



## A Visual Approach to Teaching Properties of Water in Engineering Thermodynamics

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### ABSTRACT

Overcoming the challenge of using the steam tables can be considered a rite of passage in undergraduate thermodynamics courses. Students often circumvent the use of steam tables and resort to simpler digital alternatives to retrieve properties. In fact, the steam tables and their digital relatives that supply numeric property values fail to reinforce the fundamentals; namely, how state properties are related to each other. Supplying state properties without context adds to the abstractness of water properties which lack a simple equation of state. Instead, research has demonstrated that replacing the steam tables with property charts can greatly improve student's ability to visualize property relationships and facilitate the creation of a mental model of the complicated equation of state for water. Recognizing these results, the traditional use of the steam tables for property retrieval was entirely replaced by property charts for an engineering thermodynamics course. To leverage the highly visual nature of the property charts, animated videos and related multimedia resources were produced and used in a flipped classroom setting for instruction. This new implementation greatly reduced instructional load and allowed deeper engagement with the concepts taught. The new instructional practice was evaluated by a controlled impact study and student feedback. The evaluation study showed that the students who used property charts as their primary reference were significantly better at predicting water property trends when compared to students who relied on the steam tables accompanied by property chart sketches. When surveyed, students favored property charts and the supplementary videos for their ability to visually convey the complex relationships. The results support existing research and make a strong case for revising thermodynamics pedagogy within engineering. By embedding an intuitive and evidence-based approach to teach the engineering fundamentals, educators can ensure that students are better equipped for professional practice.

**Key words:** Engineering Curriculum, Visualization, Instructional Design

**INTRODUCTION**

Almost all engineering thermodynamics textbooks in use today include some form of tabulated properties of water, also known as the steam tables. The steam tables present various thermodynamic properties as a function of pressure  $P$  and temperature  $T$  across multiple tables of data conventionally divided by phases. Instructors teach how to identify the appropriate tables and use them to retrieve properties; eventually to study the Rankine Cycle. While the Rankine Cycle is an important application within power generation, the table-based retrieval of properties presents a notable hurdle for students and instructors alike (Balmer & Spallholz, 2006; Hagge, *et al.*, 2017). Instructors have to dedicate a lecture or more elaborating on the mechanics of property retrieval from the steam tables including a reminder on how to interpolate. Instructors value this exercise either due to engineering tradition or to train students for the *Fundamentals of Engineering* (FE) exam that continues to rely on a more limited version of the steam tables (Dixon, 2001; Miller, 2007). Students who struggle with using the steam tables quickly turn to other available resources to solve thermodynamic problems involving water. These alternatives come in the form of a computer application (e.g., Taylor, *et al.*, 2008 & EES), web-based tool (e.g., NIST Webbook, IRC Fluid Property Calculator, & SmoWeb Property Calculator), or a mobile app (e.g., International Steam Tables & Steam Tables). These digital relatives of the traditional paper-based steam tables promptly deliver the unknown property given two known properties of a state and are commonly used in engineering practice. Whether the students use the paper-based steam tables or its digital cousins, *what value does property retrieval process add to the student understanding of the concepts?* The retrieval process presents the user with a single set of values pertaining to a state point. The outcome is analogous to supplying GPS coordinates without a map to go along with it. The context matters for a deeper connection with the data presented. For instance, given a thermodynamic state, can the students predict how these properties will change if the temperature is increased? Going back to the GPS analogy, if one moves north, how does the elevation change? An accurate mental model captures the relationships and the overall trends. The relationships between the thermodynamic properties is far more important and fundamental than the exact state values. The relationships facilitate development of engineering intuition necessary to examine computer generated models.

The ideal gas law provides an explicit equation of state. The  $Pv = RT$  equation is a fundamental concept when discussing processes involving ideal gases within engineering thermodynamics. The ideal gas relationship between the thermodynamic properties of specific volume  $v$  as a function of pressure  $P$  and temperature  $T$  is functionally apparent and forms a key learning outcome for any thermodynamic course. The ideal gas law augments the intuitive understanding of how



gases behave. However, when switching the fluid to water, the property values are emphasized over the relationships due to the complex relationships hidden behind the steam tables. The relationships between the various properties is not obvious with the presence of phase change (e.g. boiling) occurring within typical engineering conditions. As a result, students often fail to develop an intuitive understanding of water property relations. Later in engineering careers, the intuitive deficiency can manifest itself through an over reliance on the computer generated models. Therefore, there is a need to emphasize property relations for water similar to the treatment of ideal gases.

In lieu of a simple mathematical relationship between the thermodynamic properties of water, property charts serve an important purpose by allowing students to visualize processes and cycles. Engineering students are already encouraged to sketch their cycles on temperature-entropy ( $T$ - $s$ ) charts and to study various modifications of the Rankine Cycle. Such property chart sketches are useful for highlighting how most ideal engineering processes follow constant property lines such as isobars and isotherms. However, without connecting these sketches to the property values, students fail to recognize the interdependence of thermodynamic properties. Rather than relying on supplementary function of the property charts, it would greatly benefit the students to use the property charts for property retrieval as well. Using property charts this way not only allows students to retrieve state properties from a single chart but also contextualizes the state with respect to other relevant parameters surrounding the state (Dixon, 2001). Students can quickly recognize how the properties will evolve if one of the property changes by navigating the two-dimensional chart. Repeated use of property charts for instructional purposes allows students to develop a mental map of water properties and reinforce the inherent relationships, even in the absence of an explicit equation of state. And, considering the vast majority of thermal design and analysis within engineering practice relies heavily on computational resources, such maps serve as mental checks for the advanced modeling outcomes. Therefore, developing an intuitive understanding of water property relations is an important student learning outcome for an engineering thermodynamics course.

This work focuses on effective implementation of property charts within thermodynamics instruction to reinforce water property relations. Instructional framework and relevant tools are presented to facilitate adoption of this visual approach and advance thermodynamics instruction to match the current educational needs. The implementation is evaluated: (a) directly with an effectiveness study that highlights the advantages of eliminating the use of the steam tables and subsequent replacement with property charts, and (b) indirectly with student feedback on the practice. The outcomes are overwhelmingly positive and easily transferable to motivate broad pedagogical change within engineering thermodynamics.



## BACKGROUND

Liu and Stasko (2011) and Purchase, *et al.*, (2008) document numerous studies in the broad field of information visualization that demonstrate the utility of graphs in developing internal representations or mental schemas. Imagine providing the original tabulated values generated by Johann Nikuradse (1894-1979) for internal pipe flow in fluid mechanics instead of the now ubiquitous Moody Chart first presented by Lewis F. Moody in 1944. Within thermodynamics, psychrometric charts are extensively used to study moist air processes for HVAC applications (Baughn, 2007). Both these examples forgo accuracy for convenience and improved learning outcomes (Manteufel, 2013). The traditional reliance on the steam tables was justified in the absence of computer-based data. With readily available data, there is a need to reevaluate the utility of steam tables in the modern age and identify the fundamental knowledge that we wish to impart. Rather than focusing on the exact values, we must refocus our attention on the property relationships. Specifically, visual relationships with predictive potential to develop technical intuition.

A graphical approach to thermodynamic properties of water has been advocated by a number of other educators including Urieli (2010) and Maixner (2006). Pfothenauer, *et al.*, (2015) for instance, developed a 3D game that uses the pressure-specific volume-temperature ( $PvT$ ) space to visualize the inter-dependence of properties. Even so, these tools perform supplementary functions and are challenging to adopt without an instructional framework. The instruction of thermodynamic properties of water still broadly relies on the steam tables. The prevalence of steam tables can be attributed to their seamless integration within textbooks and the lack of effective instructional approach using property charts. Additional challenge to the adoption of property charts comes from the use of steam tables within the FE exam. To counter that we must recognize the FE exam already relies exclusively on the pressure-enthalpy ( $P-h$ ) property chart for refrigerant R-134a to solve refrigeration problems; at the same time supplying the tables to solve steam problems. Our own research has shown that students using water property charts are able to internalize property trends (Bakrania and Carrig, 2016), predict changes in properties (Bakrania and Mallouk, 2017), and perform better on engineering problems involving steam as a working fluid (Bakrania and Haas, 2019). This body of evidence must be translated into engineering education practice that is easy to adopt and fit the existing instructional content.

## METHODOLOGY

Building on the past research studies and instructional design, a new instructional practice was developed and implemented; a blended-learning approach was adopted. A variety of supplemental



tools were used to enhance student engagement with the new alternate content. Later, the effectiveness of property charts to help students develop a better mental model of property relations was studied by assessing the students' ability to predict property changes.

### **Instructional Implementation with Property Charts**

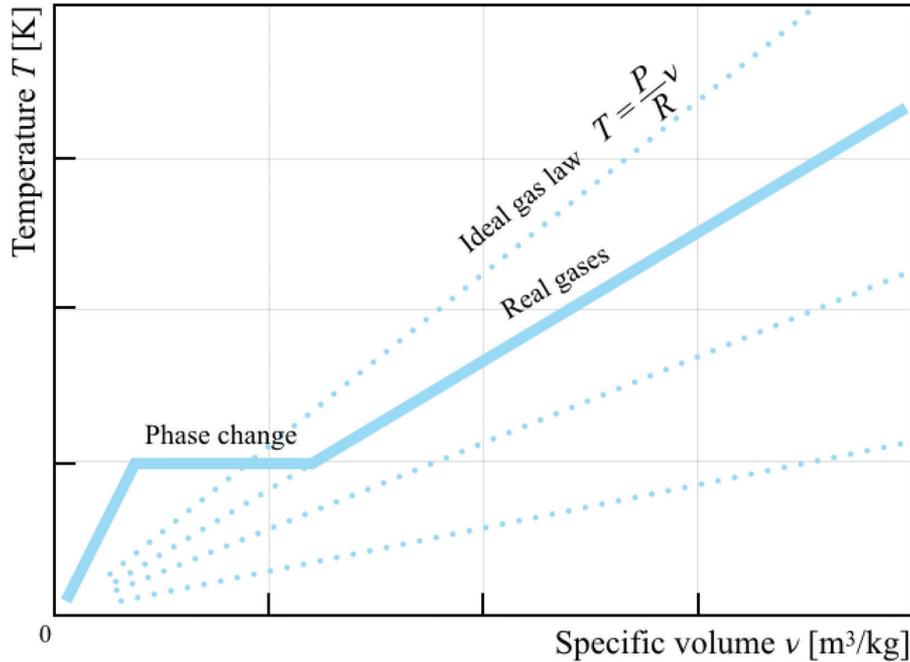
The instructional redesign focused on effective integration of property charts across multiple topics within thermodynamics courses. The integration addressed three distinct objectives: (a) introduce property charts using the ideal gas model, (b) use the property charts to bridge the ideal gas equation of state (EOS) with the phase change behavior of water, and (c) deliberate practice of property retrieval using property charts for all subsequent topics. Considering the highly visual nature of the content, instructional videos were produced to incorporate the dynamic features of the water property chart construction. This aspect naturally paved way for a flipped classroom setting and further reduced instructional burden. The flipped classroom arrangement allowed more classroom time to be spent on practice. The details of the instructional design are discussed broadly below for a traditional lecture. Importantly, several resources, including the animated videos that explain each concept, are publicly available for review and adoption.

#### ***The Ideal Gas Model***

As with most engineering thermodynamics instruction, the ideal gas model is one of the primary topics of discussion that provides a crucial bridge to the discussion of phase change within water. With the ideal gas model, students become familiar with the concepts of properties, states, and processes. For the new implementation, the ideal gas equation of state,  $Pv = RT$ , was deliberately presented on a two-dimensional  $PvT$  space, or the property charts ( $P$ - $v$ ,  $T$ - $v$ , and  $P$ - $T$ ). Ideal gas processes involving change of states were also depicted on property charts. It was important to emphasize the clear connection between the simple mathematical EOS and its two-dimensional representation on a property chart. In other words, each point on the property chart is a manifestation of the underlying  $Pv = RT$  relationship. This relationship was considered a fundamental concept when discussing processes involving ideal gases.

#### ***The Bridge***

Next, the limitation of the ideal gas model is presented using the temperature-specific volume ( $T$ - $v$ ) chart, specifically highlighting how real gases behave with phase change on a property chart. Figure 1 presents a key-frame schematic contrasting the ideal versus real gas condensation behavior used to introduce properties of water. This schematic demonstrates that as an ideal gas is cooled, the model relationship predicts smaller and smaller volume occupied by the gas until the

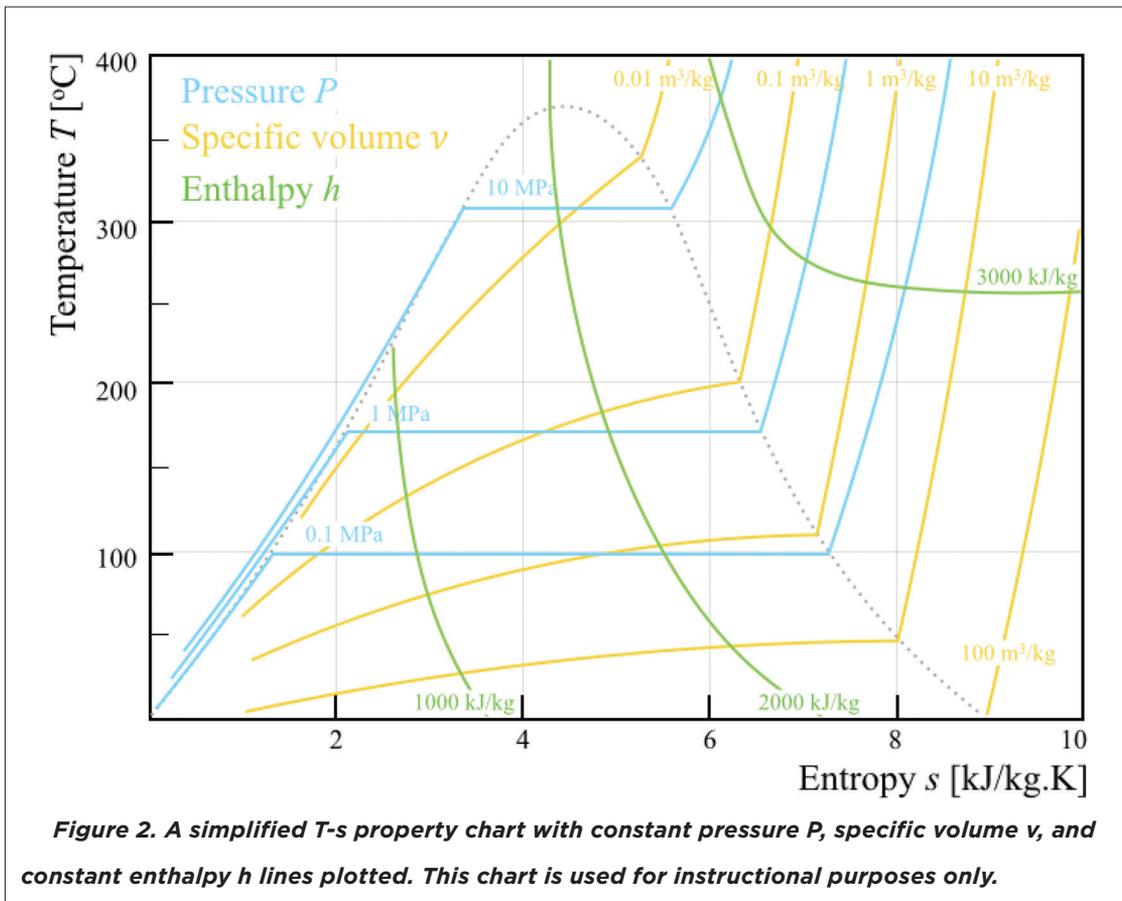


**Figure 1. A  $T$ - $v$  property chart schematic contrasting ideal gas behavior and real gas behavior; showing how real gas behavior is analogous to water. This key-frame schematic is used to launch a discussion of water properties.**

specific volume  $v$  approaches  $0 \text{ m}^3/\text{kg}$ . This apparent disagreement between the model and reality is corrected by the constant temperature phase change process (condensation) that is analogous to the familiar properties of another common substance, water. The students are also informed how the EOS for a real gas, or water for that matter, is more complicated than  $Pv = RT$  and must be corrected when used in engineering practice. Yet, we can use such charts to acquire their properties if the correct values are plotted. The subsequent discussion seeds the creation of a mental model for property relationships.

### **Water and Phase Change**

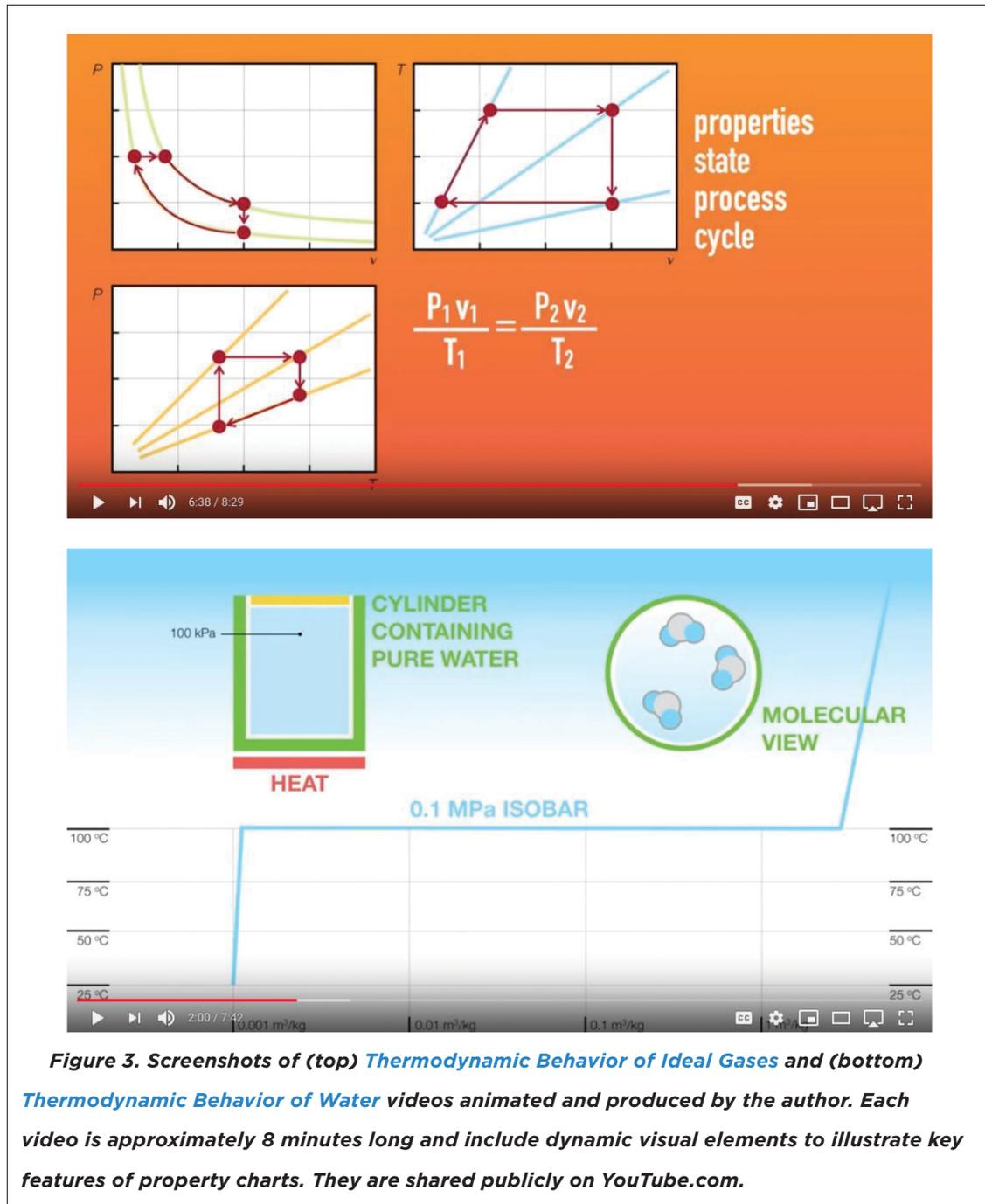
Using the  $T$ - $v$  chart and a piston-cylinder setup for water, a single isobar is constructed step-by-step via a heating process. Additional isobars are plotted by increasing the weight on the piston. This rudimentary property chart lays the foundation for a detailed chart that includes mass specific energy components. Figure 2 presents a simplified  $T$ - $s$  property chart to demonstrate how properties relate to one another and that every point on that chart represents a state. At this point, entropy



is presented as ‘just another thermodynamic property’. Several points on this chart are studied to retrieve  $P$ ,  $T$ ,  $v$ ,  $h$ ,  $u$ , and  $s$  values. The same chart is used to develop a definition of quality  $x$  within the saturated mixture region.

### Instructional Videos

Two animated videos were produced and shared with the students. The “Thermodynamic Behavior of Ideal Gases” video discuss the utility of property charts within the ideal gas model. The “Thermodynamic Properties of Water” video demonstrates how a property chart can be a powerful tool for studying properties of water. Each video is approximately 8 minutes long and illustrates the information in a dynamic and engaging fashion. Figure 3 provides screenshots of the videos produced. In this implementation, the students were asked to watch the videos outside of class time and respond to multiple choice questions to ensure they reviewed the content prior to class. The videos are freely available on YouTube.com for adoption and referenced herein.



### Deliberate Practice

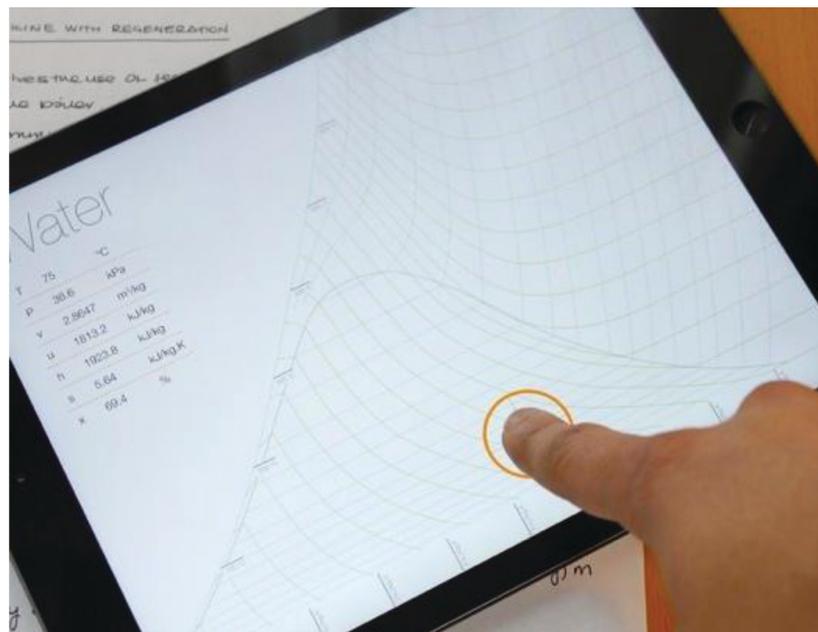
Whether videos are used for primary instruction or a traditional in-class lecture, substantially less time is dedicated to the mechanics of property retrieval using property charts due to the intuitive format of the data. A more accurate  $T$ - $s$  property chart by Cengel & Boles, *Property Tables Booklet*



(2015), is shared with the students to solve textbook engineering problems. The paper-based property chart fits on a single sheet of paper and accommodates the typical pressure and temperature conditions seen by engineering students. This detailed chart is introduced with a 15-minute orientation to the units (e.g. bars) and the logarithmic scales represented for density. It is expected that this introduction can be effectively replaced by a third video. The discussion is followed by example problems involving water. Next, students participate in a think-pair-share activity to practice their retrieval skills for the rest of the class period.

### Supplemental Media

To further engage with the property charts, two more supplemental resources were developed and used. An iPad app, *Clausius*, was developed to reinforce the concepts covered. The functionality of the app is presented in the “[Introducing Clausius](#)” video (Bakrania & Carrig, 2016). *Clausius* presents  $T$ - $s$ ,  $P$ - $h$ , and  $P$ - $v$  charts with properties changing dynamically as the users glide their fingers across the tablet screen. The app is used during the introductory discussion to highlight the interdependence of the properties and how they evolve across the property charts. Figure 4 provides a photo of the



**Figure 4.** A photo of the *Clausius* mobile app used to reinforce the interdependence of thermodynamic properties in real-time. Properties change in real-time in response to the user's touch.



*Clausius* app. Furthermore, each student in this class received a *T-s* chart t-shirt to prompt discussions outside the confines of the course (Bakrania, 2017; Bakrania & Mallouk, 2017). The t-shirts were designed to promote familiarity with the diagrams and encourage a sense of belonging to the course (Shwartz, Blair, & Tsang, 2016).

### ***Changes to the Assessments***

Apart from instructional redesign, every assigned problem from the textbook and assessments was translated to accommodate the use of property charts. Specifically, the problems were changed to accept a small range of values because of the uncertainties associated with reading the *T-s* property chart. For homework assignments, approximately 10% deviation from the textbook numeric solution was considered acceptable. Alternatively, acceptable numeric ranges could have been supplied to further guide assignment attempts. Assessments were digitized to accept multiple choice responses in an effort to provide rapid-feedback to the students (Wildgoose and Bakrania, 2017). The multiple-choice options allowed students to pick the values that best matched their results from property charts.

### ***Beyond the Basics***

For cycle analysis, students were encouraged to draw their processes directly on the paper-based *T-s* chart for a realistic depiction of change of states. Students often submitted their annotated charts for assessments. While the existence of the steam tables (and their digital alternatives) was mentioned during instruction, these were not explicitly taught or used during lectures. The students were made aware of the need for accuracy within their professional careers. The property retrieval from digital resources was demonstrated to provide an example of common engineering practice. This approach has been followed and improved thrice in the past, with the latest iteration involving videos, and will be used in the future offering of the Thermal-Fluid Sciences course by the instructor.

### **Effectiveness Study and Student survey**

The effectiveness study was designed to evaluate the new instructional implementation involving property charts. The study investigated the hypothesis that property charts allow students to develop a better mental model of property relationships. Conversely, the use of steam tables is not conducive to the development of a property relation mental model. To test the accuracy of two mental models, groups of students were asked to predict changes in properties. The group with better predictive abilities possessed a better mental model of property relationships. Later, students who participated were surveyed for their feedback on the implementation.

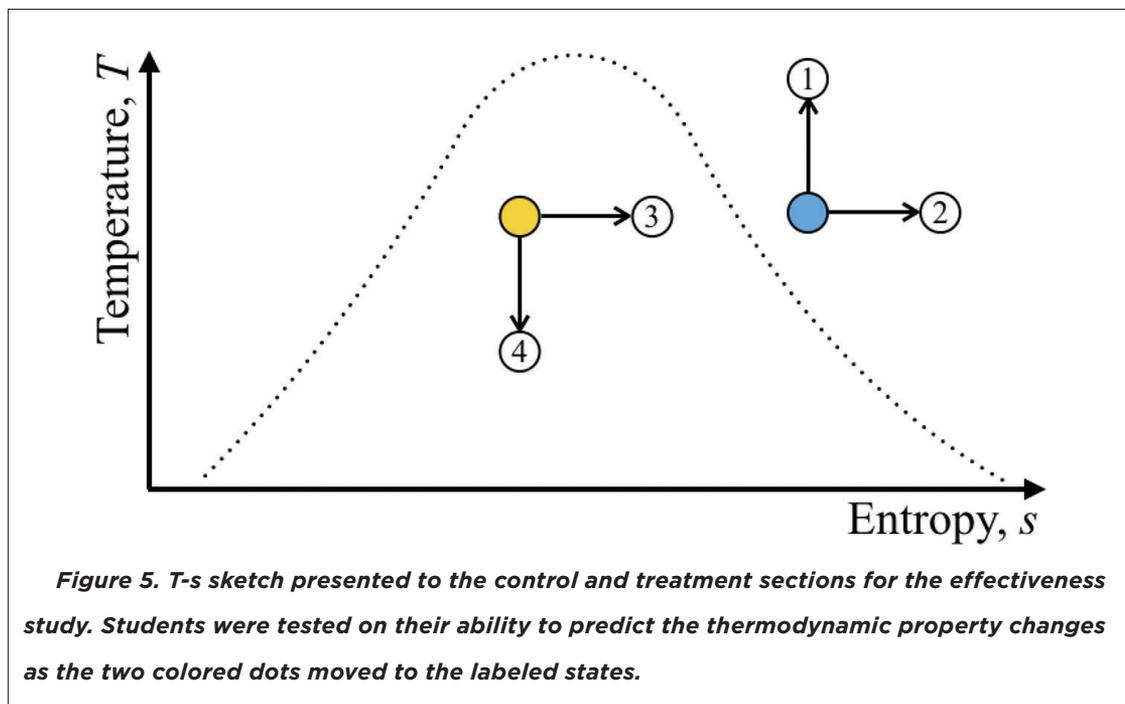


## Research Context

For this study a *control* section of a Chemical Engineering (Ch.E.) Thermodynamics course was selected to compare with the Mechanical Engineering (M.E.) Thermal-Fluid Sciences *treatment* section. The control section relied on the steam tables for properties of water while the treatment section exclusively relied on property charts as far as the instruction was concerned. Care was taken to ensure identical content coverage between the two sections. While the control group relied exclusively on the steam table, they were familiar with the qualitative  $T$ - $s$  chart because they regularly sketched their processes on a  $T$ - $s$  chart. The study was scheduled for the end of the term to ensure both sections were experienced with the two distinct sources of water properties. The study was designed to test the hypothesis that the treatment group had an advantage of constructing a better mental model of the water equation of state simply by using the property charts. Conversely, it was assumed that control group possessed a poor mental model of the property relations. Therefore, the students with a better mental model of property relations will be able better at predicting property changes.

## Method

Both sections were tested on their ability to predict properties of states shown on Figure 5. The two initial states indicated with a blue and yellow dots on the  $T$ - $s$  chart. Students in both sections





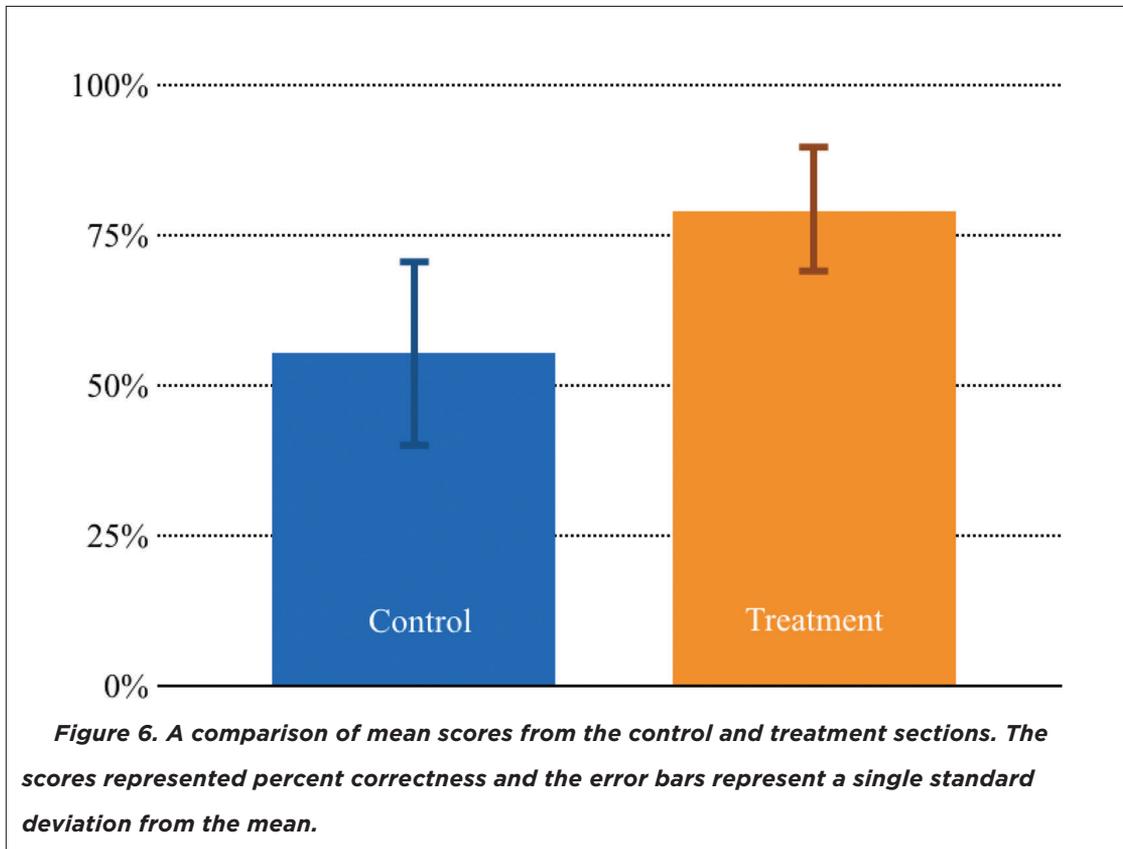
were asked to predict how  $T$ ,  $P$ ,  $v$ ,  $h$  and  $s$  properties change as the states indicated by the dots move from their original state to the two connected numbered state. Specifically, the states moved to states 1 and 2 for the blue state and states 3 and 4 for the yellow state. The students were asked to select “increases”, “decreases”, “remains the same”, and “not enough information” as their predictions for each property.

The students had to predict without having access to their steam tables or property charts as a reference. If the hypothesis that property charts help students develop a better mental model was correct, students in the treatment section would be better at predicting the evolution of properties as the dots move to the labeled states. Conversely, students who relied on the steam tables would find it challenging to predict the change due to the steam tables' inherent focus on point values. In other words, it is hypothesized that steam tables do not help students build a better mental models of the relationships. Keep in mind, students who used the steam tables were still familiar with a qualitative  $T$ - $s$  chart since they are typically asked to sketch their processes on such a chart during problem solving. Therefore, the setup in Figure 5 does not necessarily place the control group at a disadvantage to begin with. In fact, exercise of  $T$ - $s$  chart sketching should help the control group perform better within this study. Following the assessment, a brief survey was conducted to solicit feedback from the students about the implementation.

## RESULTS AND DISCUSSION

The study was conducted during regular lecture period with instructor supervision. Google Forms tools were used to collected student responses from the control section ( $N = 22$ ) and the treatment section ( $N = 35$ ). Students used their personal smartphones to work independently and *without any other external resources* to respond to the questions. Specifically, students did not have access to the steam tables or property charts when responding to the conditions presented in Figure 5. The responses from the control and the treatment sections were collected anonymously and analyzed for correctness. The mean percent correct predictions were computed for each section. Figure 6 presents the outcome of the analysis from the control and treatment sections.

Analysis of the data presented in Figure 6 shows that the treatment group performed statistically better than the control group with an associated  $p$ -value calculated to be less than 0.0001. The study showed that the students who used the property charts were better at predicting changes compared to the students who used steam tables. Even if the students using steam tables were used to sketching the qualitative  $T$ - $s$  charts, this additional visualization step did not help the control group. In other words, students using the property charts possessed a better model of the property



relations compared to students using steam tables. The results corroborate with the outcomes of our previous study using the iPad app *Clausius*. There the students who used *Clausius* to observe property trends were better at predicting properties when compared to students who used the steam tables (Bakrania & Carrig, 2016). The results from the effectiveness study highlight the distinct advantage of integrating property charts over the steam tables: *students internalize the property trends simply by using property charts without any further specialized instructions (e.g., sketches) on property relationships*. Added to this, is the benefit of reduced instructional load and the apparent student preference for this tool based on student feedback discussed next.

With the current setup of the study, it would be difficult to objectively compare student preference for using property charts over the steam tables, since neither sections used both tools concurrently. However, in an attempt to gather students insights on the new approach, the treatment group students were asked how property charts helped them. The responses were categorized by themes and are summarized here. Approximately 44% of the students surveyed noted that the property charts helped them visualize the thermodynamic relationships. The steam tables greatly lack in this regard. When using steam tables, instructors must use *T-s* chart sketches to visualize



processes post-retrieval. With property charts, property retrieval and visualization is combined into a single step. For instance, one student noted, “Visualization is key to understanding the processes”. Interestingly, 19% of the responders thought the property charts allowed rapid retrieval of properties when compared to the steam tables. How did they know? A brief discussion with the class related to this response revealed some students occasionally used the steam tables to check their answers for accuracy and thus quickly recognized the involved nature of the steam table retrieval process. 14% of the responders felt the property charts helped them recognize property trends and another 14% felt the property charts helped them better understand property relationships. The remaining 8% of the responses were categorized as ‘Others’ with comments, such as, “Eliminates unnecessary calculations that are needed when using the steam table”. Such a comment may refer to the elimination of interpolation or saturation quality calculations that are frequent when using the steam tables. The combined outcome of the impact study and the student feedback is that the effective use of property charts can approach the same comfort as the use of the ideal gas model equation of state (EOS) does in a typical thermodynamic classroom. Students are able to generate a mental model of the property relations without an explicit EOS; showing they are able to use these models to predict changes in properties. The outcome of this study is not unlike various other visual approaches.

From an instructional perspective, due to the visual nature of the property charts, less time needs to be devoted to training students to use the steam tables. Thus, more time can be allocated to the concepts surrounding properties of water. This is especially the case if the instructional videos are used to highlight the dynamic aspects of property relations. A subsequent study on the use of the discussed instructional videos showed students relied heavily on them for review prior to assessments (Bakrania and Haas, 2019). Both the instructional effectiveness study and the student feedback support the switch to property charts. The switch away from the steam tables imposes minimal instructional load with an appreciable gain in student learning outcomes. The instructional implementation combined with the resources presented here provide a strong foundation for a broader change in curriculum that is better aligned with the needs of the engineering profession. Specifically, more emphasis on the broader concepts that develop engineering intuition and less on the exact property values that are abundantly available.

## CONCLUSION

A subsequent survey of students using steam tables yielded the student comment, “Old school steam tables are a thing of the past with modern software”. While we can challenge the notion that just because something is old it is irrelevant, we must recognize the dangers of existing alternatives



available to the students. Alternatives to the steam tables, often in the digital form, are inherently inferior from the student learning perspective. These alternatives rapidly supply answers without reinforcing the fundamental thermodynamics concepts; giving preference to property values over property relationships. In fact, this approach would be analogous to an app that supplies specific volume  $v$  of an ideal gas when a user enters pressure  $P$  and temperature  $T$ , hoping the students intuitively derive the underlying  $Pv = RT$  relationship. Instead, we must shift our focus away from the steam tables and embrace property charts when introducing properties of water. This work presented an effective instructional framework with supporting media for integrating property tables within an engineering thermodynamics course. The subsequent study showed that students developed a better mental model of property relations using property charts over mental models generated using steam tables. Once students grasp the fundamental thermodynamic relationships, they may begin to explore software with built-in property tools for advanced application of thermodynamic analysis. The proposed approach is similar to the study of fluid mechanics fundamentals before embarking on CFD-based analysis. Despite the restricted scale of the effectiveness study, the outcomes and the overall proposal are well-supported by extensive literature on the impact of visualization on human cognition. The resources presented within this work provide sufficient guidance for the proposed pedagogical switch.

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