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10-23-2008

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Recommended Citation
Nottis, Katharyn E. K.; Prince, Michael J.; and Vigeant, Margot A., "Addressing Misconceptions about Heat Transfer in Undergraduate Chemical Engineering Instruction" (2008). *NERA Conference Proceedings 2008*. Paper 18.
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Addressing Misconceptions about Heat Transfer in Undergraduate Chemical Engineering Instruction

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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 sort out the world (Smith, 1991) and can act as a filter for new learning (Smith et al., 1993). Prior knowledge can also interfere with concept mastery. In addition, there is a broad realization that meaningful learning of science content requires conceptual understanding rather than memorization of facts and formulas (Bransford, Brown, & Cocking, 2000; Lightman & Sadler, 1993), along with a growing appreciation that traditional instructional methods can be ineffective at altering students' preconceptions (Suping, 2003).

Concepts related to heat and temperature can be found throughout science curricula, at both the pre-college and college levels (Jasien & Oberem, 2002). These concepts are known for creating conceptual difficulties for students (Thomaz, Malaquas, Valente, & Antunes, 1995) and previous literature has shown that students hold a variety of alternate conceptions (Carlton, 2000; Thomaz et al., 1995). Furthermore, Jasien and Oberem (2002) found that both students and teachers of physical science were unable to accurately assess their understanding of heat and temperature concepts. The researchers found that the majority of the participants rated their understanding as "good" or "fair" but concept assessments revealed otherwise, and that there was no significant relationship between perceived understanding and actual conceptual understanding.

Difficulty with 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 that 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 that 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. Concepts targeted for this study were selected from a Delphi study (Streveler, Olds,

Miller, & Nelson, 2003) and focused on the distinction among heat, energy and temperature. Confusion regarding these concepts is widely recognized in the literature (e.g., Carlton, 2000; Jasien & Oberem, 2002; Thomaz et al., 1995).

Methodology

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- 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. A Kuder-Richardson #20 was computed on the post-test to determine the internal reliability of the instrument.

Participants

An intact, sample of convenience of 23 undergraduate chemical engineering students participated in this pilot study. Participants were given an assessment of 10 questions targeting relevant concepts before and after being taught with inquiry-based activities. One participant did not complete the pre-test so 22 participants were compared.

Instrument

Student understanding of concepts in heat transfer 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 expert evaluation of questions.

Concept inventory questions were designed to assess students' performance on questions closely related to the activities and questions which required students to apply concepts to analogous questions in new contexts or what has been labeled as near and far transfer, respectively (Brynes, 2008). Table 1 shows the Heat Transfer Concept Inventory questions without their distracters.

Insert Table 1 about here

The first six questions related directly to the active learning activities used for instruction and were designed to be near transfer questions (Byrnes, 2008). Questions seven through 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 (#5, #6) 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). Heat and mass transfer are frequently taught together. The ninth question, about coal dust, was also a rate versus amount

problem but it was a mass transfer problem analogous to the crushed ice questions (#3, #4). Finally, the tenth question about ethanol versus water asked students to think specifically about heat transfer as a rate process and required they address the question in a different way in which the question is traditionally taught to be answered.

Inquiry-Based Learning Activities

Three active learning activities, first implemented the previous academic year, were designed by the researchers. Inquiry-based was operationalized using the 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 they started an activity, using technology when appropriate, and evaluation of understanding throughout the instructional process. Appendix A 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. Students frequently believe that temperature is a good measure of energy so the activity was designed to challenge this misconception. The first two questions on the concept inventory were constructed to assess students' understanding of this concept. 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. In this particular activity, students sometimes think crushed ice makes something colder. The third and fourth questions on the concept inventory were included

to assess students' understanding of this. Finally, the third inquiry-based activity focused on cooling hot metal blocks with ice. 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, primarily because it was too difficult to generate sufficiently identical metal blocks at the proper temperatures in a physical experiment. 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.

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. 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.

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. Participants continued to have access to the computer simulation (Activity #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.

Results

Results from the Wilcoxon test showed that participants performed significantly better on the post-test than on the pre-test, $Z = -3.84$, $p < .01$. 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- and the post-test.

Insert Table 2 about here

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 (#6) 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-test scores for five of the questions: #1 – Liquid N2

rate, #2 – Liquid N2 Amount, #6 – Metal Blocks Rate, #7 – Sponge Amount, and #8 – Sponge Rate. There was no significant difference in scores between pre- and post-testing on the remaining five questions.

Insert Table 3 about here

The internal reliability of the post-test as measured by the Kuder-Richardson #20 formula was moderately high at 0.68.

Conclusions and Educational Implications

Results indicated that incorporating inquiry-based activities can significantly improve students' conceptual understanding of heat transfer as measured by questions closely related to the instructional activities. Further research should re-examine the activities to determine whether they can be designed to encourage far transfer.

Methods used in the inquiry-based learning activities may have made a difference in students' learning. For example, there was a significant increase in the percentage of students correctly answering Question #6, dealing with hot blocks. The activity used to teach the concepts involved a computer simulation. Previous research (Krajcik, 1994; Nottis & Kastner, 2005) has 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 needed memory support to the students in the current study. In addition, participants had access to the computer simulation after the lab period. The significant improvement that was seen could also be

the result of increased time using the simulation to understand the concept, since participants' exposure to the other two activities ended at the end of the laboratory period.

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 and required participants to look at time as a factor. It was the only question to add this additional variable. Previous research has found that questions related to heat and temperature that required integration of multiple ideas were the most difficult for students (Jasien & Oberem, 2002). This raises questions about whether the level of students' understanding is deep enough in the absence of explicit instruction to enable them to understand time as a factor with rate versus amount. Future research should consider the development of another set of activities that focuses more specifically on this.

There are a number of limitations in this preliminary study that should be recognized and addressed in future studies including the assessments that were used, the sample size and sampling procedure. Assessment questions were pulled from pre-existing concept inventories and developed by the researchers. Although internal reliability was calculated for the current instrument, the reliability coefficient should be higher. Subsequent work should focus on raising the 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, 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 shows that some of these difficult to understand concepts can be addressed using specially designed, inquiry-based activities. Using more computer simulations may provide needed memory support to students as they learn these concepts. However, students' continued difficulties with questions that either integrate multiple ideas and/or are designed to assess far transfer indicate the need for further refinement of the activities.

This research was funded by NSF Grant # DUE-0442234

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Table 1

Heat Transfer Concept Inventory Questions

H1) Either 15 ml of boiling water or 60 ml of ice cold water ($0^{O}C$) 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) Ice at $0^{O}C$ is melted by adding hot blocks of metal. One option is to use <u>one</u> metal block at a temperature of $200^{O}C$ to melt ice and a second option is to use <u>two</u> metal blocks each at a temperature of $100^{O}C$ 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 $200\ ^{O}C$. Which option will melt more ice?
H6) Which option 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) 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?
H10) Two identical beakers contain equal masses of liquid at a temperature of $20\ ^{O}C$. One beaker is filled with water and the other beaker is filled with ethanol (ethyl alcohol). The temperature of each liquid is increased from $20\ ^{O}C$ to $40\ ^{O}C$ using identical hot plates. It takes 2 minutes for the ethanol temperature to reach $40\ ^{O}C$ and 3 minutes for the water to reach $40\ ^{O}C$. Once a liquid had reached $40\ ^{O}C$, its hot plate is turned off. To which liquid was more energy transferred during the heating process?

Table 2

Percentage Selecting the Correct Answer on Pre and Post Tests

Question	Pre-test (n= 22)	Post-test (n= 23)
1. Liquid N2 Rate	68%	100%
2. Liquid N2 Amount	73%	100%
3. Chipped Ice Amount	82%	100%
4. Chipped Ice Rate	96%	100%
5. Metal Blocks Amount	86%	96%
6. Metal Blocks Rate	41%	91%
7. Sponge Amount	59%	96%
8. Sponge Rate	52%	96%
9. Coal Dust	91%	100%
10. Heating Ethanol vs. Water	50%	65%

Table 3

Significance of the Difference Between Pre- and Post Test Scores for Individual Questions, Determined by the *McNemar* Test

Question	Number of Pairs	*p*
1. Liquid N2 Rate	22	.016*
2. Liquid N2 Amount	22	.031*
3. Chipped Ice Amount	22	.125
4. Chipped Ice Rate	22	1.00
5. Metal Blocks Amount	22	.375
6. Metal Blocks Rate	22	.001**
7. Sponge Amount	22	.008**
8. Sponge Rate	21	.002**
9. Coal Dust	22	.500
10. Heating Ethanol vs. Water	22	.375

** $p < .01$, * $p < .05$

Appendix A: Descriptions of Inquiry-Based Learning Activities

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).

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.

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 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.