USE OF CONCEPT INVENTORIES TO IDENTIFY MISCONCEPTIONS IN THERMAL SCIENCES

Ronald L. Miller[1], Ruth A. Streveler[2], Barbara M. Olds[3]

[1]Colorado School of Mines, Chemical Engineering, Golden, CO 80401 USA, rlmiller@mines.edu
[2]Purdue University, Engineering Education, West Lafayette, IN 47907 USA, streveler@purdue.edu
[3]Colorado School of Mines, Education Innovation, Golden, CO 80401 USA, bolds@mines.edu

ABSTRACT

This paper reports preliminary evidence that a significant number of engineering students possess robust misconceptions about rate processes such as transfer of heat even after years of study in thermal and transport sciences including fluid mechanics, heat transfer, and thermodynamics. Data from the Thermal and Transport Concept Inventory (TTCI) currently under development and additional questions specifically written for the present study are reported and analyzed. Results indicate the presence of a persistent misconception about the relationship between the rate of heat transfer and amount of energy transferred in processes of engineering interest.

KEYWORDS

Misconception, conceptual change, concept inventory

INTRODUCTION

With funding from the National Science Foundation (DUE-0127806), our research team is completing development of a concept inventory instrument to measure engineering students' understanding of difficult concepts in thermal and transport sciences (e.g. heat transfer, fluid mechanics, thermodynamics). [1-4] Version 2.21 of the instrument, known as the Thermal and Transport Concept Inventory (TTCI) has been beta-tested at six United States engineering institutions and psychometric results have been used to test instrument validity and reliability. Preliminary beta test results from this facet of the instrument development have been reported previously. [4] Nine of the original 32 questions did not perform at expected levels of reliability and have been replaced in version 3.0 of the TTCI. Additional beta testing is on-going and will be completed before wide-spread dissemination of the instrument via the web scheduled for late 2006.

As part of our psychometric work, we use factor analysis and cross-tabulations to identify common misconceptions which are robust and which transfer across question contexts and disciplines (e.g. fundamental misconceptions which exist in, say, both fluid mechanics and heat transfer). The goal of this analysis is to identify student misconceptions which can be repaired in one context with the expectation of far transfer to other disciplinary contexts students might be expected to encounter. So far, this technique has allowed us to identify and group three overall categories of misconceptions:

- energy vs. temperature
- steady-state vs. equilibrium processes
- rate vs. amount of transfer (e.g. heat transfer, momentum transfer, mass transfer)

Details about the first two misconceptions were reported previously [4] and results indicated that at least 10-20% of engineering students in the study did not understand how energy and temperature were related by heat capacity or when processes could be considered at equilibrium. In this paper, we report preliminary evidence that a significant number of engineering students (many of whom have completed courses in fluid mechanics, heat transfer, thermodynamics, and/or transport phenomena) also possess a fundamental misconception about the relationship between rate of energy transfer and the amount of energy transferred in various heat transfer processes and contexts.

INITIAL EVIDENCE FOR EXISTENCE OF THE “RATE VS. AMOUNT” HEAT TRANSFER MISCONCEPTION

As the data from the TTCI beta testing were analyzed, we noticed several heat transfer questions were yielding far fewer numbers of correct responses than we expected. For example, Table 1 shows a cross-tabulation for TTCI beta test results from the *Meltice* and *Carpet* questions. In such a table, we can see frequency counts of how many students selected each answer for the two posed questions. By observing the individual entries in each row and column, we can determine how many students answered both questions correctly. More importantly, when students choose incorrect but conceptually-related wrong answers (known as distractors), we have obtained evidence of a misconception which is robust enough to carry across the context of both questions. In the case of two-part questions like *Meltice*, we also obtain evidence of reliability when a large proportion of students answer each question consistently (that is, they select both correct answers or select a pair of distractors that are logically related).

Results in Table 1 indicate that only 18% of the beta test students answered both the *MeltIce1* and *Carpet* questions correctly and only 19% answered both the *Meltice2* and *Carpet* questions correctly. Overall, 27% of the students correctly answered the *MeltIce1* question, 24% identified the correct reason (*Meltice2*), and ~64% correctly answered the *Carpet* question. Of interest is the significant number of students (approximately 13%) who incorrectly answered all three questions by selecting distractors that provide evidence for the existence of the same misconception ("a" for *MeltIce1*, "e" for *MeltIce2*, and "d" for *Carpet*).

In the *Meltice* question, the "a,e" combination of distractors was chosen by students who think the process of melting ice with hot blocks is governed by the rate of melting rather than the amount of energy that will be transferred from blocks to ice. Distractor "d" for the *Carpet* question was chosen by students who incorrectly believe that carpet and tile are at different temperatures because of differences in the rate of convective heat transfer off the two surfaces rather than considering the amount of energy transferred into tile or carpet from a bare human foot. These results were our first indication of the "rate vs. amount" misconception in students who beta-tested the TTCI instrument.

Table 1: Cross-Tabulation of Student Responses to *MeltIce1*, *MeltIce2* and *Carpet* Questions[1]

	Carpet responses				Total
	a	b	c (correct)	d	
MeltIce 1 responses					
a	6	1	33	15	55
b	3	0	12	4	19
c (correct)	5	0	21	6	32
d	2	0	8	1	11
Total	16	1	74	26	117
MeltIce2 responses					
e	5	1	30	15	51
f (correct)	3	0	21	3	27
g	3	0	13	5	21
h	1	0	1	0	2
i	3	0	8	1	12
Total	15	1	73	24	113

[1]yellow cells are located in rows and columns of the correct response to each question; the blue cell represents an example distractor pair which indicates persistent misconceptions in significant numbers of student respondents. In this example, 15 students chose distractor 'a' on the *MeltIce1* question and distractor 'd' on the *Carpet* question. By comparing these two distractors, incorrect ideas (or misconceptions) about the concepts can be recognized.

Cross-tab analysis of beta results for other heat transfer questions in the TTCI also indicated the presence of the "rate vs. amount" misconception. For example, ~17% of students answering the *HotPlate* question selected answer "e" which indicates an inability to link the rate of fluid heating with the amount of energy added to the fluid and its relationship to fluid heat capacity. About 40% of these students also answered "d" for the *Carpet* question, once again indicating conceptual confusion focusing on the rate of convective heat transfer off the two floor surfaces rather than considering the amount of energy transferred into tile or carpet from a bare human foot.

Finally, we found that ~55% of the students selecting distractors “c” or “e” for the *Hotplate* question also choose the “a,e” distractor pair for the *Meltice* questions. This combination of results again suggests conceptual difficulties with the relationship between temperature change, the amount of energy transferred, and the rate of transfer. Amount and rate are concepts in two different ontological categories, substances and processes, respectively. Chi, Slotta and de Leeuw [5] have proposed that students often misconceive process concepts as substance concepts. Furthermore, Slotta et al. found that physics novices adopted such substance-based conceptualizations across a broad range of topics including light, heat, and electricity. [6]

Based on these early findings, we developed additional questions designed specifically to probe for conceptual understanding of heat transfer rate vs. the amount of transferred energy in several simple heat transfer processes. The new questions contained both multiple-choice responses (the correct answer plus several distractors based on expected student misconceptions) and open-ended responses to allow students to explain and justify their answers. We used these comments to help understand the nature of the “rate vs. amount” misconception in this student cohort.

The purpose of this paper is to provide the results from this extended study and to speculate on why some engineering students still possess the “rate vs. amount” misconception even after completing significant coursework in thermal science and transport processes.

PARTICIPANTS AND METHODS

Data reported in this study come from two sources: 1) TTCI beta test data from the Thermal and Transport Concept Inventory (TTCI) presently under development and 2) additional concept inventory data using new questions specifically focused on the “rate/amount” misconception.

For ease of beta testing, version 2.21 of the original 32-question multiple-choice TTCI was divided into subsets for heat transfer (6 questions), fluid mechanics (12 questions), and thermodynamics (13 questions). Approximately 120 undergraduate engineering students ranging from sophomores to seniors at six U.S. engineering schools answered the heat transfer portion of the TTCI. Nearly all of the participants had completed at least one course in thermal or transport sciences (e.g. heat transfer, fluid mechanics, thermodynamics).

The new question set was administered to 29 chemical engineering seniors, all of whom had completed courses in fluid mechanics, heat transfer, thermodynamics (2 courses), mass transfer, and an integrated transport phenomena course. These students also answered 3 heat transfer questions from the TTCI (*Meltice, Carpet, Hotplate*) to compare their performance with the TTCI beta test results.

RESULTS AND ANALYSIS

In this section, we report findings from the study using 29 chemical engineering seniors. So that we could anchor these new data with previously collected results from the TTCI beta test reported above and in previous papers [3,4], we administered the *Meltice*, *Carpet*, and *Hotplate* questions to the chemical engineering test group. Results of this comparison are shown in Table 2.

Table 2: Comparison of Responses to Selected TTCI Questions

Question	TTCI Beta Test Results (n = 117), % correct responses	ChE Students in Present Study (n=29), % correct responses
Meltice1	27.4	37.9
Meltice2	23.9	37.9
Carpet	63.2	55.2
Hotplate	47.9	62.1

With the exception of the *Carpet* question, the chemical engineering group of senior students performed statistically better that the TTCI beta test group which consisted of a mixture of sophomore, junior, and senior mechanical and chemical engineering students. Thus, Table 2 provides preliminary evidence that traditional instruction in thermal science and thermodynamics courses can help <u>some</u> students repair <u>some</u> misconceptions about heat and heat transfer including the rate/amount misconception. However, the results in Table 2 also clearly show that significant numbers of senior-level engineering students persist in their misconceptions about rates and amounts of heat transfer, even after completed several thermal science courses including a transport phenomena course which specifically discusses and models rate processes in great detail.

To further explore this finding, we administered to the chemical engineering test group additional questions focusing specifically on heat transfer rates vs. the amount of energy transferred. Key results for these questions are shown in Table 3.

Table 3: Results of Chemical Engineering Student Responses to "Rate vs. Amount" Questions (n=29)

Question	% correct responses	Most commonly chosen distractor and % of students who choose it
Heatblock1	96.6	---
Heatblock2	75.9	f (17%)
Househeat	17.2	a (55%)
Twohouse1	96.6	---
Twohouse2	48.3	f (28%)

The *Heatblock* question was designed to verify results originally obtained using the *Hotplate* question summarized in Table 2. *Hotplate* results indicated a significant number of chemical engineering seniors (~38%) could not identify the relationship between the amount of time each fluid (water and ethanol) was heated and the amount of energy added to the fluid. Approximately 10% indicated that each fluid received the same amount of energy since the change in temperature was the same for each and thus, ignored the amount of time each fluid was heated at the same rate. Another 17% believed that they couldn't answer the question without heat capacity data even though the information given could be used to determine the relative size of each fluid's heat capacity. As indicated in Table 3, slightly fewer chemical engineering seniors missed the *Hotplate* question, but the misconception persists.

Interestingly, ~86% (6 out of 7) of the chemical engineering students who incorrectly answered the *Heatblock2* question also missed the *Hotplate* question and conversely ~55% (6 out of 11) of the students missing the *Hotplate* question also missed *Heatblock2*. The correlation coefficient for the (*Heatblock2, Hotplate*) correct answer pair (e,a) and conceptually related distractor pairs (f,c) and (b,d) was 0.45 indicating that the rate/amount misconception is held by a significant number of these students across contexts.

It is possible to argue that some students may be confused by *Hotplate* if they consider other heat transfer effects such as liquid evaporation or convection. The *Heatblock* question was designed to eliminate this potentially confounding effect by focusing on heating of solid blocks rather than liquid samples. As the results in Table 3 indicate, nearly every student was able to identify which block was heated faster but ~24% still could not identify which received more energy during the heating process. Most of the students incorrectly answering *Heatblock* indicated that both blocks received the same amount of energy, a result that agrees closely with the *Hotplate* results we've observed. These data once again indicate the persistence of student confusion about the relationship (or lack of) between the rate at which a body is heated and the amount of energy it absorbs.

Students answering *Heatblock* were asked to explain and justify their multiple-choice answers. The following excerpts show how students get confused about the rate/amount concept:

> "The rate of heating is faster for block 1, so it has more energy transferred."
>
> "Because they [the blocks] eventually reached the same temperature, the same amount of energy is transferred."
>
> "If the blocks have the same heat transfer coefficient and same heat transfer rate, the amount of energy transferred must be the same."

The *Househeat* question was developed based on a discussion about mental models in Don Norman's book about the design of everyday objects. [7] He mentioned that most of us consider an ordinary house thermostat as a device which controls the rate of heating when in fact (ignoring the new "intelligent" thermostats which can anticipate achieving a temperature setpoint and turn off the furnace before the temperature is reached) a thermostat is simply an on-off switch to control the amount of energy delivered to the house. As Table 3 indicates, nearly 83% of the chemical engineering seniors in this study also believed that a thermostat will heat more rapidly if the setpoint is far above the desired house temperature.

Clearly, an engineering education does not repair the misconception that a simple thermostat controls the rate of heating rather than the amount of heating as the following student explanations of their *Househeat* answers illustrate:

> "Faster heating gives more energy into the house."
>
> "A higher setting will blow out air and energy at a higher rate."
>
> "The thermostat controls the power output so a higher setting gives more power."

Finally, the *Twohouse* question was developed to ask another seemingly simple question about the relationship between the rate of heat loss in insulated and uninsulated houses and the amount of energy required to reheat both houses to the same temperature. As the results in Table 3 show, the chemical engineering students studied nearly all correctly indicated that the uninsulated house will cool faster from 20 ^{O}C towards the atmosphere temperature of 0 ^{O}C once the furnace stopped working. However, only 48% correctly believed that both houses would require the same amount of energy to be reheated from 0 ^{O}C to 20 ^{O}C with another ~28% indicating that the uninsulated house would require more energy to reheat since they believe it lost more energy during the cool down process. Thus, a significant number of the students persist in their belief that the house which cooled faster also lost a larger amount of energy.

CONCLUSIONS AND IMPLICATIONS

Beta test data from the Thermal and Transport Concept Inventory (TTCI) collected at six engineering schools of varying size, demographics, and geographical location has been used to identify the presence of a persistent engineering student misconception about the relationship between the rate of heat transfer and amount of energy transferred. Additional questions have been developed and data collected with a cohort of senior chemical engineering students. Results again indicate that a significant number of the students make incorrect predictions about the behavior of simple heat transfer processes even after completing ~6 courses in thermal and transport sciences.

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