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Blowing off Steam Tables

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Blowing off Steam Tables

In thermodynamics courses, there is appreciable time and effort devoted to teaching steam tables. Despite this, students still find the ability to use steam tables for retrieving thermodynamic properties a challenging skill to master. The challenges arise from the need to interpolate, the need to identify the correct region, and the requisite familiarity with property trends. The use of steam tables to retrieve thermodynamic properties is often presented to students as a keystone skill for subsequent study of steam power plants. However, if graduates do not require this skill in practice, perhaps we are simply teaching an obsolete system that serves the course objectives but not beyond. Several compelling alternatives exist. Among them, computerized thermodynamic property databases for common substances are readily available and can rapidly supply state properties. However, we want to avoid tools that simply supply property values without reinforcing thermodynamic fundamentals. For instance, steam tables can supply accurate property values, but they fail to emphasize the interdependence of these properties. Instead, the use of property diagrams to solve thermodynamic problems can greatly improve students' understanding of thermodynamics by visualizing property relationships. As a highly visual and intuitive tool, property diagrams eliminate the time devoted to mastering steam tables. After teaching steam tables for multiple years within a year-long thermal-fluid sciences course and recognizing the poor pedagogic utility, the steam tables were entirely replaced by the temperature-entropy (T - s) diagram as the primary source for water thermodynamic properties. This paper discusses the implementation, challenges, and the outcomes of this introduction. Apart from developing instructions aligned solely to property diagrams, a number of visual tools were identified, adopted, and developed to facilitate the transition. The overall outcomes were notably positive from a student learning perspective. Students quickly became comfortable using the T - s diagram to solve the same textbook problems they would have solved using steam tables. The loss of accuracy was more than made up by their ability to quickly identify a state and retrieve its properties. Furthermore, students improved their ability to predict property trends when compared to students who relied primarily on steam tables. The results highlight the need for change in thermodynamics pedagogy by abandoning steam tables and emphasizing the fundamentals necessary to study steam power plants.

Introduction

Mixed-phase systems are ubiquitous in the world of power production, refrigeration, and chemical reactions. The analysis of processes and devices that use mixed-phase systems (specifically, Rankine Cycle components) is dependent on defining the thermodynamic properties of the state. Water is of particular interest due to its use in steam-based power generation and the thermodynamic properties of water have been tabulated within appendices in thermodynamics textbooks as “Steam Tables”. These steam tables are familiar to nearly every student of engineering thermodynamics courses and, indeed, instructors routinely require the use of steam tables to determine state properties of water-based systems and compute quantities such as a change in enthalpy, h , or cycle efficiency. Additionally, steam tables can also be used to quantify the quality, x , of steam for a saturated state.

Given that the tables can provide precise property values, they can be particularly cumbersome and, at times, challenging to use. The challenges arise from the need to interpolate for states at intermediate values, define quality x within the saturated regions to compute other properties, and recognize the property trends within the saturated and superheated regions. Therefore, students often resort to computerized tables that swiftly deliver accurate state properties without the aforementioned requirements from students. In doing so, students regularly struggle to recognize the interdependent nature of the thermodynamic properties and the subsequent property trends that are fundamental to the study thermodynamics. This fundamental skill can be restored by using detailed property diagrams that help visualize the steam tables. In fact, one can argue steam tables seldom reinforce property relationships and trends; whereas property diagrams inherently focus on the trends to define states. For instance, the ideal gas behavior of steam is clearly visible from the horizontal enthalpy lines on the far right of the vapor dome on a Temperature-Entropy (T - s) diagram. This trend, however, is not evident when using steam tables.

Additionally, the ability to have a mental image of how various thermodynamic properties are affected by one another is likely to improve conceptual understanding. It is well established that visual representation of concepts improves cognitive retention of those concepts^{1,2}. Additionally, visual representations can increase the cognitive efficiency of interacting with a concept over more tabular representations^{3, 4} meaning that less cognitive load is required when a visual representation exists. Providing students with a visual representation of a complex concept like the thermodynamics of steam is, therefore, likely to not only help them remember how various properties change with temperature or pressure, but also improve their ability to solve problems related to these concepts. Indeed, several authors have highlighted the importance of visual representations of thermodynamic data in courses ranging from chemistry^{5, 6} to mechanical engineering^{7,8,9}.

This work and the impact study herein attempts to highlight the advantages of eliminating the use of steam tables and subsequent replacement with traditional property diagrams. Instructional implementation is presented to encourage adoption of this approach.

Background

The implementation was conducted within the yearlong Thermal-Fluid Science (TFS) course series developed at Rowan University. The course series and the relevant components are briefly described here to provide context to the introduction of property diagrams and the subsequent impact study. The outcomes and the conclusions of this work apply to any undergraduate engineering thermodynamics course, and not just to an integrated approach presented here.

Thermal-Fluid Sciences (TFS) Course Series

In the Rowan University Mechanical Engineering (M.E.) department, the discrete courses of thermodynamics, heat transfer, and fluid mechanics were integrated into a yearlong 12 credit Thermal-Fluid Sciences course series: Thermal-Fluid Sciences I course (6 credit hours) offered in the Fall semester and Thermal-Fluid Sciences II (6 credit hours) course offered in the Spring semester. A total of 4 credit hours over the year are dedicated to Practicum, where students apply their thermal-fluid sciences knowledge to design, test, and solve hands-on engineering design problems. Past projects have included an air engine design, air cannon design, solar air heater design, and Computational Fluid Dynamics (CFD) design study of racecar aerodynamics. The focus on design projects as opposed to experiments has yielded Practicum as the most popular aspect of this course, based on student feedback.

Course Textbook

Stephen R. Turns' *Thermal-Fluid Sciences: An Integrated Approach*¹⁰ was selected as the textbook for the entire course series. Turns' book was selected after reviewing multiple textbooks that attempt to combine the traditionally discrete subjects into a single course. Most textbooks or their combinations failed to fully integrate thermodynamics, heat transfer, and fluid mechanics into a coherent subject; rather the collated sections produced a disjointed reference. Turns' book focusses on the conservation principle to produce a coherent text. Additionally, the text is student-friendly, providing relevant history and examples to contextualize learning. Overall the textbook was well aligned with the philosophy of TFS.

Nevertheless, Turns' book like most other thermodynamics textbooks relies on steam tables for water properties. As a result, the instruction, homeworks, and assessments were designed to use the steam tables as the primary source of water thermodynamic properties. Adopting property diagrams as the primary source of water properties meant revising the instruction, homework solutions, and the assessment to reflect the change.

Implementation

Instruction using Steam Tables

Thermodynamic properties of mixed phase substances typically follow a complete treatment of ideal gas behavior. Within the discussion of ideal gas behavior, the thermodynamic properties of Pressure P , Temperature T , Density ρ , Specific volume v , internal energy u , and enthalpy h are introduced. Water undergoing boiling at atmospheric pressure is used to demonstrate the existence of mixture phase with liquid and vapor phases coexisting. The mixture quality x is defined to quantify the extent of phase change. A T - v diagram, such as Fig. 1, is effective for depicting the constant temperature phase change processes at different pressures, leading to the familiar vapor dome. This depiction is important to contextualize the property regions before introducing the steam tables. Because the steam tables serve as the primary source for retrieving the properties when solving problems, the T - v diagram is a convenient visual aid to highlight the discrete regions that divide steam tables. Students must recognize these regions before retrieving water properties. They then spend a considerable time familiarizing themselves with the procedure of reading states from the steam tables. Often students struggle to recognize the continuous nature of the properties through the various regions; and furthermore tediously interpolate to acquire precise values for the intermediate states. Apart from in-class assessments (quizzes, tests, or examinations), students typically avoid steam tables to solve problems. They prefer to use online databases or other computer-based applications to quickly retrieve properties, such as the NIST thermophysical property website¹¹, IRC Fluid Property Calculator¹², or Engineering Equation Solver (EES) software¹³. This exercise, in turn, weakens their comfort with the use of paper-based steam tables, especially for assessment purposes.

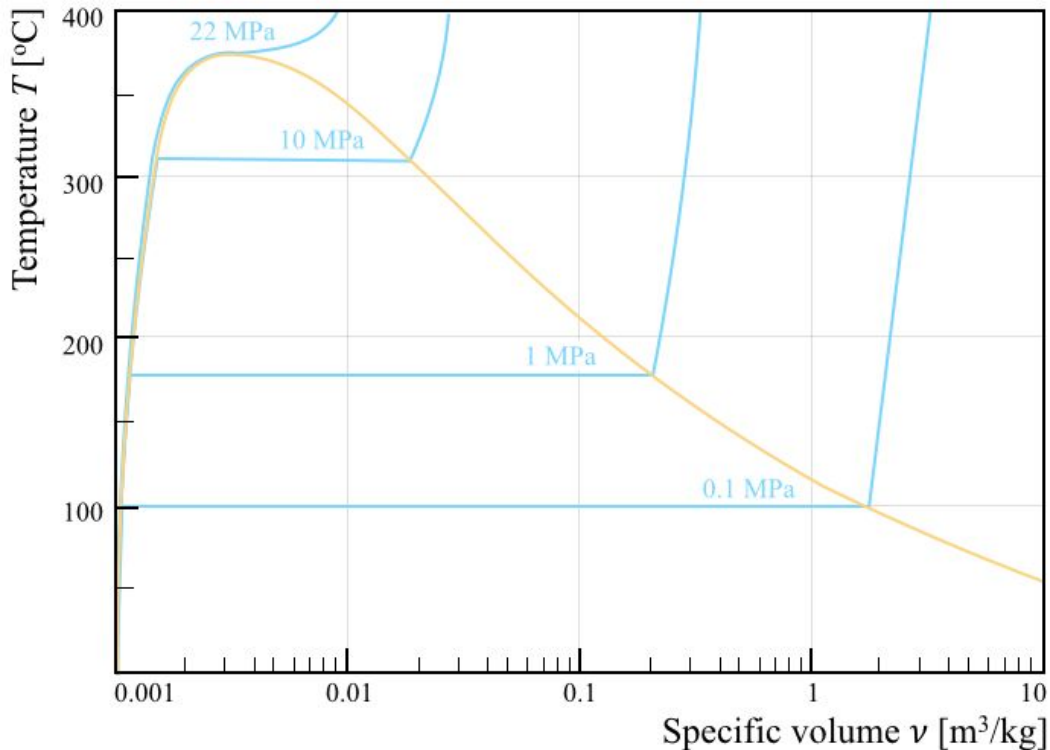


Figure 1. T - v property diagram depicting constant pressure lines.

Instruction using Property Diagrams

To provide continuity with the visual approach that began with the T - v diagram discussion, for the Fall 2016 term of the Thermal-Fluid Sciences course, an alternative approach was adopted. After presenting the T - v diagram for water, entropy s was introduced as ‘yet another thermodynamic property to be discussed later in detail’. Students were simply informed of entropy’s importance in defining the efficiency of a process or a cycle. Considering, entropy s is a thermodynamic property, the students were shown a T - s diagram (such as Fig. 2), with notably familiar features to the T - v diagram presented earlier. For the moment, students were asked to focus on the known properties. Upon discussing the general trends, a detailed T - s diagram for water was shared from Cengel, *et al.*, *Property Tables Booklet*¹⁴. This diagram maps constant P , h , ρ , and x lines at regular intervals. A simplified T - s diagram with relevant trend lines is presented as Fig. 3 for illustration purposes. The detailed T - s diagram was used to illustrate how each point on the diagram represents a thermodynamic state with unique set of properties. Properties that can be retrieved directly from the T - s diagram. The gradual introduction was intentional to promote familiarity with the information dense property diagram.

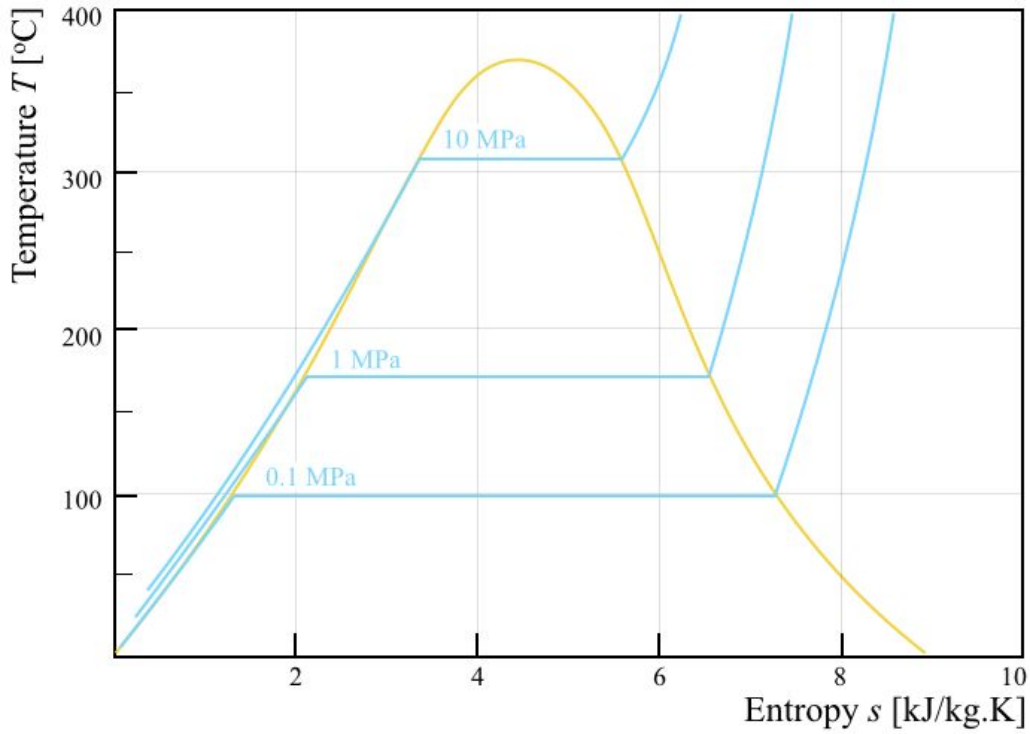


Figure 2. T - s property diagram depicting constant pressure lines.

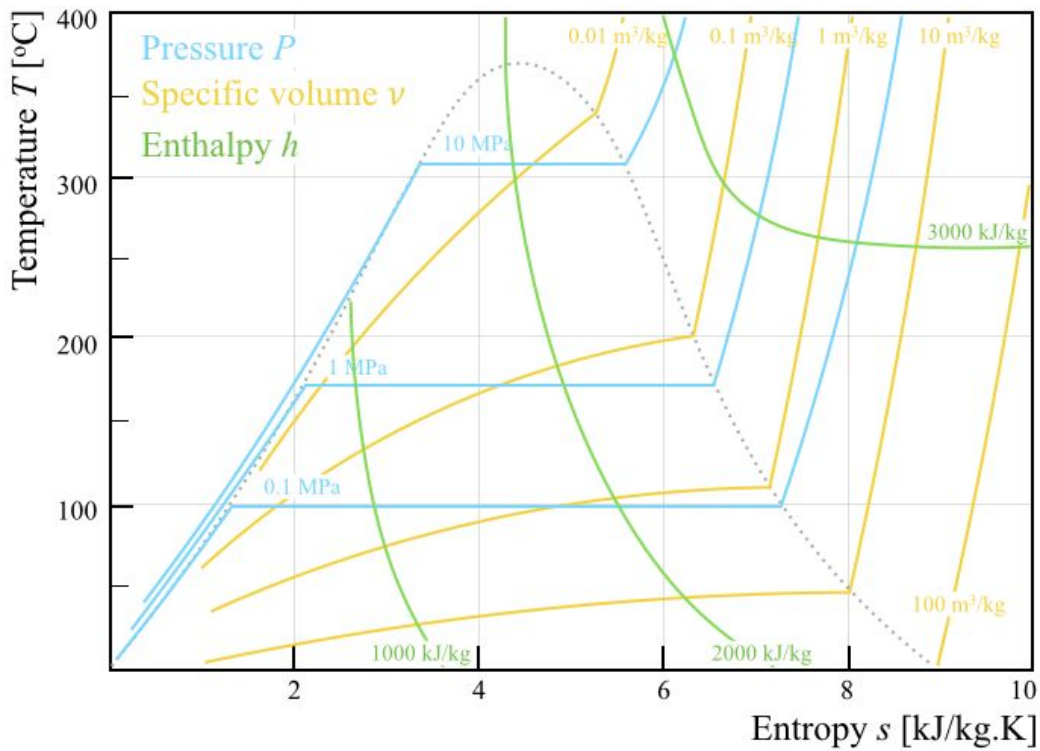


Figure 3. T - s property diagram with constant pressure P , specific volume v , and constant enthalpy h lines.

Supplementary Materials

To reinforce the concept of state properties on a property diagram, *Clausius* mobile application that was developed by the author, was utilized^{15,16}. *Clausius* provides real time property values across property diagrams simply by gliding your fingers across a $T-s$, $P-h$, and $P-v$ (see Fig. 4). In a previous study, the *Clausius* app has been shown to enhance students' comfort with thermodynamic property trends over students relying on steam tables⁹. Students were encouraged to download the app for their Apple iPads to explore the trends. However, due to the limited access to iPads, the app was not a required tool. Instead, the analog version of the $T-s$ diagram was selected as the primary source.

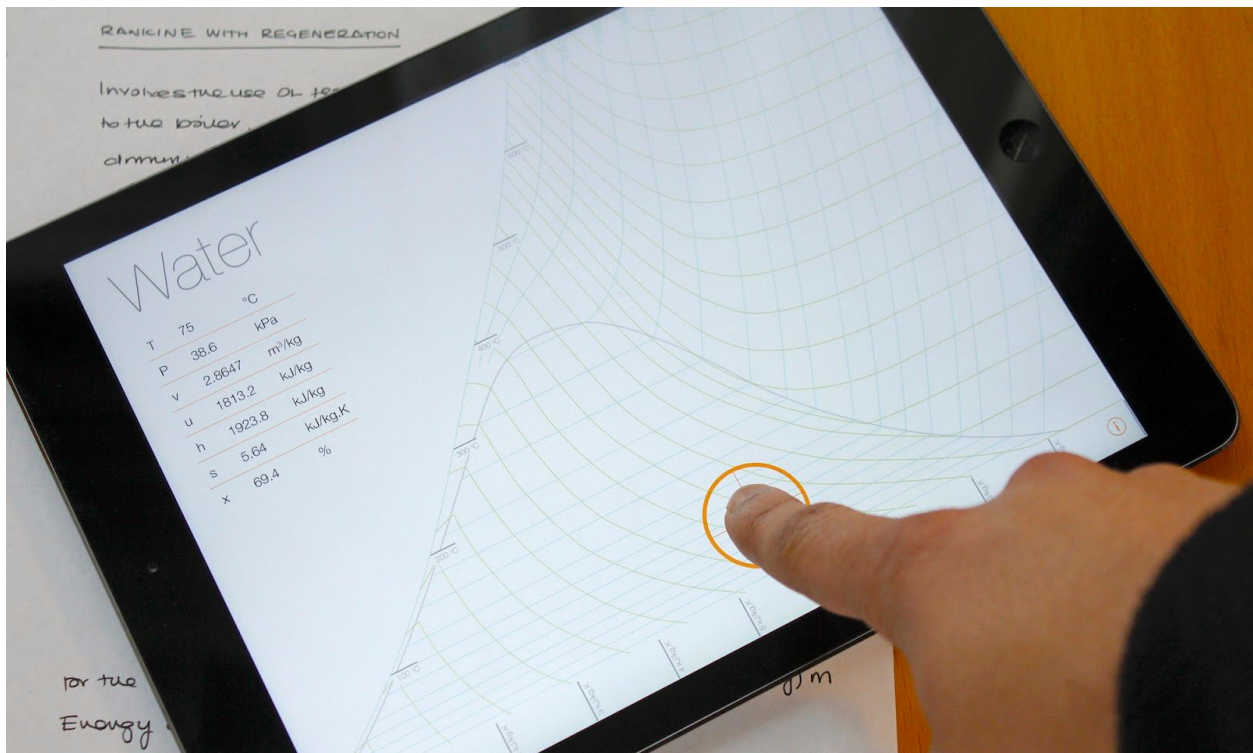


Figure 4. A photo of the Clausius mobile app used to reinforce the interdependence of thermodynamic properties in real-time.

A course reference manual (similar to the *Fundamentals of Engineering Reference Manual*) that included the detailed $T-s$ diagram and relevant equations was shared. Students used the reference manual for solving homework problems and during assessments. Following property diagram introduction, sample problems were solved using the reference manual and compared to the steam table values to highlight the approximate nature of using the $T-s$ diagram. Students were

simply shown how the steam tables were organized. However, students were requested to use the T - s diagrams exclusively to solve problems for homework assignments and assessments.

Finally, a custom T - s diagram T-shirt was designed for each student to wear and become familiar with the property diagram. The T-shirt was meant to serve as a visual anchor to reinforce the property trends. Wearing the T-shirt was optional. Figure 5 is a photo of the TFS section wearing T - s T-shirt.



Figure 5. A photo of the M.E. TFS section wearing the T - s diagram T-shirt.

Impact Study

The lecture time dedicated to the alternative introduction of property diagrams was relatively equal to the traditional approach using steam tables. Anecdotally however, the students became comfortable relatively quickly with property retrieval using property diagrams and performed better on the assessment related to the water properties. Since there are several factors that could have influenced these outcomes, a study was designed to assess how the reliance on steam tables versus property diagrams impacted the students' ability to recognize property trends. As stated previously, steam tables do not explicitly reveal property trends and the inherent interdependence of thermodynamic properties the way property diagrams do. As a result, property diagrams serve

as a better instructional tool than steam tables by providing contextual information to the user as they retrieve properties. To test this hypothesis, a control section of a Chemical Engineering (Ch.E.) thermodynamics course was selected to compare with the Mechanical Engineering (M.E.) TFS treatment section. The control section primarily used steam tables to determine state properties and the treatment section primarily used the property diagrams.

The study was scheduled for the end of the Fall 2016 term to make sure both sections were familiar with the general concept of entropy s . Both the control and the treatment section were presented with a problem involving a T - s diagram sketch shown in Fig. 6. They were asked to predict how T , P , v , h and s properties change as the green or the red dot moves from their starting positions to the two numbered positions (1 and 2 for the green dot and 3 and 4 for the red dot). The students had the option of selecting “increases,” “decreases,” “remains the same,” and “not enough information” as their predictions. If the hypothesis was correct, students in the treatment section would be better at predicting the evolution of properties as the dots move to the labeled positions. Conversely, students who relied on steam tables would find it challenging to predict the change due to the steam tables’ inherent focus on the numeric property values. Following the assessment, a brief survey was conducted to solicit feedback from the students about the implementation.

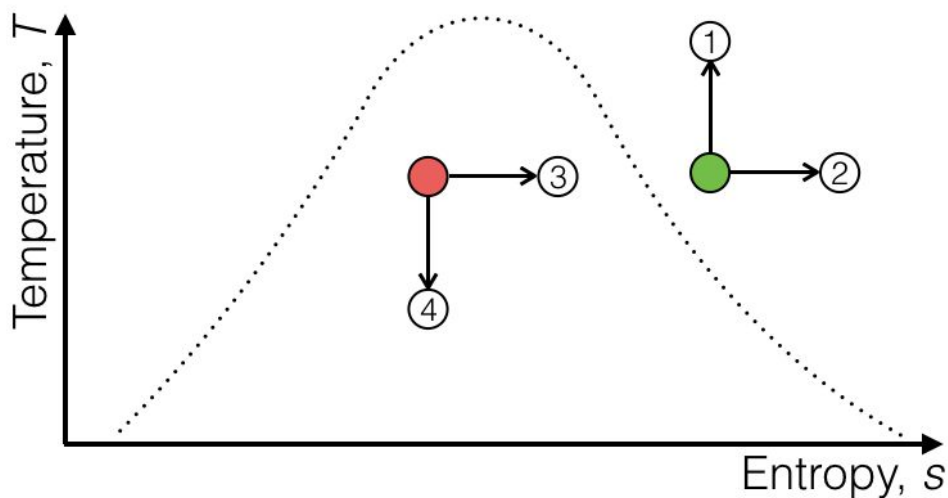


Figure 6. T - s sketch associated with the assessment problem. Students were asked to how the properties changed as the two dots moved to the labeled positions.

Results and Discussion

While the instructional revision was minimal, the changes to the homework problem solutions and the corresponding assessments were somewhat more involved. The changes primarily involved revised numeric solutions to allow for the inaccuracies associated with reading the property diagram. Yet these revisions were insignificant overall. The instructor’s observation of

student attitudes and outcomes towards the property diagrams have been reported elsewhere¹⁷. In general, students quickly became comfortable with the T - s diagram, often drawing processes directly on the property diagram handout. This is a practice that will directly assist them while analyzing the Rankine cycle and its modifications later in their coursework. More importantly, the students were notably familiar with the property trends on the T - s diagram. Thus, the following study is an effort to quantify this observation and provide a more compelling reason to abandon the steam tables.

Impact Study

The study was conducted using Google Forms to collect responses from the control section ($N = 22$) and the treatment section ($N = 35$). Students worked independently and without any other external resources (without steam tables or property diagrams, respectively) to respond to the questions on their personal smartphones. The responses were collected anonymously and analyzed for correctness. Percent correct predictions were averaged for each section. Figure 7 presents the mean scores from the control and treatment sections. In addition, the associated p -value was calculated to be less than 0.0001, suggesting the treatment group performed statistically better than the control group.

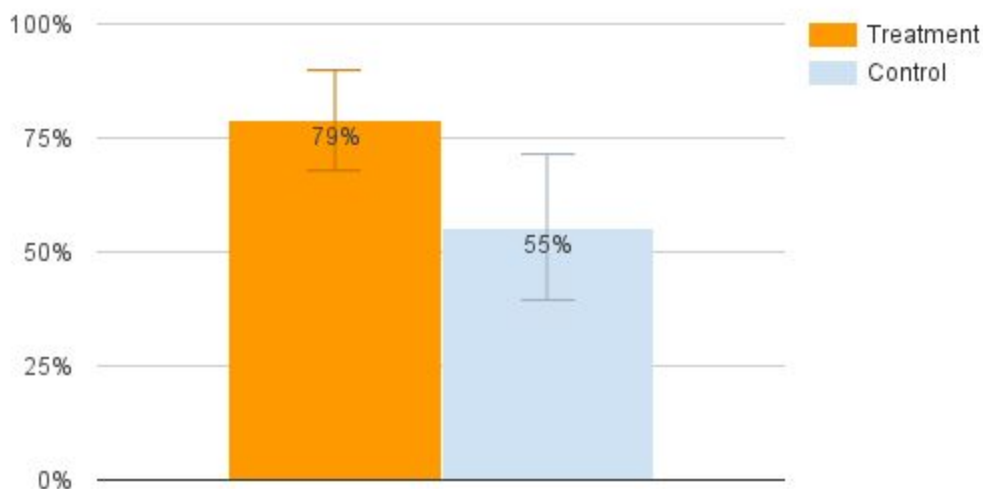


Figure 7. Comparison of mean scores from the control and treatment sections. Error bars represent standard deviations.

The difference in the treatment section's ability to predict is even more defined when considering properties that are not mapped to the axis (such as T and s). It is also important to note that the Ch.E. Thermodynamics students were introduced to the thermodynamics properties within a previous Ch.E. course and were studying the properties again in their current course, whereas for the M.E. students the Fall term of TFS was their first detailed treatment of thermodynamic properties. Therefore, the results conclusively demonstrate the power of property diagrams to

reinforce property trends over steam tables while serving as an equally effective property retrieval tool.

Student Feedback

Based on the design of this study, it is difficult to objectively compare student perceptions of using steam tables over property diagram, since neither sections used both tools concurrently. However, in an attempt to gather students insights on the new tool the treatment group students were asked to rate their attitude towards the use of property diagrams. Table 1 presents a summary of four ratings-based and two open-ended questions that were asked at the end of the assessment. For the open-ended questions, the student responses were reviewed for general themes, and each response was tagged with corresponding themes. The tag frequencies were translated into percent weights and are reported in Table 1.

Table 1. Summary of student feedback questions and the corresponding ratings.

Question	Question Type	Mean Rating
Rate your comfort with using the property diagram when solving problems.	Rate 1 for Not Comfortable to 5 for Very Comfortable	3.4 ± 0.7
Rate your frequency of using steam tables instead.	Rate 1 for Never to 5 for Always	2.5 ± 1.3
Rate your preference for using property diagrams over steam tables.	Rate 1 Not Preferred to 5 for Highly Preferred	3.6 ± 1.3
How would you rate your attitude towards the Water T-Shirt?	Rate 1 for Very Negative to 5 for Very Positive	4.1 ± 0.9
In what ways, do you think the property diagrams help you?	Open-ended	44% Visualize 19% Rapid retrieval 14% Recognize trends 14% Property relations 8% Other
Are there any other comments related to the use of property diagrams?	Open-ended	82% Too inaccurate 18% Information dense

In general, the Table 1 summary suggests the students did not embrace the use of property diagrams with the same enthusiasm as suggested by the positive assessment outcome. The mean ratings for their comfort (3.4 out of 5) and preference (3.6 out of 5) towards the property tables is

relatively low, despite being positive. These results can be explained by their response to the second open-ended question requesting general comments. Students were overwhelmingly (82%) concerned with the accuracy of their answers when compared to either the textbook supplied answers to the homework assignments or the course assessments (quizzes). Below is a representative response highlighting this sentiment:

“Overall I like them, it's difficult sometimes though to get precise answers, which can make doing the homework sometimes difficult to get the right answers”

In fact, to gain some comfort with their calculations some students checked their responses using the steam tables, as indicated by the slightly higher rating (2.5 out of 5) for their frequency of using the steam tables. The outcome stems from the approximate nature of values obtained from property diagrams when typical thermodynamics problems provide a singular value with high precision. This phenomenon can be easily mitigated by recognizing and emphasizing the approximate nature of thermodynamic analysis; and intentionally providing a less precise numeric solution. The approach clearly works when solving problems involving the Moody diagram for friction drag f_D and the Drag Coefficient C_D for Cylinders and Spheres within fluid mechanics. Therefore, students' comfort with the property diagrams can be readily addressed with minor changes to how the problems are presented. It is also likely that their preference for property diagrams will improve once the power cycles are analyzed directly on the T - s diagrams for the Spring term. The strongest positive response was garnered by their attitudes towards the T - s diagram T-Shirts (with a rating of 4.1 out of 5). This was also evident from the fact that students often wore the T-Shirts outside the TFS course. The direct impact of the T-Shirt on their ability to correctly predict the property trends is challenging to assess. Based on individual discussion however, some students felt a sense of comradery in their quest to master this challenging subject by wearing the T-Shirt. Notably, the students felt the T-shirt should become a tradition for the TFS course.

When asked how the property diagrams helped the students, the responses highlighted the key strengths of property diagrams over steam tables. A majority of the students felt the property diagrams helped them *visualize* properties of water, thermodynamic processes, and cycles. Students sensed they were able to *quickly retrieve properties* using property diagrams. The rest of the responses acknowledged the property diagram's ability to demonstrate *property trends* and the *property relations* that steam tables fail to deliver. The following are representative responses for the themes identified.

“I'm a visual person. I'd rather follow lines on the diagram to find my properties.”

“They're usually quicker to find information than the tables.”

“They help understand general trends for cycles and how things will change.”

“They allowed me to understand the relationship of the properties and if something were to change I would be able to find the change in multiple properties.”

Furthermore, a second section of Mechanical Engineering TFS was surveyed with a separate instructor (that did not use property diagrams). This section was not included in the assessment results, recognizing the students had yet to be introduced to entropy s . Therefore, for this section the T - s diagram assessment had to be altered making a direct comparison challenging. Nevertheless, these students were asked to comment on the use of steam tables within thermodynamics. A majority preferred Engineering Equation Solver (EES) or IRC Fluid Property Calculator to retrieve properties and solve problems over using steam tables, as the following representative response confirms.

“Steam tables are unnecessary with the advent of computers. Things like EES and the IRC calculator provide much more accurate answers and remove the need for interpolation. In a real application I would never use a steam table when I have access to such computerized resources.”

These students highlight an important deficiency in using steam tables: they are tedious to use compared to computer-based alternatives. However, the authors would argue that direct replacement of steam tables with these alternative (like EES) before reinforcing the trends, property relationships, and the ability to grossly predict property changes can prove disadvantageous from a pedagogical standpoint. These are fundamental thermodynamics problem-solving skills and need to be emphasized before embracing computerized alternatives. The recommendation is analogous to the use of CFD packages within Fluid Mechanics courses. Almost all undergraduate level problems can be solved using CFD packages, yet we use empirical correlations and their corresponding diagrams (e.g. Moody and Drag Coefficient diagrams) to learn to estimate the results for simplified geometries before embarking on a detailed analysis. Thermodynamic property diagrams provide students with an opportunity to quickly estimate an outcome of a thermodynamic process and, in turn, establish the general trends and relationships. Then, when they move to a more complicated analysis, these fundamentals guide their ability to evaluate their analytical outcomes. Therefore, if accuracy is sought in thermodynamic analysis, then a software solution is ideal to supply state properties. On the other hand, if our objective is to develop proficiency in simplified thermodynamic analysis, then property diagrams are highly effective visual tools. The reliance on steam tables simply encourages students to seek alternatives that are not conducive to their learning thermodynamics fundamentals.

Conclusions

Here we propose replacing steam tables with property diagrams to solve simple thermodynamics problems involving water as a working fluid. Through this work, we have shown that students seek alternatives to steam tables, which are seen as tedious and archaic. However, without an effective steam table alternative, students naturally gravitate towards computerized alternatives, which are even further removed from thermodynamic fundamentals than the steam tables themselves. The property diagrams used in this work acted as visual anchors for students allowing them to develop a conceptual understanding of the thermodynamic properties tabulated in steam tables. The results presented here show that the use of property diagrams reinforces not only the property trends and relationships, but also the students' ability to predict changes in these properties within a process. From an instructional standpoint, property diagrams provide a more natural transition to property retrieval without overhauling the current practices.

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