the total and subset scores: item discrimination and item difficulty. The Discrimination Index (D-Index), ranging from –1.00 to +1.00, was used to estimate discrimination of test items [51]. Participants were divided into the upper- and lower-third, based upon their overall scores. Students' scores on a particular question were then correlated with their overall score. The greater the positive value, the better the question discriminated.

The 'difficulty' of each question was measured by the percentage of students correctly answering a given question. Questions of either very high or very low difficulty and those with low or negative discrimination indices were selected for revision or elimination in each evolution of the instrument. When questions were targeted for modification, a distractor analysis was also done to ensure that phrasing of the responses was not leading students to select an incorrect answer. Throughout the entire process, it was recognized by the researchers that a major limitation of using Classical Test Theory is that both item difficulty and discrimination are dependent upon the participants [48], which is why the sample of students tested was chosen to be similar to the students who might use the inventory in the future.

Both validity and reliability are important to consider when designing instruments [52]. Content validity was determined by panels of engineering faculty who teach in these areas. Internal reliability was assessed through calculation of split-half and KR20 (Kuder-Richardson 20 Formula) reliabilities. Huck and Cormier [53] define internal reliability as, '[C]onsistency across the parts of a measuring instrument, with the 'parts' being individual questions or subsets of questions' (p. 78). The KR20 does not require that all items are of equal difficulty [52]. Researchers aimed for an overall internal reliability of approximately 0.70 as that is generally considered acceptable for research purposes [52].

One of the goals of this study was to identify the persistence of student misconceptions. Therefore, the final version of the assessment instruments was used to examine the changes in students' conceptual understanding which resulted from taking the relevant engineering course. A one-group pre-test-post-test design [53] was used for this study. Descriptive statistics were used to examine changes in knowledge as measured by the overall scores of participants on the concept inventory and also to analyze performance on individual questions. Paired sample t-tests were used to test the significance of changes in knowledge from pre- to post-test. The paired samples t-test is the appropriate statistical test when the same participant is measured twice [53]. A one-way Analysis of Variance (ANOVA) was used when more than two groups of scores were compared [53]. Both t-tests and ANOVAs are considered resistant to problems created by most cases of non-normality if the combined number of data (in this case scores) in the data sets are equal to or greater than 40 [54]. The McNemar's Chi-Square Test [53] was used to assess the significance of the difference between pre- and post-test performance on individual questions. To enable this test to be performed, scores on individual questions were dichotomized into correct and incorrect.

4. INSTRUMENT DEVELOPMENT

4.1 Heat transfer

4.1.1 Phase 1: Preliminary Results

Early work in this study drew extensively from parallel efforts developing the Thermal and Transport Concept Inventory (TTCI) [44]. Question 1 shown in Fig. 1 was drawn from the TTCI and tested with students as part of a larger group of concept questions used in our study. This was the most difficult question asked. Of 31 chemical engineering undergraduates in the first two weeks of a heat transfer course, only 14% were able to answer question one correctly. While poor performance early in the semester was perhaps not surprising, only 41% of students were able to answer the question correctly after 14 weeks of relevant instruction, suggesting the presence of a

1) You are in the business of melting ice at 0°C using hot blocks of metal as an energy source. One option is to use one metal block at a temperature of 200°C and a second option is to use two metal blocks each at a temperature of 100°C.

All the metal blocks are made from the same material and have the same weight and surface area.

Which option will melt more ice?

a. The 100°C blocks.
b. The 200°C block.
c. Either option will melt the same amount of ice.
d. Can't tell from the information given.

2) because:

e. 2 blocks have twice as much surface area than 1 block so the energy transfer rate will be higher when more blocks are used.
f. Energy transferred is proportion to the mass of blocks used and the change in block temperature during the process.
g. Using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer.
h. The temperature of the hotter block will decrease faster as energy is transferred to the ice.
i. The heat capacity of the metal is a function of temperature.

Fig. 1. Most difficult heat transfer concept question from Phase 1.

robust misconception. The most common incorrect answer was that the two blocks would increase the total amount of ice melted because the higher surface area would result in greater overall heat transfer rates. The majority of students failed to recognize that surface area affected the rate but not the total amount of energy transferred at equilibrium. Open-ended questions designed to probe students' understanding in more detail further suggested that students misconstrued the role of surface area in determining the answer to this question, for example:

- *'The 100C blocks will melt more because there is more mass and surface area.'*
- *'More surface area = more opportunities for heat to be transferred to ice.'*
- *'Surface area is much larger so heat transfer area is larger and therefore more efficient.'*

These preliminary results suggested the following robust misconception:

> *Undergraduate engineering students often cannot distinguish between those factors which affect the rate of heat transfer and those which affect the amount of energy transferred in a given physical situation. For example, students frequently believe that factors that increase the rate of heat transfer also increase the amount of heat transferred and vice versa.*

Literature suggests the prevalence of related misconceptions in other fields. For example, Thomas and Schwenz [55] report that students confound similar factors related to chemical reactions, confusing factors which increase the rate of reaction and those which increase the amount of product formed at equilibrium. The related misconception regarding reaction kinetics further suggested that engineering students might hold an analogous misconception related to heat transfer.

4.1.2 Phase 2: Development of Additional Questions

These preliminary results stimulated the development of several additional questions assessing the degree to which students held the hypothesized misconception. These questions, some drawn or modified with permission from existing instruments, are shown in Fig. 2. Each question was designed to test students' ability to distinguish factors that promoted the rate vs. amount of energy transferred using different scenarios. Question H3, for example, asks students to discriminate between whether increased surface area of crushed ice used in cooling a beverage influences the rate or the amount of cooling of that beverage. Here, while 90% or more of students recognized that the crushed ice would cool the drink more quickly, approximately a quarter of chemical engineering juniors predicted the crushed ice would also make the drink ultimately colder. Results from senior chemical and mechanical engineering students on a similar question in a separate study showed even higher levels of this misconception, with approximately 45% of engineering seniors answering the question incorrectly and believing that chipped ice reduced the final beverage temperature relative to using an equal amount of block ice [15].

H1) Either 15 ml of boiling water or 60 ml of ice cold water (0°C) poured into an insulated cup of liquid nitrogen will cause some of the liquid nitrogen to evaporate.

Which situation will ultimately cause *more* liquid nitrogen to evaporate?

H2) Which situation will cause the liquid nitrogen to evaporate more *quickly*?

H3) You would like to cool a beverage in an insulated cup either by adding large ice cubes or the same mass of finely chipped ice. Which option will cool the beverage to a colder temperature?

H4) Which will do so more quickly?

H5) (same as Fig. 1)

Which option will melt more ice? [44]

H6) Which option in question H5 will melt ice at a faster rate?

H7) An engineering student has two beakers containing mixtures of dye in water. The first beaker has a 1% dye solution (1 gram of dye in 100 grams of solution) and the second beaker has a 2% dye solution (2 grams of dye in 100 grams of solution). The student places 2 dry sponges in the 1% dye solution and 1 dry sponge in the 2% dye solution.

Which of these combinations will remove more dye from the beaker?

(H8) Which of these combinations will remove dye from the beaker faster?

(H9) Two identical beakers contain equal masses of liquid at a temperature of 20°C. One beaker is filled with water and the other beaker is filled with ethanol (ethyl alcohol). The temperature of each liquid is increased from 20°C to 40°C using identical hot plates. It takes 2 minutes for the ethanol temperature to reach 40°C and 3 minutes for the water to reach 40°C. Once a liquid had reached 40°C, its hot plate is turned off. To which liquid was more energy transferred during the heating process? [44].

Fig. 2. Heat transfer scenarios and questions

Table 1. Student performance on Phase 2 Heat Transfer Questions (Performance is measured in % of students answering correctly).

Question #	2005 N = 21	2006 N = 21	2007 N = 30
H1	53	73	67
H2	79	90	70
H3	74	82	73
H4	89	95	100
H5	74	86	60
H6	63	41	23
H7	33	56	67
H8	10	50	43
H9	43	50	50

Student performance on the questions in Fig. 2 at the beginning of each of several offerings of a heat transfer course is provided in Table 1. While the difficulty of the questions and student performance obviously varied year-to-year, results suggested that students exhibited the targeted misconception in several of the proposed scenarios. Results of phase two testing were used to refine questions for the final round of instrument development. Questions were modified or dropped based on their difficulty and discrimination indices, as well as feedback on their validity for addressing the targeted misconception as assessed by a panel of engineering faculty.

4.1.3 Phase 3: Development of a Reliable Assessment Instrument

Results from phase two supported the presence of a possible misconception, but a valid and reliable instrument to assess students' conceptual understanding was necessary to confirm this. Refining earlier efforts, a total of 8 questions were developed to examine the hypothesized misconception. While the specific questions are not published here in order to protect the integrity of the instrument for research purposes, access to the instrument can be obtained by e-mailing the authors.

The instrument developed in this study was initially piloted with 119 undergraduate engineering students from four different institutions; 88 were chemical engineering majors and 31 were mechanical engineering majors. Approximately 56% were juniors, about 41% were seniors, and the remainder in other years of schooling. Seventy-nine (approximately 66%) were taking a course on heat transfer at the time they completed the concept inventory. The remainder had previously taken a course in heat transfer. Professors of classes where students were given the inventory were given detailed directions for administering the instrument in order to provide similar test-taking conditions among the different schools.

Faculty administering the concept inventory were also asked to note whether each question assessed a particular concept well and a ratio of agreement was calculated to assess content validity. Questions with a low content validity ratio were targeted for significant revisions. Results were also examined for reliability, with an eye towards improvements in subsequent rounds of testing. The split half reliability for version 1 of the instrument was 0.79 and the Kuder-Richardson-20 (KR20) value was 0.74. Analysis of a smaller subset of only five questions within this grouping also produced good reliability values with a split-half reliability of 0.77 and a KR20 value of 0.76.

Although internal reliability requires only one administration of an instrument to a specific group of participants, additional reliability testing was conducted to further refine problematic questions, to determine whether the instrument would be equally reliable when given to a broader sample and to improve question validity. An example of how questions were refined is shown in Fig. 3, which illustrates the final version of 'hot blocks' question (H5 in Fig. 2). Here the question was refined to more explicitly distinguish students' ability to predict the effect of relevant parameters on both the rate and total amount of energy transferred by separating those issues into distinct questions.

The final concept inventory was re-tested with a sample of 228 undergraduate engineering students from six different institutions; 119 were mechanical engineering majors, 93 were chemical engineering majors and 16 were other engineering majors. Approximately 52% were juniors, 40% were seniors and the remainder was sophomores. The majority (96%) were currently enrolled in a heat transfer course. There were eight questions used to assess the targeted misconception area. Validity was assessed by an expert panel of engineering faculty from diverse institutions who taught undergraduate transport courses and there was 100% agreement that the entire set of rate vs. amount questions assessed that concept well. In terms of reliability, a split-half reliability of 0.83 and a KR20 value of 0.77 were found for the instrument, indicating that it had sufficient reliability for research purposes. This instrument was therefore used to document the prevalence and persistence of the targeted misconception.

4.2 Thermodynamics

4.2.1 Phase 1: Preliminary Results

While the educational literature suggested that students had misconceptions about entropy, phase one attempted to examine more precisely what about entropy was confusing for chemical engineering students. Drawing questions from the thermodynamics concept inventory of Clark and Midkiff [13, 41], a small number students (n=27) were asked concept questions about energy and entropy, including questions T3–T7 from Fig. 4, during the first two weeks of a thermodynamics course. As this course immediately follows a physical chemistry course, it might be expected that students would be familiar with concepts of

You would like to melt ice which is at 0^{O}C using hot blocks of metal as an energy source. One option is to use one metal block at a temperature of 200^{O}C and a second option is to use two metal blocks each at a temperature of 100^{O}C. Each individual metal block is made from the same material and has the same mass and surface area. Assume that the heat capacity is not a function of temperature.

1) If the blocks are placed in identical insulated containers filled with ice water, which option will ultimately melt more ice?

- a. Either option will melt the same amount of ice.
- b. The two 100°C blocks.
- c. The one 200°C block.

2) Because. . .

- d. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used.
- e. Using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer
- f. The amount of energy transferred is proportional to the mass of blocks and the change in block temperature during the process.
- g. The temperature of the hotter block will decrease faster as energy is transferred to the ice water.

3) Which option will melt ice more quickly?

- a. Either option will melt ice at the same rate.
- b. The two 100°C blocks.
- c. The one 200°C block.

4) Because . . .

- d. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used.
- e. The higher temperature block creates a larger temperature gradient which will increase the rate of energy transfer.
- f. The temperature of the hotter block will decrease faster as energy is transferred to the ice water.
- g. The rate heat transfer is proportional to the surface area of blocks and the temperature difference between the blocks and ice.

Fig. 3. Revised version of question H5.

energy and entropy. In general, the entropy questions proved to be more difficult than the other questions asked. For example, question T7 on engine efficiency shown in Fig. 4 was the most difficult from phase 1 and was answered correctly by only 1/3 of the students both before and after instruction, suggesting a prevalent and persistent misconception.

Of further concern was the observation that when the same questions were asked at the end of the course, scores improved on six of the eight non-entropy questions but only three of eight entropy questions showed any improvement at all. Taken together, this indicated that entropy is a topic where students appear to have persistent misconceptions. Therefore it was decided to focus further testing on the relationship between entropy and engine efficiency.

4.2.2 Phase 2: Development of Additional Questions

Based on the results from phase 1, an expanded number of questions on the topic of entropy and engine efficiency, shown in Fig. 4, were tested with a larger number of students. Note that T3-T7 had also been used in phase one. These questions drew heavily from both the Thermal and Transport Sciences Concept Inventory [44] and from the Thermodynamics Concept Inventory [13].

Student performance on questions in Fig. 4, asked at the beginning of a thermodynamics course over multiple years, is shown in Table 2. Student performance indicated that entropy and its impact on system efficiency was still an area of concern even with different phrasing of the questions and a larger population. As can be seen in Fig. 4, questions approach this concept from different angles, asking about efficiency *or* maximum work output *or* the relationship between heat source/ sink temperatures and work output. With a single exception, fewer than 70% of the class answered correctly.

Students in the 2006 offering of the course were given open-ended short-answer questions as well. Responses indicate that many students managed to hold contradictory ideas about the second law and engine efficiency. For example, for questions similar to T11 and T13 students stated the following:

- *T11: 'The entropy of the universe always needs to be equal or greater than zero. Which means that not all the energy put in is turned into work because there is a heat sink, it can't be exactly 100kJ/hr' T13: 'If this was true, then the maximum rate could be exactly 100 kJ/hr but this is impossible in real life.'*
- *T11: 'Some of the energy will be converted to other forms i.e. entropy.' T13: 'Yes—all the energy goes to work.'*
- *T11: 'A Carnot heat engine produces the same amount of work as energy it takes. The change in entropy is 0 and it is a reversible process assuming no frictional losses.'*

T3) For Questions 3 and 4, consider the following. You have access to two sources of energy that can be used to turn a steam turbine (a device that converts thermal energy into mechanical work) :

- 1000 KJ of energy stored as superheated steam at 400°C and 20 bar.
- 1000 KJ of energy stored as superheated steam at 600°C and 20 bar.

You may assume that each steam source will leave the turbine at 200°C and 1 bar.

T3. Which of these two energy sources can be converted into more mechanical work per unit mass of steam?

a. 400°C steam
b. 600°C steam
c. both will give the same amount of work
d. can't decide with the information given [44].

T4) The result in question 3 is because:

a. Steam at different temperatures can't exist at the same pressure so turbine performance is not known.
b. Turbine will extract the same amount of energy from both steam sources since performance is only a function of mechanical design.
c. Turbine will extract more energy from higher temperature steam source because hotter steam provides a larger temperature difference between energy source and waste energy rejection.
d. Turbine will extract more energy from lower temperature steam source because colder steam is easier to process mechanically.
e. The amount of energy in each steam source is the same.

T6) Heat from a source at 550K is added to the working fluid of an engine operating at a steady rate. The temperature of the surroundings is 300K. The efficiency of this process is defined as the ratio of the mechanical power produced by the engine to the rate at which heat is provided. The maximum efficiency of this engine is: (a) Much greater than 1 (b) About equal to 1 (c) Much less than 1 (d) Insufficient information [13].

T7) Consider the best possible heat engine working in air at 25°C. The engine continuously converts heat from a source at 300°C to work, and heat is continuously transferred into the engine at a rate of 100 kJ per second. The maximum possible rate at which the engine can continuously produce work is: (a) Greater than 100 kJ per second (b) Equal to 100 kJ per second (c) Almost 100 kJ per second (d) Significantly less than 100 kJ per second [13].

T11) For Questions 11, 12 and 13, consider the following situation:
A steam turbine (a device that converts thermal energy into mechanical work) takes 100 kJ/hr of steam from a furnace operating at 600K (327°C) and produces work. The waste steam is rejected at 300K (27°C) to a cooling tower.
For this process, the maximum rate of work that can be produced by the turbine will fall into which of these ranges?

a. 80–100 kJ/hr
b. 50–79 kJ/hr
c. 20–49 kJ/hr
d. 0–19 kJ/hr [44]

T12) The answer to 11 is right because:

a. Thermal efficiency in commercial steam turbines is usually less than 50%.
b. Energy is conserved according to the 1st law of thermodynamics.
c. Maximum work output is ½ of the heat input if the absolute fluid temperature drops by ½ through the turbine.
d. Maximum work will equal the heat energy supplied to the turbine.
e. Most of the steam energy is being sent to the cooling tower [44].

T13) If the heat engine can be made to operate without frictional loss or heat loss to the atmosphere (i.e. the engine is reversible and adiabatic), does the maximum rate of work change?
Yes, because friction and heat losses both cause less work to be produced.
No, because maximum work output already means adiabatic and reversible operation of the heat engine.
Yes, because eliminating inefficiencies will always increase work output [44].

T14) A student proposes a method for converting thermal energy to mechanical work without wasting any energy as waste heat. It consists of the following three steps involving a well-insulated cylinder and a frictionless piston that moves up and down in a cylinder between stops as shown.
Step 1—gas at 25°C is contained in the cylinder; 100kJ of energy is added to the gas from a thermal reservoir.
Step 2—the added energy increases the gas temperature, causing it to expand and raise the loaded piston until it reaches the upper stops; at this point, the load is removed and the gas temperature is 80°C; the work done to raise the load is 15kJ.
Step 3—excess thermal energy is returned to the same thermal reservoir, which causes the gas temperature to drop back to 25°C and the piston to return to its original position on the lower stops; no energy is lost as waste.
The net result of this cycle is that 15kJ of thermal energy has been converted to work with no net loss of thermal energy (all unused thermal energy is returned to the thermal reservoir and saved).
What would you say to the student who proposed this process?

a. The process will not work because the thermal reservoir is at a higher temperature than the gas in step 3.
b. The process will work if the piston is truly frictionless and none of the transferred heat is lost to the atmosphere.
c. The process will work because energy is conserved in the system.
d. The process may work, but only if more details are known about the heat transfer rates in steps 1 and 3 [44].

Fig. 4. Thermodynamics scenarios and questions.

Table 2. Student performance on Phase 2 Thermodynamics Questions (Performance is measured in % of students answering correctly).

Question #	2005 N = 27	2006 N = 20	2007 N = 23
T3	56	33	61
T4	56	29	61
T6	59	67	78
T7	26	29	52
T11		10	61
T12		57	52
T13		57	43
T14		67	57

In sum, many students grasp that no system can be 100% efficient, but then wrongly assume that if we made the system reversible, frictionless, and (in appropriate steps) adiabatic it would closely approach a thermal efficiency of 100%. This led to the following statement of the student misconception:

> *Undergraduate engineering students often misconstrue the impact of entropy on the efficiency of real systems, specifically believing that the only barrier to 100% thermal efficiency is friction and heat losses, i.e. Carnot engines have a thermal efficiency of 1.0.*

4.2.3 Phase 3: Development of a Reliable Instrument

Having identified a potentially prevalent and persistent misconception, the next step was to develop a valid and reliable concept inventory for assessing students' conceptual understanding of entropy and its relationship to engine efficiency. The inventory contains eight questions drawn from the Thermal and Transport Sciences Concept Inventory [44] or developed in collaboration with the authors of the TTCI.

The thermodynamics instrument was piloted with a sample of 78 undergraduates from three universities for purposes of validity and reliability testing. All students were chemical engineering majors. The concept inventory had a split-half reliability of 0.72 and a KR20 of 0.66. Feedback on validity from faculty content-experts, as well as student comments led to edits for several questions and a new version of the concept inventory.

This was piloted with 131 students at five schools. The majority of the students (73.4%) were in their junior year, while the remainder were split between sophomores (16.4%) and seniors (10.2%). 70.2% were Chemical Engineering majors, with 19.1% General Engineers, 5.3% Mechanical Engineers, 3.8% Civil Engineers, and 1.5% Environmental Engineers. 73.3% of the students were male and 26.7% were female, which is a fairly typical distribution for this field. The split-half reliability was 0.69 and the KR20 was 0.66 for 114 students (post-tests were not completed by all participants). Reliability results were considered sufficient for use as a research instrument. As with the development of the heat transfer instrument, the final concept inventory questions are not reported in order to protect the integrity of the instrument for future research, however a copy of the instrument is available from the authors.

5. RESULTS AND DISCUSSION

5.1 Heat transfer

Table 3 presents data on student performance for each of the individual questions on the final concept inventory. The table incorporates aggregate data from each of the six universities included in this study. The data indicate that students find the questions quite challenging and that the misconceptions appear to be resistant to change, with only three of the eight questions showing a statistically significant increase in the number of students able to answer correctly. Even where the improvement is statistically significant, the difficulty remains high. To the extent that these questions reveal the targeted misconception, that misconception appears to be both wide-spread and resistant to change.

Another way to examine the data is by looking at the mean student performance on the complete instrument both before and after instruction. Here, a statistically significant difference was found, [t (203) = –3.889, $p < 0.01$]. Student performance on the eight questions went from a mean score of 37.4% before instruction to a mean score of 44.0% after instruction. However, the mean post-test score of the students was still below mastery, suggesting that the targeted concept was both difficult to learn and may have required different or additional instructional strategies.

Looking at the results by demographic group, one perhaps unsurprising finding is that students with a higher G.P.A. in general performed better on both the pre- and post-instruction assessments. Using a One-way ANOVA, differences in performance by G.P.A. were statistically significant for both the pre-test, [F (3,223) = 3.52, $p < 0.05$] and post-test [F (3,199) = 6.39, $p < 0.01$].

Table 3: Question Difficulty: Heat Transfer Final Version. Percentage of Students Getting Each Question Correct

Question #	% Correct Pre-Test N = 228	% Correct Post-Test N = 202
1	32	51**
2	43	50
3	13	26**
4	18	27*
5	49	54
6	50	54
7	62	65
8	33	30

* Significant improvement $p < 0.05$.

** Significant improvement $p < 0.01$, determined by McNemar Test.

Table 4. Question Difficulty: Thermodynamics Final Version. Percentage of Students Getting Each Question Correct.

Question #	**% Correct Pre- N = 131**	**% Correct Post- N = 123**
1	67	85**
2	68	85**
3	57	64
4	51	60
5	40	52**
6	33	52*
7	68	86*
8	25	57**

* Significant improvement $p < 0.05$.
** Significant improvement $p < 0.01$, determined by McNemar Test.

It was also found that mechanical engineering students with a mean score of 42.3% (n = 119) outperformed chemical engineering students with a mean score of 32% (n = 93) when the instrument was administered before instruction, with a statistical significance of [F (3,224) = 2.74, $p < 0.05$]. The mechanical engineering students (n = 105) continued to have significantly higher mean post-instruction scores (48.9%) compared to chemical engineering students (n = 88), scoring 38.1%, [F (2,201) = 3.30, $p < 0.05$].

5.2 Thermodynamics

Table 4 shows the percentage of students responding correctly to final entropy concept questions aggregated across all schools for both the pre-and post- tests. There was a significant improvement in entropy concept scores after instruction on six of the eight questions. Also for three of the questions, 85% or more students answered correctly on the post-test. Despite this, there are signs that the misconception persists for a significant number of students. Looking at individual students test scores for entropy, the mean pre-test score was 50.3%, (n = 131) while the mean post-test score was 63.9% (n = 123). While there is significant improvement in score, t (122) = –4.393, $p < 0.01$, the majority of students do not demonstrate a high level of mastery.

As with heat transfer, relationships between demographics and concept inventory scores were considered. A significant difference was found for G.P.A. on the entropy pre-test, F (3, 123) = 2.98, $p < 0.05$ but not on the entropy post-test. Insufficient numbers of non-chemical engineers were tested determine if there were performance differences between the groups.

6. CONCLUSIONS AND FUTURE WORK

Research conducted over several years of phased testing has helped to identify and document two prevalent and persistent misconceptions held by undergraduate engineering students in the core engineering sciences of heat transfer and thermodynamics. Specifically, the research suggests that students hold misconceptions related to (1) factors which influence the rate and amount of heat transfer and (2) the relationship of entropy to the efficiency of thermodynamic engine cycles. This work contributes to engineering education in two ways. First it has resulted in the development of concept inventories that can assess conceptual understanding and detect commonly held misconceptions in both heat transfer and thermodynamics. The internal consistency of each instrument, as determined by both the split-half and KR20 methods of determining reliability, has been found to be adequate for research purposes. Second it has contributed through the multi-institution study that documents the prevalence and persistence of the identified misconceptions among a body of undergraduate engineering students.

The work has a number of practical implications for both researchers and classroom instructors. For instructors, the work provides hard evidence to suggest the degree to which engineering students have and retain these misconceptions. It also provides valid and reliable tools for assessing conceptual understanding of students in their own classes. As such, the study helps to address two of the identified issues hindering engineering educators from building on the existing successful models for conceptual change in science education, namely a lack of awareness of the problem among engineering students and the lack of readily available reliable assessment instruments.

As mentioned in the introduction, this report is also part of a larger effort that attempts to apply these research findings in practical ways in the engineering classroom. The authors are in the process of completing broader concept inventories for both heat transfer and thermodynamics in order to expand this work to document a broader range of misconceptions in each content area [40]. In addition to documenting misconceptions, our work seeks to develop inquiry-based activities, similar to those developed in the sciences, to help repair persistent misconceptions which are resistant to change through traditional instruction. Preliminary work to adopt these methods to engineering seems encouraging [42]. This effort provides an excellent vehicle to apply educational research in productive ways in the undergraduate classroom to address a nationally recognized educational need, namely identifying and engaging student misconceptions in core areas of engineering science.

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