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Building an understanding of heat transfer concepts in undergraduate chemical engineering courses *

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Abstract: Understanding the distinctions among heat, energy and temperature can be difficult for students at all levels of instruction, including those in engineering. Misconceptions about heat transfer have been found to persist, even after students successfully complete relevant coursework. New instructional methods are needed to address these misconceptions. This pilot study examined whether researcher-developed and inquiry-based activities could increase conceptual understanding of heat transfer and alter common misconceptions. Twenty-two undergraduate chemical engineering students were assessed before and after instruction with inquiry-based activities using a ten-item concept inventory. Concept inventory questions were developed to assess students' performance on questions closely related to the inquiry-based activities and questions applying concepts in new contexts. Participants significantly improved their overall scores from pre-test to post-test. An examination of performance on individual items revealed significant improvement on half of those questions closely related to the instructional activities and half of those applying concepts in new but related contexts. Results are examined in light of the assessment and inquiry activities that were used, as well as the difficulty of the concepts. Educational implications and suggestions for future research are discussed.

Key words: heat and temperature misconceptions; concept inventory; inquiry-based activities; engineering education

1. Introduction

Prior knowledge has a major influence on what and how much students learn (Shuell, 1992; Smith, diSessa & Roschelle, 1993). It provides learners with an interpretive structure to communicate and make sense of the world (Smith, 1991), filters new learning (Smith, et al., 1993), and can interfere with concept mastery. Traditional methods of instruction have been found to be ineffective at altering these preconceptions (Laws, Sokoloff & Thornton, 1999; Suping, 2003). This is especially important because meaningful learning of content requires conceptual understanding rather than memorization of facts and formulas (Bransford, Brown & Cocking, 2000; Lightman & Sadler, 1993; Mayer, 2002).

Heat and temperature concepts are found throughout science curricula, at both the pre-college and college

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levels (Jasien & Oberem, 2002). Carlton (2000) stressed the importance of assessing prior knowledge of heat and temperature because these concepts are known for creating conceptual difficulties for students (Thomaz, Malaquas, Valente & Antunes, 1995). Previous literature has shown that students hold a variety of alternate conceptions about heat and temperature (Carlton, 2000; Thomaz, et al., 1995). For example, Thomaz, et al (1995) noted that students had difficulty in discriminating between heat and temperature. Carlton (2000) found that prior to instruction, many pre-service science teachers defined temperature as "… a measure of how hot or cold something feels" (p. 102). Furthermore, Jasien and Oberem (2002) discovered that both students and teachers of physical science were unable to accurately assess their understanding of heat and temperature concepts. The researchers found that although the majority of the participants rated their understanding as "good" or "fair", concept assessments revealed otherwise. There was no significant relationship between perceived understanding and actual conceptual understanding.

Difficulty understanding concepts related to heat and temperature has also been found in engineering education. Thirty recognized educators listed the concepts taught in thermal and transport science that were both important and difficult for students to learn in a Delphi study (Streveler, Olds, Miller & Nelson, 2003). While the Delphi study cited identified general areas of misconceptions, concept inventories previously developed and given to engineering students showed that they had notable misconceptions about heat versus energy (Miller, Streveler, Olds, Chi, Nelson & Geist, 2006; Prince & Vigeant, 2006). For example, it was found that engineering students had difficulty distinguishing between factors that affect the rate of heat transfer and those affect the total amount of energy transferred in a given physical situation. Confusion in these areas was also shown to persist, even when students successfully completed relevant coursework (Miller, et al., 2006). In order to design engineering systems to both heat and cool things, students need to have an accurate understanding of factors that affect the rate of heat transfer and those affect the amount of energy transferred. A failure to understand these factors could result in both inappropriately designed equipment and future safety issues.

Engineering education has started to examine students' conceptual understanding and the instructional methods used in undergraduate courses. Guidance for addressing these issues in engineering education can be found in physics education. However, what has prevented engineering education from capitalizing extensively on the success in physics education has been the lack of knowledge of the relevant literature, concept inventories to assess conceptual understanding in engineering, and inquiry-based activities in engineering similar to those shown to be effective in physics.

Therefore, the purpose of this pilot study was to determine whether inquiry-based activities, designed to address previously identified misconceptions in heat transfer, could change the conceptual understanding of undergraduate chemical engineering students. Confusion regarding these concepts has been widely recognized in the literature (Carlton, 2000; Jasien & Oberem, 2002; Prince & Vigeant, 2006; Thomaz, et al., 1995). Concepts targeted for this study were selected from a Delphi study (Streveler, Olds, Miller & Nelson, 2003) and focused on the distinctions among heat, energy and temperature.

2. Methodology

2.1 Design

A one group, pre-test-post-test design was used. Descriptive statistics examined changes in knowledge, as measured by the overall scores of participants. A Wilcoxon Matched-Pairs Signed Rank Test was used to test the significance of the overall changes in knowledge of participants prior to and after the introduction of inquiry-based activities. The McNemar's Chi-Square Test (Huck & Cormier, 1996) was employed to assess the significance of the difference between pre-test and post-test performance on individual questions. In order to compute the McNemar change tests, scores on individual questions were dichotomized into correct and incorrect. To determine the internal reliability of the instrument, a Kuder-Richardson #20 was computed on the post-test.

2.2 Participants

An intact sample of convenience of 23 undergraduate chemical engineering students participated in this pilot study. They were from a private, liberal arts institution in the Northeastern United States. Participants were given an assessment of ten questions targeting relevant concepts before and after being taught with inquiry-based activities. One participant did not complete the pre-test and 22 participants were compared.

2.3 Instrument

Student understanding of heat transfer concepts was assessed using a concept inventory with 10 multiple-choice questions. This assessment was patterned after concept inventories developed in other disciplines such as the force concept inventory in physics (Hestenes, Wells & Swackhamer, 1992). The fifth, sixth, and tenth questions were taken from previous concept inventories (Miller, Streveler, Olds, Chi, Nelson & Geist, 2006); the other questions were developed by the researchers. Content validity of the concept inventory was obtained through a preliminary evaluation of questions by content experts.

Table 1 Heat transfer concept inventory questions

(Q1) Either 15 ml of boiling water or 60 ml of ice cold water (0℃) 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?
(Q2) Which situation will cause the liquid nitrogen to evaporate more quickly?
(Q3) 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?
(Q4) Which will do so more quickly?
(Q5) Ice at 0℃ is melted by adding hot blocks of metal. One option is to use one metal block at a temperature of 200℃ to melt ice and a second option is to use two metal blocks each at a temperature of 100℃ to melt ice. The metal blocks are identical in every way except for their temperature, however, since there are two blocks at the lower temperature, they have twice the mass, surface area, etc. of the single block at 200℃. Which option will melt more ice?
(Q6) Which option will melt ice at a faster rate?
(Q7) 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?
(Q8) Which of these combinations will remove dye from the beaker faster?
(Q9) Coal dust has the potential to cause tremendous damage under certain conditions, and dust explosions are a serious concern in both coal mines and coal processing facilities. However, larger pieces of coal found in mines or piled for storage in processing facilities pose a less significant safety hazard. Why does the dust pose a more significant safety issue?
(Q10) Two identical beakers contain equal masses of liquid at a temperature of 20℃. 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℃ to 40℃ using identical hot plates. It takes 2 minutes for the ethanol temperature to reach 40℃ and 3 minutes for the water to reach 40℃. Once a liquid had reached 40℃, its hot plate is turned off. To which liquid was more energy transferred during the heating process?

It has been noted that, "Two of the most important education goals are to promote retention and to promote transfer (which, when it occurs, indicates meaningful learning)" (Mayer, 2002, p. 226). It is because of this that the researchers decided to focus on questions in the concept inventory that could assess transfer and be indicative of meaningful learning. For this particular assessment, transfer was conceptualized as two categories, near and far

(Byrnes, 2008). Concept inventory questions which were designed to assess students' performance on questions closely related to the activities were designated as assessing near transfer (Byrnes, 2008). Questions which required students to apply concepts to analogous questions in new contexts were labeled far transfer (Brynes, 2008). Table 1 shows the heat transfer concept inventory questions without their distracters.

The first six questions were related directly to the inquiry-based activities used for instruction and were considered to be near transfer questions (Byrnes, 2008), while questions seven to ten asked students to apply the concept to situations very different from the activities and were considered the far transfer questions (Byrnes, 2008). The seventh and eighth far transfer questions were analogous to the metal block questions (Q5 and Q6) but instead of transfer of heat, they focused on mass transfer, a related but distinct content area. Whereas heat transfer focuses on how fast energy transfers due to a temperature difference, mass transfer focuses on how fast mass transfers due to a concentration difference (McCabe, Smith & Harriott, 2005). Because heat and mass transfers are frequently taught together, it was determined that mass transfer questions would also be appropriate in the current assessment. Although the ninth question, about coal dust, was a rate versus amount problem, it dealt with the energy released in a chemical reaction. Finally, the tenth question about ethanol versus water asked students to think specifically about heat transfer as a rate process and required that they address the question in a way that is different from how it is traditionally taught.

2.4 Inquiry-based learning activities

Three inquiry-based learning activities were designed by the researchers. Inquiry-based learning was operationalized using eight instructional recommendations to improve student science learning provided by Laws, Sokoloff and Thornton (1999). These recommendations included the use of collaborative activities, getting students involved with materials, having students make predictions before starting an activity, using technology when appropriate, and evaluating understanding throughout the instructional process. The Appendix provides a description of the activities that were developed.

The first inquiry-based activity focused on boiling liquid nitrogen and was developed to help students understand rate versus amount of heat transferred. It has been found (Streveler, et al., 2003) that students frequently believe that temperature is a good measure of energy so this activity was designed to challenge this belief. The first two questions on the concept inventory were constructed to assess students' understanding of this. The second activity focused on heat transfer in chipped versus block ice. This activity was designed to again help students learn rate versus amount of heat transfer and to address the commonly found misconception that something occurring faster results in more heat transferred. With this particular activity, students have sometimes believed that crushed ice makes something colder than block ice does. The third and fourth questions on the concept inventory were included to evaluate students' comprehension of this. Finally, the third inquiry-based activity focused on the rate and amount of ice melting when contacted with hot metal blocks. This activity was intended to help students learn rate versus amount of heat transfer. In this case, the activity combined two variables, surface area and temperature. The fifth and sixth questions on the concept inventory assessed students' knowledge of this.

The first two activities used physical experiments while the third used a computer simulation. The simulation was employed primarily because of the difficulty generating sufficiently identical metal blocks at the proper temperatures in the physical experiment. In addition, when the physical experiment was used, students frequently interpreted small differences due to experimental "noise" as real differences, which only served to reinforce misconceptions. The simulation created the desired situations accurately and also allowed the students to quickly "experiment" with a number of other situations of their own devising which would have been difficult to do experimentally.

The inquiry-based activities had first been implemented the previous year.

2.5 Procedure

The pre-test was administered on the same day but prior to when students used the inquiry-based activities in a two-hour lab period. The three activities were all completed in one lab period on the same day. Prior to the introduction of all the activities, students were asked to make predictions about which condition would transfer more energy and which would transfer heat faster. After participating in the activities, students then returned to their original predictions to see whether they were correct. Students worked in teams during the lab period and were encouraged to talk with group mates about the results and to interpret what they meant. They were not given the answers by the instructor.

Participants continued to have access to the computer simulation (Activity No.3) after the designated lab period and could go back and play with it whereas there was no access to the first two activities after the lab period. The post-test, which asked the same questions, was turned in one week later.

3. Results

Results from the Wilcoxon test showed that participants performed significantly better on the post-test than on the pre-test, $Z=-3.84$, $p<0.01$. The median score on the pre-test was 70% while the median score on the post-test was 100%. The most frequent score on the pre-test was 50% while the most frequent score on the post-test was 100%. Table 2 shows the percentage of students correctly answering each question on the pre-test and the post-test.

Table 2 Percentage selecting the correct answer on pre- and post-tests

Question	Pre-test (n=22)	Post-test (n=23)
Liquid N2 rate	68%	100%
Liquid N2 amount	73%	100%
Chipped ice amount	82%	100%
Chipped ice rate	96%	100%
Metal blocks amount	86%	96%
Metal blocks rate	41%	91%
Sponge amount	59%	96%
Sponge rate	52%	96%
Coal dust	91%	100%
Heating ethanol vs. water	50%	65%

On all ten questions, a greater percentage of students had the correct answer on the post-test than on the pre-test. An examination of individual questions revealed a substantial improvement on one of two near transfer questions (Q6) designed to assess understanding after instruction with the metal block computer simulation activity. On the pre-test, 41% of the students had the correct answer for this question while on the post-test 91% correctly answered it. One far transfer question, dealing with energy transfer when ethanol and water are heated, remained problematic. Although there was improvement, only 65% of participants had that question correct on the post-test.

Table 3 provides the results of significance testing for individual questions using the McNemar Chi-Square

Test. As can be seen in the table, there was a significant difference between pre- and post- tests scores for five of the questions: Q1—Liquid N2 rate; Q2—Liquid N2 amount; Q6—Metal blocks rate; Q7—Sponge amount; and Q8—Sponge rate. There was no significant difference in scores between pre- and post- tests on the remaining five questions.

Table 3 Significance of the difference between pre-test and post-test scores for individual questions, determined by the McNemar test

Question	Number of pairs	*p*
Liquid N2 rate	22	0.016^{*}
Liquid N2 amount	22	0.031^{*}
Chipped ice amount	22	0.125
Chipped ice rate	22	1.000
Metal blocks amount	22	0.375
Metal blocks rate	22	0.001^{**}
Sponge amount	22	0.008^{**}
Sponge rate	21	0.002^{**}
Coal dust	22	0.500
Heating ethanol vs. water	22	0.375

Notes: * $p<0.05$; ** $p<0.01$.

The internal reliability of the post-test as measured by the Kuder-Richardson No.20 formula was moderately high at 0.68.

4. Conclusions and educational implications

Results can be interpreted from a number of perspectives: The assessment and inquiry activities that were used, as well as the difficulty of the concepts taught. First, incorporating inquiry-based activities significantly improved students' conceptual understanding of heat transfer as measured by overall scores on the heat transfer concept inventory. There was also a significant improvement from pre- to post- tests on 50% of both near and far transfer (Byrnes, 2008) questions. However, some researchers (Mayer, 2002) would question whether items labeled as "near transfer" (Brynes, 2008) involved any transfer and if they were really assessing recall of information from the activities. Mayer (2002, p. 226) defined retention as follows, "(T)he ability to remember material at some later time in much the same way it was presented during instruction". Furthermore, the researcher noted, "[R]etention focuses on the past; transfer emphasizes the future" (p. 226). The first six questions on the concept inventory directly related to the inquiry-based activities and the time between activity and post-test was short enough that students might have solely recalled the information. Further refinements of the concept inventory should examine ways to ensure the assessment of conceptual understanding rather than retention or recall. In addition, the inquiry-based activities should be further evaluated to determine whether they are encouraging transfer rather than recall.

Methods used in the inquiry-based learning activities may have affected students' learning. For example, there was a significant increase in the percentage of students correctly answering Q6, dealing with hot blocks. This was the most difficult question on the pre-test but by the post-test, it was correctly answered by 91% of the participants. The activity used to teach the concepts involved a computer simulation. Previous researchers (Krajcik, 1994; Nottis & Kastner, 2005) had found that use of computer courseware may provide students with needed memory support as they learn new concepts, allowing students to reflect on what they have seen and learned. The computer simulation, in addition to ensuring that the concepts could accurately be conveyed, may have also given essential memory support to the students in the current study. Furthermore, participants had access to the computer simulation after the lab period. Therefore, the significant improvement could also be the result of increased time using the simulation to understand the concept. Participants' exposure to the other two activities ended at the end of the laboratory period. Future research should either include computer simulations for all activities or include increased contact with physical experiments after the lab period so that the level of support and access to activities can be more standardized. This would enable researchers to better determine whether time on task was a reason for improvements seen on the sixth question.

The tenth question was the most difficult question for students on the post-test. This question did not tie as clearly to the "rate versus amount" concept. In addition, there were some other potential issues. First, it explicitly required participants to look at time as a factor. It was the only question to add this additional variable. Previous researchers have found that questions related to heat and temperature that required integration of multiple ideas were the most difficult for students (Jasien & Oberem, 2002). Second, a typical way to answer this type of question requires heat capacity (Cp) in the rote application of formulas, something not needed for this question's solution. This raises questions about whether the level of students' understanding was deep enough in the absence of explicit instruction to enable them to understand time as a factor with "rate versus amount" and to go beyond rote knowledge of formulas.

Previous researchers (Johnstone, 1993; Nakhleh & Krajcik, 1994) have identified the problem of novices moving among different levels of knowledge in disciplines such as chemistry. Johnstone (1993) identified these levels as "macrochemistry" or that which can be seen, touched or eaten, "submicrochemistry" or the particulate level of matter, and "representational", the chemistry "(O)f symbols, equations, stoichiometry, and mathematics" (p. 702). Nakhleh and Krajcik (1994) included an additional level, the algebraic system, "[I]n which the relationships of matter are presented and manipulated using formulas and graphs" (p. 1078). Even though experts can work simultaneously at all levels and shift between them, novices have difficulty doing so.

Problems navigating between different levels of knowledge could also be used to explain students' problems correctly answering the tenth question. Previous research examining the teaching of heat and temperature concepts has noted the need for students to understand and discuss what is occurring on a particulate level (Carlton, 2000). The issue then, with the tenth question, may have been that students (novices) were focusing on one level of knowledge (e.g., the "algebraic system") distinct from the others, something previously identified as an issue by Gabel (1993). This over-reliance on one level of knowledge indicates a need to scaffold students between the levels. Future research should consider the development of another set of activities that focuses more specifically on moving among the different knowledge levels to answer questions that involve integration of multiple ideas. Since previous research has found that computer courseware, where visualization is provided for the different levels, has helped learners do this (Khoo & Koh, 1998), a computer program should be considered.

There are a number of limitations in this preliminary study that should be recognized and addressed in future studies including the assessment that was used, the sample size and sampling procedure. Assessment questions came from multiple sources. Some were pulled from pre-existing concept inventories while others were developed by the researchers. A new set of questions specifically designed to evaluate transfer is needed. Although internal reliability was calculated for the current instrument, the reliability coefficient should be higher. Subsequent work should focus on raising the internal reliability of the instrument and include an item analysis of questions.

There were two key sampling limitations, the lack of a random sample or random assignment to groups, and the small size. Researchers attempted to compensate for these limitations by using a non-parametric significance test that can be used with smaller and non-random samples (Huck & Cormier, 1996). Future studies should consider random assignment to groups and larger samples.

New instructional methods are needed to alter misconceptions about heat transfer in undergraduate engineering classes. The improvement that was seen in students' scores in this pilot study showed that some of these difficult concepts could be addressed using specially designed, inquiry-based activities. However, students' continued difficulties with questions that either integrate multiple ideas and/or were designed to assess far transfer point to the need for further refinement of the concept inventory and inquiry-based activities. Using more computer simulations may provide needed memory support to students as they learn these concepts, as well as a way to standardize time learning the concepts.

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(Edited by Nicole and Lily)

Appendix: Descriptions of inquiry-based learning activities

1. Heat transfer activity 1, boiling liquid nitrogen

Have available both boiling water and ice water (liquid part only). Using electronic laboratory balances, place an insulated cup, such as a coffee cup, on each balance. Fill each cup with an equal mass of liquid nitrogen; 100g works well. Simultaneously add 50ml of ice-water to one cup and 10ml of boiling water to the other. Observe the rate of liquid nitrogen boil-off, which is most easily seen as the rate of generation of “smoky” vapor, and then the final amount of liquid nitrogen remaining after 1 minute. Students will observe that the boiling water initially produces a much bigger cloud of vapor than does the ice-water (faster initial heat transfer rate due to larger temperature difference). However, after a minute, they will see that the ice-water was able to boil off more liquid nitrogen (more heat transferred).

2. Heat transfer activity 2, chipped ice vs. block ice

Fill two 1000ml beakers with 600ml of liquid water, and place each on a stir plate. Insert a data logging thermocouple into each, and allow each to come to room temperature. Take two 40g samples of crushed ice and form one into a “snowball” while leaving the other loose. Start the data recording and simultaneously place one ice sample into each beaker. Observe the temperature change in the stirred water over time until all ice is melted and the beakers’ temperatures are again constant, typically in 10 minutes or less. Students will observe that while the crushed ice does indeed cool the water more quickly due to higher surface area, both beakers reach the same final temperature.

3. Heat transfer activity 3, hot blocks

Each student team will need access to an internet-connected computer with a web browser enabled with Flash Player 7.0 or above. Students activate the simulation by visiting the following website: http://www.facstaff.bucknell.edu/mvigeant/thermo_demos/heat_transfer.html. The simulation allows students to place virtual metal blocks in an ice water bath and observe ice melt and temperature change in the water over time. Students control the physical parameters in the simulation. Questions guide students through assessing the impact of block mass, block surface area and block temperature, but students are free to change the other variables alone or in combination as well and observe the outcome.