

# Comparing Student Conceptual Understanding of Thermodynamics in Physics and Engineering

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**Abstract.** Thermodynamics is a core part of curricula in physics and many engineering fields. Despite the apparent similarity in coverage, individual courses in each discipline have distinct emphases and applications. Physics education researchers have identified student difficulties with concepts such as heat, temperature, and entropy as well as with larger grain-sized ideas such as state variables, path-dependent processes, etc. Engineering education research has corroborated some of these findings and has identified additional difficulties unique to engineering contexts such as confusion between steady-state and equilibrium processes. We are beginning a project that provides an opportunity to expand the interdisciplinary research on conceptual understanding in thermodynamics. This project has two goals: first, determine the overlapping content and concepts across the disciplines; second, compare conceptual understanding between these groups using existing conceptual questions from PER and EER. We present a review of PER and EER literature in thermodynamics and highlight some concepts that we will investigate.

**Keywords:** thermodynamics, education research

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## INTRODUCTION

Physics education research (PER) is one facet of a greater body of discipline-based education research (DBER). DBER has gained national attention partly due to an increasing demand for STEM-trained professionals [1]. More broadly, improving STEM-related education, especially in introductory courses, serves all majors and helps move toward a more scientifically literate society.

The University of Maine offers several courses covering intermediate or advanced thermodynamics topics. Four of these courses explicitly have thermodynamics in the course title, but others, such as general chemistry, include this topic as well. During the 1995-96 academic year, an inter-department committee was formed to determine the feasibility of offering fewer introductory thermodynamics courses, since they all appeared to deliver similar content. The conclusion that none of these courses could reasonably be combined due to the distinctive discipline-specific emphases raises interesting questions about what makes each approach to thermodynamics unique.

We are beginning a comparison study of student conceptual knowledge of thermodynamics between physics and engineering students. One component of this study is comparing the treatment of thermodynamics in physics to that in mechanical engineering, both in content and approach. Examination of a typical mechanical engineering textbook (e.g., [2]) shows that it shares many chapter themes with a typical physics textbook (e.g., [3]). For example, both textbooks have chapters on definitions

of terms, the First Law, and the Second Law. However, while the physics of thermodynamics is the same, the application of thermodynamic principles and concepts is approached differently across disciplines.

In physics, there is a strong marriage between conceptual knowledge and the mathematical forms of the equations that govern thermodynamics such as thermodynamic potentials and Maxwell relations. Calculating quantities usually involves both an application of conceptual knowledge and the ability to carry out differential and integral calculus. Physics emphasizes theoretical limits of ideal processes and use of the state function principle to find changes in quantities such as entropy.

In mechanical engineering, the state function property is still imperative and equations of state may be used, but mechanical engineers also use additional tools such as steam tables<sup>1</sup> (Table 1) and Mollier diagrams<sup>2</sup>. Further, mechanical engineers are most often dealing with open systems, in which mass flows through a region of interest (called a “control volume”) whereas most situations in physics are closed systems (which engineering calls “control mass”).

These differences suggest that there is much to be

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<sup>1</sup> Steam table quantities are given in per mass units. While internal energy, enthalpy, and entropy are familiar, specific volume ( $v = \frac{1}{\rho}$ ) is usually tabulated instead of density.

<sup>2</sup> Mollier diagrams are best viewed in larger dimensions than possible in this paper. Please visit: [http://www.engineeringtoolbox.com/mollier-diagram-water-d\\_308.html](http://www.engineeringtoolbox.com/mollier-diagram-water-d_308.html).

**TABLE 1.** Steam tables (not strictly limited to water vapor) are commonly used by engineers to determine state variables under specific conditions. This excerpt [2] is from a larger set of tables associated with superheated (gaseous phase) water vapor where each table has a different vapor pressure.

T °C	$v^*$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg·K
$p = 0.06 \text{ bar} = 0.006 \text{ MPa}$ ( $T_{sat} = 36.16^\circ\text{C}$ )				
Sat.	23.739	2425.0	2567.4	8.3304
80	27.132	2487.3	2650.1	8.5804
120	30.219	2544.7	2726.0	8.7840

\* specific volume

learned about student thinking and understanding of thermodynamics across disciplines.

## PAST RESEARCH

Physics education research (PER) has been growing and expanding as a field of study. The community of researchers has also grown to include neighboring fields of inquiry. The field incorporates a wide range of research techniques from clinical interviews [4] to individual short-answer questions [5, 6, 7] to large-scale multiple-choice tests [8, 9]. Research in the field includes student attitudes, conceptual understanding, and problem solving, to name but a few, and covers every population from K-12 through graduate students.

Engineering education research (EER) is less developed as a field of study than PER but shares many methodologies, areas of inquiry, and goals. The goals of EER are to attract and retain more students, to deepen student conceptual understanding, and to better prepare them for their role in the global society. Facets of EER include attention to project design and institutional change as well as conceptual understanding and instructional resource development and assessment [10, 11].

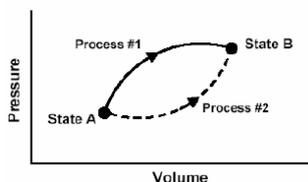
## Physics

Historically, terms such as heat, internal energy and thermal energy were not consistently defined across the disciplines. Teaching and learning are further complicated as the current definitions are not consistent with the concept of heat developed by children [12]. More recent research from the 1980s and 1990s [13, 14, 15] shows that concerns with teaching and student misconceptions were consistent with those from the 1970s [16, 17, 18].

Recent research of student understanding in thermodynamics has been more focused on the application of concepts. In one study [5] students in several different university courses were asked to either determine how the temperature changed or account for the temperature increase which resulted from an adiabatic compression. Many students (58%-100% depending on course) were correctly able to say that the temperature increased, but correct reasoning peaked at 57% for students asked for the cause of the temperature change. Those who were told it increased only had a correct explanation 9% of the time. Analysis of student reasoning showed difficulties with distinguishing heat, temperature, and internal energy. Further difficulties included failure to apply the First Law ( $\Delta U = Q - W$ ), misapplication of the ideal gas law, or general confusion about mechanical work as a mechanism for energy transfer to the gas.

More difficulties with work, heat, and the First Law were also found by Meltzer [7] among upper-division students. He provided students with a  $p$ - $V$  diagram showing two different processes that connected states A and B (Figure 1). After instruction, as many as 30% of the students (depending on sample population) incorrectly used path-independent reasoning for work. More students (33% - 45%) were successful in predicting the heat transfer comparison but fewer (11% - 30%) provided correct reasoning. Among the most advanced students, 10 out of 11 who correctly compared the heat transfers gave an adequate explanation. While it is encouraging that advanced students could more frequently provide correct reasoning for an answer, it is concerning that two thirds of the advanced students had difficulties correctly determining the correct answer in the first place.

The Second Law also poses difficulties for students. In one study [6], pre-instruction upper-division students were presented with descriptions and images (figure 2) of two systems that begin in the same initial state. One undergoes a reversible isothermal expansion and the other undergoes an irreversible free expansion such that they both end in the same final state. Between 55% and 75% of the students (depending on process) successfully determined the sign of the entropy change for both the system and surroundings. Thirty percent correctly concluded that both processes have the same change in system entropy. The post-test question included an additional process (adiabatic expansion) starting in the same initial state. On the post test, more students (75% - 94%) successfully determined the sign of the entropy change for the system and surroundings, but only 44% could correctly rank the three changes in system entropy. The comparison task was clearly the most difficult as it required reasoning beyond determining the direction of heat transfer.



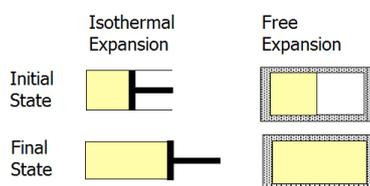
**FIGURE 1.** A task [7] in which students compare the work, heat transfer, and change in internal energy for a system undergoing two different process shown.

## Engineering

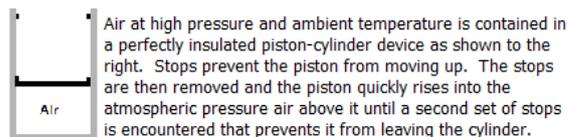
In the early 2000s, a number of engineering education researchers began work on an ensemble of concept inventories [11]. Two of these inventories, the Thermodynamics Concept Inventory (TCI) [19] and the Thermal and Transport Concept Inventory (TTCI) [20] relate to thermodynamics.

The TCI was designed similarly to, and is patterned after, the Force Concept Inventory (FCI) [8], with multiple-choice questions that target specific student difficulties. Questions were generated by authors and colleagues noting common incorrect student ideas while teaching relevant courses. Most of the questions describe a process and ask students to determine whether various state properties increase, remain the same, decrease, or if there is insufficient information. The TCI is available online [21] for use by faculty and researchers, but there do not appear to be any published results from the TCI beyond its early development [19].

The TTCI was developed using a Delphi study to identify key concepts, after which the authors generated or borrowed concept questions. Students participated in think-aloud interviews to test and further develop these questions. The authors of the TTCI have published preliminary results as they worked to modify the inventory into a final form [20]. Some of the questions on the TTCI are paired questions, where the first question asks for the outcome and the second question provides reasoning options. In one question from the TTCI, students were asked to determine which of two methods would melt



**FIGURE 2.** A task [6] in which students compare entropy changes for an isothermal and free expansion between the same two states.



**FIGURE 3.** This figure is adapted from the TCI [19] and is part of a series of questions in which the students must determine if the temperature and internal energy change and if work is done by the air during the expansion.

more ice at  $0^{\circ}\text{C}$ : using one block of hot metal at  $200^{\circ}\text{C}$  or two blocks at  $100^{\circ}\text{C}$ . Comparison of the answer to the first part with the reasoning in the second part revealed a confusion between the total *amount* of ice melted and the *rate* at which it melted. Only 20% of students correctly answered the question with correct reasoning about the total amount melted, while 57% chose answers consistent with reasoning about the rate of melting. Factor- and cross-tabulation analysis of questions on the inventory revealed that students had difficulty differentiating between energy and temperature, steady-state and equilibrium processes, and rate and amount of heat transferred [20].

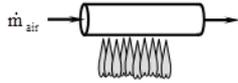
## STUDY DESIGN

This study seeks to compare differences in student conceptual knowledge of thermodynamics across disciplines using existing conceptual questions. We wish to gain as clear a picture as possible of the conceptual content covered and cultural differences between disciplines. We will be collecting data using three different methods: 1) classroom observation, 2) short answer questions, and 3) interviews.

*Classroom observation* provides data in the form of field notes. From these data we will be able to determine time allocation, preferred methods of problem solving, and the general culture of each discipline.

*Short answer questions* provide written explanations from individual students; reasoning can be inferred from the explanations. Research on upper-division student knowledge in physics is often hindered by low numbers. As such, data must either be accumulated over years or between universities. We will be using survey questions from physics that have been used in the past. This has two benefits: 1) the questions have been shown to have some validity and 2) there are several years' accumulation of data. From the engineering community, we will be using questions drawn from concept inventories.

Questions are selected based on what we believe students from both populations will be capable of answering after instruction. For example, Meltzer's [7] Two Process question (Figure 1) is an example of a physics



**FIGURE 4.** A series of questions from the TCI in which the students must determine if the velocity, mass flow rate, energy and entropy of the air changes as it flows through the heated pipe.

question that should be reasonable for mechanical engineers, as both populations have significant exposure to p-V diagrams. However, Bucy's [6] Entropy Comparison question (Figure 2), in which students compare entropy changes in an isothermal and a free expansion, is deemed inappropriate for mechanical engineers since free expansions are not usually part of the introductory curriculum. A series of questions from the TCI [19] (Figure 3), which asks students to find the change in temperature, internal energy and work done by the air in a cylinder during an isobaric expansion, should be very reasonable for physics students. However, another series of TCI questions focusing on mass flow through a heated pipe (Figure 4) are expected to be inappropriate for physics students, since it deals with an open system.

*Interviews* should provide significantly more information about how students in each discipline approach problems. As yet, specific interview protocols have not been developed. Among other ideas, we are considering giving students one of the survey questions that has been deemed inappropriate to see how the students approach it. We may also offer a question typical of the student's discipline to find out what tools are needed to solve it (steam tables, Mollier diagrams, equations, etc). A deeper understanding of the different approaches used by each discipline may offer insight into how we may learn from each other to improve conceptual understanding across all disciplines.

## SUMMARY

Previous research has shown that there remains conceptual difficulty in thermodynamics in multiple disciplines. We intend to broaden the understanding of student conceptual knowledge and strategies used in the larger context of thermodynamics to identify whether discipline-specific themes are evident. Also, by comparing teaching strategies, tools employed, and learning outcomes, we expect these data will be valuable for some if not most of the various disciplines engaged in thermodynamics education.

## ACKNOWLEDGMENTS

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