What Conceptual Models Do Engineering Students Use to Describe Momentum Transfer and Heat Conduction?

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Objective and Purpose

Faculty members who teach courses in thermal and transport sciences often observe that even students who can correctly solve problems in fluid dynamics, heat and mass transfer, or thermodynamics still believe that "processes stop when they reach equilibrium." These faculty observations are supported by literature suggesting that science and engineering students do not conceptually understand many fundamental molecular-level and atomic-level phenomena including heat, light, diffusion, chemical reactions, and electricity (Fuchs, 1987; Garnett & Hackling, 1995; Jones, Carter & Rua, 2000; Marek, Cowan & Cavallo, 1986; Reiner, Slotta, Chi & Resnick, 2000). The problem is more than simply one of confusion or misunderstanding, but instead involves fundamental <u>misconceptions</u> by students about differences in the way that molecular-scale processes differ from observable, macroscopic causal behavior we experience in our daily lives (Chi & Roscoe, 2002).

Engineering instructors find that molecular-scale phenomena such as viscous fluid flow, conductive heat transfer, diffusional mass transfer, and thermodynamic equilibrium are very difficult for students to learn and, even after instruction, students persist in their misconceptions. For example, engineering students often describe molecular momentum transfer as faster molecules "dragging slow molecules along," heat as a "substance stored in hot objects" as opposed to cold which is described as a "substance stored in cold objects," heat transfer as a "flow of hot molecules to cold objects," and molecular processes as "stopping" when they reach equilibrium. Each of these conceptually flawed explanations leads to incorrect explanations of other related phenomena (for example, incorrectly predicting the absence of a temperature effect on equilibrium processes or predicting that no molecular diffusion occurs in laminar fluid flow).

Theoretical framework

<u>Why</u> are these concepts so difficult for students to learn? Part of the reason seems to be that certain beliefs are very entrenched and not easily changed (Chinn & Brewster, 1993). Based largely on life experience, these beliefs are formed early in a student's career (perhaps even before the start of formal schooling) (Erickson, 1980) and become the basis for future learning via the construction of increasingly complicated mental models (Piaget, 1977). If the student's prior knowledge is incomplete or incorrect, new concepts are difficult if not impossible to correctly assimilate and a fundamental conceptual

change in the student's mental model will be required before the new concept can be correctly understood (Chi & Roscoe, 2002).

For many traditional processes, macroscopic models and metaphors ("heat flows") still adequately describe phenomena and students should be able to use them fluently. However, given the increasing number of engineering systems that explicitly rely upon molecular-level phenomena (e.g. biotechnology, microelectronics, molecular computers, and many others), we argue that students must also understand when macroscopic models will break down and when the metaphors are no longer applicable.

In addition to the macroscopic and molecular models, students are often presented with microscopic models to explain molecular processes. An example of a microscopic model would be describing laminar fluid flow as layers of fluid moving past one another. Microscopic models may be thought of as a way of "macro-tizing" the molecular processes to make them more understandable. Microscopic models attempt to examine phenomena on a smaller scale than the macroscopic models, but still do not describe what is truly happening at the molecular level.

If the macroscopic and microscopic models are successful in describing the global behavior of simple systems, why should we care if students persist in applying these models to molecular processes such as the diffusion of colored dye into water? The answer is simple - the macroscopic and microscopic models can predict some, but not all, important behavioral characteristics of molecular processes. Given the increasing importance of dynamic molecular behavior in many fields of engineering and science, we believe identifying the models students use to describe central concepts in thermal and transport sciences is an important step towards improving the quality of student learning in these disciplines.

Procedure

In this study, we investigate the kinds of models chemical engineering seniors use to describe specific examples of transport and conduction phenomena. On the first day of a senior-level transport phenomena course, the 39 chemical engineering students enrolled in the course were asked to answer the question:

> *"Explain in your own words (no equations) how momentum is transferred through a fluid via viscous action. If you'd like, use a specific application (such as laminar flow in a circular pipe) for your explanation."*

About midway through the course the same students were asked to:

> *"Explain in your own words (no equations) how energy is transferred via conductive action. If you'd like, use a specific application (such as heat flow through a solid plate) for your explanation."*

We posed two research questions when analyzing student responses to this question:

1. What models (macroscopic, microscopic, molecular, or a mixture of these three) do students use to explain these phenomena?
2. Is students' use of models consistent across sampling times? In other words, if a student uses a microscopic model to answer question 1, will they later use a microscopic model to answer question 2?

To answer research question 1, we created sample macroscopic, microscopic, and molecular descriptions of viscous momentum transport and heat conduction. These descriptions are listed in Tables 1 and 2 and were used as rubrics to score student responses. Some students used a combination of models in their descriptions that were labeled as "mixed" models in our scoring. A few students also gave answers so vague or basically incorrect that they could not be scored. These are listed as "non-responsive."

To answer research question 2, we compared students' answers across sampling times.

Results

Thirty-nine students answered question 1 while 32 students (all students present on that day) answered question 2. No students dropped the course.

Copies of student responses were distributed to three coders for question 1 and four coders for question 2. If coders did not unanimously agree on the categorization, discussion ensued until consensus was reached. Results are summarized in Tables 3 and 4. Examples of a typical molecular, microscopic, and macroscopic answer are also provided to enhance the richness of the results.

Table 1. Macroscopic, Microscopic, Molecular, and Mixed Descriptions of Viscous Momentum Transfer in Laminar Pipe Flow Used as Scoring Rubric for Student Responses

Macroscopic Description The pressure at the pipe inlet is increased (usually by pumping) which causes the fluid to move through the pipe. Friction between fluid and pipe wall results in a pressure drop in the direction of flow along the pipe length. The fluid at the wall does not move (no-slip condition) while fluid furthest away from the wall (at the pipe centerline) flows the fastest, so momentum is transferred from the center (high velocity and high momentum) to the wall (no velocity and no momentum).
Microscopic Description Fluid in laminar flow moves as a result of an overall pressure drop causing a velocity profile to develop (no velocity at the wall, maximum velocity at the pipe centerline). Therefore, at each pipe radius, layers of fluid flow past each other at different velocities. Faster flowing layers tend to speed up slower layers along resulting in momentum transfer from faster layers in the middle of the pipe to slower layers closer to the pipe walls.
Molecular Description Fluid molecules are moving in random Brownian motion until a pressure is applied at the pipe inlet causing the formation of a velocity gradient from centerline to pipe wall. Once the gradient is established, molecules that randomly migrate from an area of high momentum to low momentum will take along the momentum they possess and will transfer some of it to other molecules as they collide (increasing the momentum of the slower molecules). Molecules that randomly migrate from low to high momentum will absorb some momentum during collisions. As long as the overall velocity gradient is maintained, the net result is that momentum is transferred by molecular motion from areas of high momentum to areas of low momentum and ultimately to thermal dissipation at the pipe wall.
Mixed Description Students use more than one model in their description.

Examples of student responses to question 1 (*"Explain in your own words (no equations) how momentum is transferred through a fluid via viscous action."* *).*

Molecular model used to answer this question

> "I think viscous action can best [be] described as the physical intermolecular interactions occurring in a fluid. Each molecule in the fluid has kinetic energy with some magnitude and direction. A portion of this energy (including magnitude and direction) is transferred to another molecule when it physically contacts it in the fluid. Though there are an infinite number of these directions and magnitudes of kinetic energies contained and transferred in the fluid, there is a net or average direction and magnitude which causes, then, a net transfer of kinetic energy in a certain direction. This transfer can be thought of as momentum transport. Specific properties of the fluid, such as size, shape, and polarity, enhance or decrease, or simply just alter the intermolecular actions and hence transport."

Macroscopic model used to answer this question.

> "Momentum is transferred through a fluid due to the energy differences within that fluid. The viscosity of the fluid dictates the momentum transfer. In the case of the laminar flow in a circular pipe, the momentum of the fluid must be conserved, and therefore the momentum into the fluid must equal the momentum out of the fluid. The viscosity of a fluid can be changed using different methods (temperature). The momentum profile is greater within the middle of the wall of a pipe and less at the walls." [Student draws a cross section of a pipe.]

Microscopic model used to answer this question

> "A fluid's viscosity contributes to momentum transfer. In a circular pipe, for laminar flow, the fluid particles in one "layer" tend to "grab a hold" of the fluid particles in the next layer. How tightly the particles grab on to each other or the walls of a pipe is its viscosity. When a fluid layer is moving with high momentum and "grabs a hold" of another fluid layer, some of that momentum is transferred to the next layer. The first layer loses some of that momentum while the second layer gains some." [The student then draws a picture of a pipe and indicates the direction of the momentum flow (in the x direction) and the direction of momentum transfer (in the y direction.)]

Table 2. Macroscopic, Microscopic, Molecular, and Mixed Descriptions of Conductive Heat Transfer Used as Scoring Rubric for Student Responses

Macroscopic Description A temperature change through a material (gas, liquid, or solid) will cause heat to flow. The larger the temperature change, the faster heat will flow. Heat always flows from a high temperature region to a low temperature region. The linear ratio of heat flow per unit area to the temperature difference is called the heat transfer coefficient.
Microscopic Description At any point in the material, a temperature gradient (temperature change per unit length) causes heat to flow from high temperature to low temperature. Total heat flux (heat flow per unit area) is proportional to the temperature gradient.
Molecular Description In liquids and gases, molecules are moving in random Brownian motion. A change in temperature through the fluid will result in a distribution of molecules with different kinetic energies. Energy (heat) will be transferred locally in 2 ways: 1) diffusion of high energy molecules to regions of low energy molecules, and 2) collisions between molecules in which some energy transfer occurs. The net result is energy (heat) transfer from a hotter to colder region.
Mixed Description Students use more than one model in their description.

Examples of student responses to question 2 (*"Explain in your own words (no equations) how energy is transferred via conductive action."*)

Molecular model used to answer this question

> "Molecules in contact or close proximity are excited through some form of energy input. These excited molecules contact other molecules, thereby passing on some of this energy to the new molecules. These new molecules are excited and continue to pass on their energy to other molecules promoting conduction. Some of these molecules are more excited than others, which is described by a simple constant obtained from experiment (or possibly molecular modeling) known as the heat transfer coefficient."

Macroscopic model used to answer this question.

> "Energy is transferred by conductive action as a result of a temperature differential over a length of material. The way the heat "travels" through the material is a result of the type of material (conductive heat transfer coefficient, k) and the change in T over a given distance, x, and the area of the material."

Microscopic model used to answer this question

> "Initially the whole plate is at constant T. When heat is applied to one side (@x_1) that side begins to heat up. As x_1 heats up it transfers heat to the area next to it and it begins to heat up until at some steady state you have a heat transfer profile though the solid. Assuming that at x_2 there is insulation then the T-profile will be uniform through the solid. If x_2 is not insulated then the T will be higher at x1 and decrease toward x_2." [Student draws a graph showing the decrease of T between x_1 and x_2. The student also adds the equation h=KA dt/dx)

Table 3. Types of descriptions used by students for Question 1 (n = 39) and Question 2 (n = 32)

Description type used in response	Number (and percent) of students for Question 1	Number (and percent) of students for Question 2
Molecular	6 (15.38%)	13 (40.65%)
Macroscopic	4 (10.25%)	3 (9.37%)
Microscopic	10 (25.64%)	5 (15.62%)
Mixed	14 (35.89%)	9 (28.12%)
Non-responsive	5 (12.82%)	2 (6.25%)

Table 4. Comparison of models used by students for Question 1 and 2

Description type used in response	Number of students responding to Questions 1 and 2
Molecular	2
Macroscopic	1
Microscopic	0
Mixed	1
Models not consistent	24

Discussion

Both questions ask students to describe molecular phenomena that are often explained to students using macroscopic or microscopic models. Our first research question asked what kinds of models students use to describe these phenomena. Only 6 of 39 students (or 15%) used molecular descriptions of momentum transfer (question 1), and 13 of 32 students (or 40%) used molecular descriptions of heat conduction (question 2). Although the percent of students giving only macroscopic answers remained about the same, the number giving molecular answers nearly tripled from question 1 to question 2 as the micro level explanations and mixed explanations decreased. Since only two students used molecular models to explain both questions, statistical analysis of these results were not conducted due to small sample size. Interestingly, the two students who consistently used molecular models were not among the group of students with the highest grades in the course.

The results from our preliminary study suggest that senior-level chemical engineering students typically do not tend to think of viscous momentum transport as fundamentally a molecular-level process even though they have been exposed to concepts of molecules and molecular dynamics in at least 8-10 courses in their curriculum. However, later in the course, a higher percentage of students were using molecular explanations to explain heat conductivity. The increase may be a result of instruction or perhaps the concept of "heat" is easier for students to think about as a molecular process. More study is needed to establish any relationship.

There also was almost no consistency of models used by students. Only seven students used a single model-- macroscopic, microscopic, or molecular – to describe both phenomena. Although this work is very preliminary, this result suggests that students are not clear about what models to use. This is not surprising since, though the phenomena are molecular in nature, some textbooks and instructional materials invoke only macroscopic and microscopic descriptions of viscous action and heat conduction. In addition, students may have fundamental misconceptions about the nature of these phenomena that they formed prior to beginning formal engineering education (Reiner et. al, 2002). It may also be the case that students, even engineering seniors, hold various models of these phenomena simultaneously. This supposition is supported by the number of students in this study who used mixed models to describe momentum transfer and heat conduction.

Given the findings in this work, we must also pose the following question:

> At what level (macroscopic, microscopic, molecular) do undergraduate engineering students <u>need</u> to understand phenomena that are fundamentally molecular in nature if they are to become effective engineers?

In fact, this issue is still not resolved in the engineering education community since until recently most faculty members have assumed the following:

- students have a fundamental understanding of physical phenomena since they have been taught these concepts somewhere in their undergraduate coursework
- students who can solve problems understand the concepts underlying them (engineering courses are almost uniformly taught as problem-solving courses)

Results reported in this paper and the recent findings of other researchers (Evans & Hestenes, 2001; Evans, 2002) now suggest that neither of these assumptions is correct, although this assertion is still controversial among engineering faculty members. Given the fairly recent emergence of student misconceptions as a field of study in engineering education (as opposed to science education where misconception work has impacted the teaching of science for nearly 20 years), the discussions have just begun about the appropriate and necessary level of conceptual understanding for engineering graduates. Although the final result is not at all clear, research on engineering misconceptions has opened the door for discussion.

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