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Touching Water: Exploring Thermodynamic Properties with Clausius App

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The effect of pressure and temperature on the properties of water is a critical concept within engineering curriculum. Instructors spend considerable effort training students to use reference databases; traditionally in tabulated forms or more recently with use of computer-aided references. The reliance on tables however, places undue emphasis on the *property values* over *property relationships*. Understanding thermodynamic relationships and the trends are of greater value from a student learning perspective than the numeric value of the properties. This aspect is highlighted by the practice of asking students to sketch thermodynamic cycles on a temperature-entropy *T-s* or pressure-volume *P-v* chart. The typical analytical steps involving property retrieval followed by depiction on a property chart is disjointed and reversed. If property values are acquired directly from a property chart, the process is integrated into a single intuitive step that promotes deeper understanding. While printed charts exist, they can be challenging to read considering a single point must supply up to six discrete values (namely P, T, v, u, h, and s). Instead, an interactive property chart that displays properties values for user-identified states can be highly effective visual aid. This was the inspiration behind the Clausius app. Clausius allows users to simply tap on a desired state within a *T-s* chart to retrieve property values. The design was driven by the need to visualize thermodynamic property relationships as opposed to simply act as a reference. The app was subsequently studied in thermodynamics courses for its impact on student learning (with a treatment group) when compared to accessing properties via steam tables (with a control group). The intervention involved a guided exploration of water properties by the participants, followed by an assessment of students' understanding of the property trends. Three sets of treatment and control groups participated, across two campuses and three departments. The outcomes provide a strong endorsement for Clausius and its ability to teach property trends. Student feedback also supported the advantages of a more visual and dynamic reference for water properties. Overall, enabling students to 'touch and explore' thermodynamic properties seems more intuitive and conducive to deeper learning than the traditional use of tabulated property values.

Introduction

While ABET does not require students to learn the mechanics of retrieving thermodynamic properties, textbook appendices are richly populated with steam and refrigerant tables. Balmer, *et al.* provide a good summary how this practice of teaching property tables has not changed since the 19th century[1]. It is common for instructors to teach how to use these tables, either for the sake of following the engineering traditions or to train students for the *Fundamentals of Engineering (FE)* exam that continues to rely on the steam tables[2]. Teaching students to use the tables can take considerable time[3] and often acts as a hurdle for students who struggle with interpolation[4]. Because steam tables fail to provide an appreciable conceptual basis for thermodynamic properties, we often introduce students to property charts to highlight regions that the tables represent. Pfotenhauer, *et al.* for instance, have developed a 3D game that uses the *PvT* space to visualize the inter-dependence of properties[5]. Similarly, Urieli[6] and Maixner[7] both advocate the importance of graphical approach to teach thermodynamic processes using property charts. Instead, why don't we ask students to retrieve property values directly from the property charts?

For instance, the FE exam relies exclusively on the *P-h* chart for R-134a to solve refrigeration problems. Such property charts are not only effective as a reference, they also help visualize property relationships. Furthermore, the use of property charts has the added benefit of teaching students to recognize uncertainties associated with their calculations. Property tables provide a false sense of accuracy in thermodynamics calculations by providing property values with 4-5 significant digits[8]. As a result, for the primary objective of teaching thermodynamic properties, the steam tables are tedious, ineffective, and outdated. Imagine providing original tabulated values generated by Johann Nikuradse (1894-1979) for pipe flow, instead of the Moody Chart first presented by Lewis F. Moody in 1944, and now commonly used in fluid mechanics. A more relevant thermodynamics example is the use of Psychrometric chart to study thermodynamic processes of moist air, with strong emphasis on visualization[9,10]. Both these examples forgo accuracy for convenience and in turn provide a way to visualize the often relatively dense information. Analogous to these charts, let us also replace the steam tables with a *P-h* chart, *T-s* chart or the Mollier diagram as property references. In fact, to facilitate this transition and augment the experience, why not harness the computational power and develop a dynamic property chart that can serve as a powerful instructional aid? Before exploring this avenue, let us briefly survey existing computer-based solutions that currently assist with thermodynamic analysis and contrast these to the solution presented here.

Once students become comfortable with the retrieval process, they can begin to analyze power cycles involving multiple property reference states. To expedite the retrieval, students can use the NIST website or other mobile or computer-based reference applications[11-16]. Advanced analysis involving comparison of cycle modifications and optimization may require thermodynamic states too numerous to rely on a single-reference or tabulated values. Instead, several computer-based solutions are available; some relying on the ubiquitous Excel, Matlab or MathCAD to program and solve the problems entirely within the application[17-21]. Among these, EES is a popular tool for both introductory and advanced stages[22]. Most of these applications recognize the importance of visualizing the processes on a property chart and eventually present the process graphically on *P-h* or *T-s* charts. While these resources can be ideal for advanced analysis, they may not be effective teaching tools when students are first being introduced to thermodynamic properties. Early adoption of such computational resources can likely leave students with a very rudimentary understanding of the properties themselves, the trends and their relationships. Instead, if students rely exclusively on *P-h*, *P-v*, or *T-s* charts, they reinforce their conceptual understanding of property relationships every time they retrieve state properties.

Inspired by the effectiveness of property charts for combining conceptual and factual information, we have developed a tablet app with the potential to transform how thermodynamic properties are introduced to engineering students. This paper introduces Clausius; an iPad app designed around thermodynamic property charts for retrieving state properties. To investigate the effectiveness of Clausius, an impact study was conducted across two campuses and involving six distinct engineering instructors. The results are presented along with student/user feedback. Overall, the positive response to the Clausius has further reinforced the drive to eliminate the reliance on tabulated property values.

Clausius App

As noted, there are a number of mobile apps and computer-based programs that provide thermodynamic properties of water and other fluids. These applications rapidly supply the numeric state property values when two independent thermodynamic properties are provided. The applications are primarily designed to provide accurate numeric values for particular thermodynamic state properties. Some of these applications take further steps to represent the state within a property chart to demonstrate the relative location of a particular state. However, for a student focused on solving the problem at hand, it is natural to simply use the numeric value without paying attention to the state's location on the property chart. Conversely, as educators, we recognize the importance of teaching the relative location of the state when analyzing a power cycle.

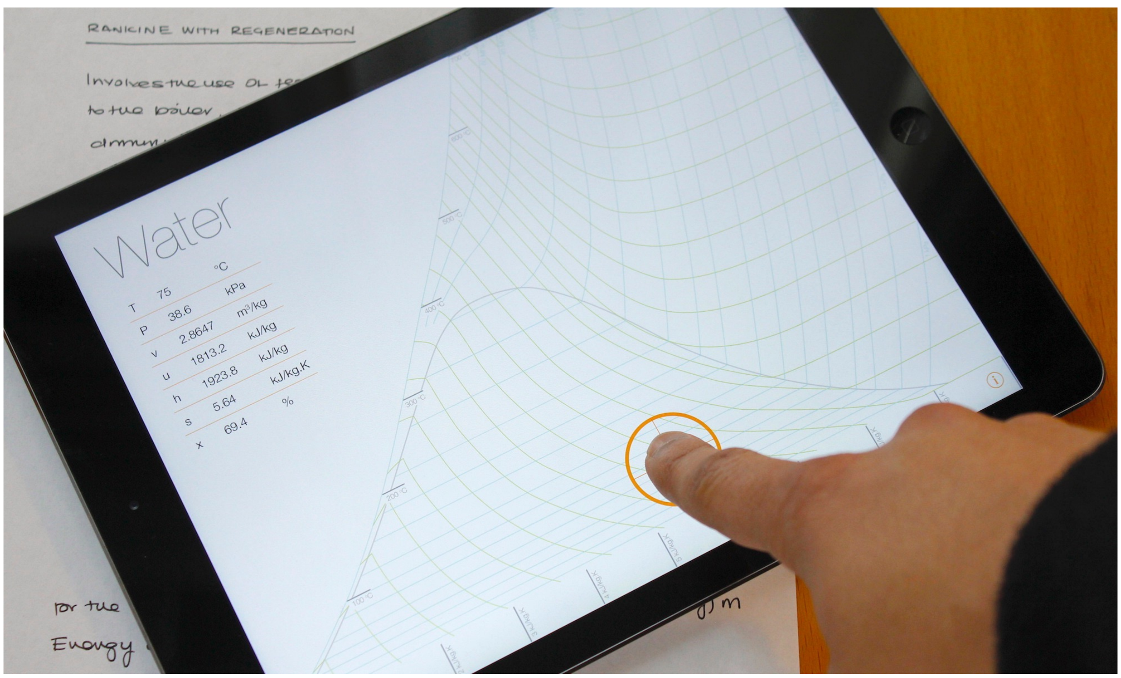

Figure 1. Clausius app with *T-s* diagram for water on Apple iPad.

Clausius reverses the approach commonly taken by existing reference applications by forcing the user to first locate the state on a property chart using their fingers to glide along a known property until they are in the desired region. As the user navigates their way to the desired state, Clausius provides instantaneous and continuous property values of the state at the finger tip. Thus, the navigation action itself delivers information related to (a) Property Trends: how the properties change across the property chart and (b) Regional Context: where the state is located within the property chart. For these reasons, Clausius is a powerful teaching tool when discussing thermodynamic properties and their relationships. For instance, instructors can use Clausius to demonstrate how properties evolve during phase change or verify the use of ideal gas model for the superheated region of water. A video demonstrating the user experience is available on YouTube.com[23]. Figure 1 provides an image of Clauisus app on the Apple iPad.

Clausius presents a temperature-entropy *T-s* chart with isobars and constant enthalpy lines. The *T-s* chart was specifically selected for its popularity in the analysis of common power generation cycles. Similarly, the specific contours also aid with the analysis of common constant pressure devices found in power cycles. The thermodynamic data originated from Wagner, *et al.*[24] with a retrieval algorithm modeled after Gottschalk, *et al.*[25]. As is common in undergraduate thermodynamic courses, Clausius assumes liquid water to be incompressible and therefore the compressed liquid properties are estimated as saturated liquid properties at the same temperature. The embedded property table provides Pressure P, Temperature T, Specific Volume v, Internal Energy u, Enthalpy h, and Entropy s in metric units. Mixture quality x is presented for states within the vapor dome. The inset table displays these property instantaneously and continuously as a user glides their finger across the *T-s* chart.

A key advantage of Clausius over other applications becomes apparent in the first few seconds of using the app. The interface is designed to be so intuitive that no introduction is necessary for initial use. Preliminary tests showed that first time users immediately understood the basic function of the app and were able to instantly appreciate its utility. This however is not the case with the computer-based programs or existing mobile apps where the user needs to have some rudimentary understanding of the properties (such as, typical value ranges and the units being used). Some applications, especially based on MathCAD, MATLAB or MS Excel, even require learning the specific functions necessary to retrieve properties[17-21]. Because Clausius does not require any numeric input, a user can simply place their fingers on the chart and retrieve relevant property values. Additionally, *P-v* and *P-h* charts for water were also incorporated in the latest version of the app. Clausius is currently available for download on the Apple iTunes App Store[26].

Impact Study

Considering Clausius markedly differs from the printed steam tables (or for that matter steam charts) by providing instantaneous and continuous property values, it is natural to hypothesize that the app is inherently superior at highlighting how properties vary across a *T-s* chart. Whereas with tabulated properties the trends are implicit unless explicitly investigated. In other words, a typical first law thermodynamic analysis of a device using steam tables, does not warrant recognition of the property trends. Once the property values are obtained from the steam tables, students are often encouraged to represent these states on a *T-s* chart. On the contrary, Clausius uses property trends to retrieve the desired property values. Therefore, a study was designed to investigate the hypothesis: *the use of Clausius provides a better platform to teach thermodynamic property trends when compared to static or printed thermodynamic properties.* The following sections provide details of the impact study that tests this hypothesis. The participants were also surveyed on their initial impressions, which are summarized later.

Methodology

The study was divided into two stages: (i) intervention with Clausius and (ii) assessment. For the intervention stage, students were asked thermodynamic questions related to properties of water. The students either used the Clausius app (treatment group) or the printed references (control group) to answer the questions. Specifically, the printed references included the *Fundamentals of Engineering Reference Manual* steam tables and a printed version of the *T-s* chart found on the Clausius app. The printed *T-s* chart was used to eliminate any systematic bias towards a particular representation of thermodynamic data. In fact, some questions referred specifically to the *T-s* chart to make sure all the participants were aware of a property chart. Following the intervention stage, assessment was designed to gage student understanding of property trends. Students did not have access to any references during the assessment stage. Following the hypothesis presented earlier, we expect the students who used the Clausius app to perform better during the assessment stage than the control group who primarily used the tabulated reference to answer the questions.

The student responses were collected using Google Forms. The participants were asked to use their smartphones to answer the questions for both the intervention and assessment stages. Apple iPads running Clausius app and printed materials were provided by the instructors to each pair of students.

(i) Intervention Details

Two sections of a thermodynamics course were used for this study. Both the treatment and control sections were presented with 19 multiple choice questions related to the thermodynamic properties of water. The students worked in pairs to answer the questions. Depending on their section, the students either used the printed reference or the Clausius app. The questions were designed to gage the level of understanding of the concepts being tested, and provide the opportunity to utilize the two contrasting thermodynamic references. The questions were divided into three questions types: (a) Questions that gaged concept familiarity, (b) Questions that required a single reference state, and (c) Questions that demanded investigation of multiple thermodynamic states to elucidate property trends. An example of each question type is provided in Table 1.

By design, the intervention exercise forced the treatment group to gain first hand experience with Clausius app, while the control group students relied on printed references to answer identical questions. The intervention was scheduled soon after the students were introduced to the thermodynamic properties of water and the associated *P-v* chart. Neither groups were formally introduced to the second law of thermodynamics or entropy as a property. Only a brief explanation of how ‘entropy *s* is yet another thermodynamic property of water’ was shared.

Table 1. Representative questions used during intervention categorized by type. The number of questions of a particular type are indicated in the parentheses.

Concept familiarity (6 questions)	**Use of reference (2 questions)**	**Property trends (11 questions)**
The following is NOT true with regards to the Quality *x* within the liquid-vapor mixture region.	What are the values of the critical pressure $P_{critical}$ and critical temperature $T_{critical}$ for water?	As pressure is increased, what happens to the boiling point of water?
a. 0% indicates only liquid water is present b. 100% indicates all liquid water has been converted to vapor c. We can use quality to calculate other properties when the saturated values are known d. Represents purity of chemical composition of water	a. 0 MPa and 0 ^{o}C b. 22 MPa and 374 ^{o}C c. 100 MPa and 700 ^{o}C d. 0.025 MPa and 700 ^{o}C	a. Decreases b. Increases c. Remains the same d. Not enough information

(ii) Assessment Details

In the lecture following intervention, an unannounced assessment was conducted. The assessment presented two thermodynamic states on a *T-s* chart sketch to both the treatment and control sections, as shown in Figure 2. The students were asked to predict how each property evolved as the state transformed horizontally or vertically. The students had to predict the effect on a list of properties after undergoing the specified thermodynamic process. The assessment questions, summarized in Table 2, were answered on individual-basis without any aid from reference data or charts.

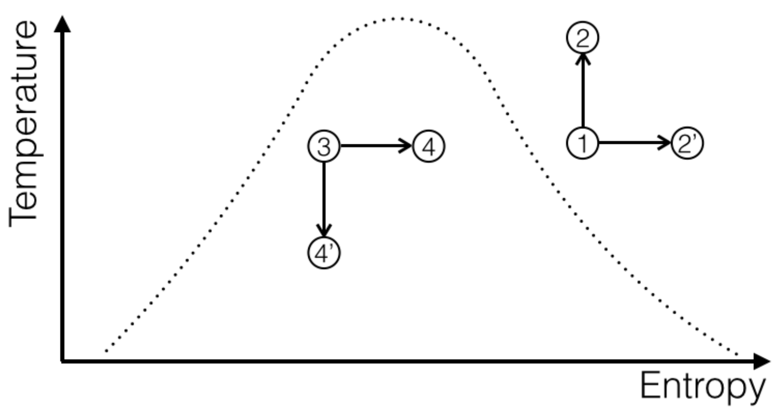

Figure 2. Assessment question sketch. Two initial states 1 and 3 were provided. Each state underwent a process yielding final four states located horizontally or vertically with respect to the initial states. The students were asked to predict the changes in thermodynamic properties at the end of each process.

Table 2. For each of the processes 1-2, 1-2', 3-4 and 3-4' depicted in Figure 2, the students predicted the change in the following thermodynamic properties, in the format presented below.

	Increases	Decreases	Remains the same	Not enough info.
Temperature *T*	☐	☐	☐	☐
Pressure *P*	☐	☐	☐	☐
Spec. Volume *v*	☐	☐	☐	☐
Internal Energy *u*	☐	☐	☐	☐
Enthalpy *h*	☐	☐	☐	☐
Entropy *s*	☐	☐	☐	☐

Participation Details

A total of three pairs of treatment-control groups were selected to conduct the impact study involving a total of 175 students participating in Fall 2015. The pairs involved two sections of Rowan University Mechanical Engineering Thermal-Fluid Sciences (RU ME TFS) course, two sections of Rowan University Chemical Engineering Thermodynamics (RU ChE Thermo) course, and two sections of Union College Mechanical Engineering Thermodynamics (UC ME Thermo) course. Each section was taught by a distinct full-time faculty with extensive experience teaching thermodynamics. Table 3 provides further details related to the participants and sample size.

Table 3. Impact study sections and participation details.

	RU ME TFS	**RU ChE Thermo**	**UC ME Thermo**	**Total**
Treatment instructor	Dr. Bakrania	Dr. Dahm	Dr. Anderson	
Treatment class size	35	33	18	86
Control instructor	Dr. Bhatia	Dr. Van Kirk	Dr. Bruno	
Control class size	40	32	17	89

Results and Discussion

The results are divided into three distinct sets: (i) paired responses from the intervention, (ii) individual responses from the assessment, and finally (iii) user survey based on student feedback.

(i) Intervention

For the intervention, student pairs were encouraged to discuss the questions and provide a paired response to the questions related to the properties of water. The intervention took at most 45 minutes for the student-pairs to complete. The 'concept familiarity' and 'reference' questions revealed insignificant differences in performance between the control and the treatments groups, suggesting all the participants were appreciably familiar with the thermodynamic properties for water and how to use the resources, respectively. [a]

With an overall baseline established between the control and the treatment sections, analysis of the 'property trends' questions revealed a clear and strong advantage of using Clausius over traditional property tables. As a reminder, the 'property trends' questions solicited responses related to how the thermodynamic properties vary across the *T-s* chart, trends that can be difficult to study using the printed reference tables. As a result, the treatment group excelled at correctly and swiftly responding to questions such as, "The specific volume is highest in this region of superheated water" and "In the throttling process, where enthalpy *h* remains constant, water at 300 ^{o}C and quality 3.2% is cooled to 100 ^{o}C. What is the final quality?" The mean score for the control section was 49 ± 15%, while the treatment section mean was 70 ± 18%. This particular advantage can be attributed to the design and functionality of Clausius app to simply scan the *T-s* chart to respond to such questions. The treatment group performed statistically better than the control group for 'property trend' questions (p-value < 0.001). The comfort that the treatment group exhibited with these question showed how *useful* Clausius can be for responding to such questions. With Clausius, students have tactile control over the range of properties and this utility is apparent from this intervention. Armed with Clausius, students can engage with thermodynamic properties in a way that was previously either tedious or required some level of comfort with programing. Nevertheless, a more critical question is if the use of Clausius *teaches* students about how properties vary across a property chart. This pedagogical attribute was the focus of the assessment conducted during the lecture period following the intervention.

(ii) Assessment

To explore the impact of using Clausius, the assessment was conducted with both treatment and control group on individual basis without using any external resources. Students responded to questions on their personal smartphones. On average, the assessment took 15 minutes to conduct.

With Fig. 2 presenting Temperature *T* and Entropy *s* as the primary axes, these two properties were expected to be relatively straight forward to predict after undergoing a thermodynamic

[a] While some exceptions were observed, all were attributed to ambiguity in instruction.

process (average scores were > 90% for both control and treatment students). As opposed to Pressure *P*, Specific Volume *v*, Internal Energy *u*, and Enthalpy *h*, that required students to retain the knowledge of how these varied across a *T-s* chart. Remember, the key difference between these groups was that the treatment group primarily used Clausius app to answer the intervention questions whereas the control group primarily used the property tables to answer the intervention questions. Therefore, treatment group was likely to rely on their experience with the Clausius app, whereas the control group relied heavily on the steam tables (and possibly the printed *T-s* chart supplied). Although the difference in average performance was closer compared to the difference during the intervention stage, the correlation supported the impact. Indeed, when comparing the predictions by each group, the treatment group performed statistically better than the control group (p-value = 0.010). It is worth noting, these results were independent of who the instructor was. The outcome supports the original hypothesis that interactive property charts are effective tools for teaching property trends. Students who simply used Clausius to explore properties of water were better equipped to predict property trends than students who used steam tables. These results are also strongly supported by the student feedback.

Table 4. A summary of questions and responses from the user feedback survey (N = 148). Combined responses from treatment and control groups.

Question	Question Type	Results: Average Rating and Response Summary
How would you rate the educational value of Clausius?	Rate 1 for Low to 5 for High	4.0 ± 0.8
How would you rate Clausius' superiority over using property tables?	Rate 1 for Low to 5 for High	4.0 ± 1.0
How would you rate the app's interface?	Rate 1 for Low to 5 for High	3.74 ± 0.9
Comment on how Clausius can impact your learning.	Open-Ended	25% Easy to Use 19% Fast Access 22% Teaches Relationships 13% Helps Visualize 22% Other
Provide any other comments or suggestions with regards to Clausius.	Open-Ended	26% Requested numeric input 14% Liked the idea 11% Requested property lock 12% Requested they use the app 9% Accuracy was a challenge 30% Others

(iii) Student Feedback

Following the intervention, all the participants (including the control sections) were introduced to the design philosophy of Clausius and presented with the video highlighting the key features of the app. The students were then asked user feedback questions presented in Table 4.

As presented in Table 4, the first three numerical rating questions received very favorable responses from students who either used the app or were simply introduced to Clausius via a short 30 second video. Students rated the educational value of the app and its superiority over using property tables with an average of 4.0, where 5 represented 'High'. The app's interface received relatively lower rating of 3.7. Considering the number of professionally designed educational applications that our students are exposed to both on their personal computers and on their mobile devices, such high scores are very encouraging for a faculty designed tool. The marginally lower interface rating can be further probed using the open-ended portion of the survey. With a large number of student comments, only a sampling of the open-ended responses are provided in Table 5. To evaluate open-ended feedback, the student comments were divided into general themes and are summarized in Table 4 as a percent of responses that belonged to a particular theme. Themes that garnered less than 5% of responses were lumped into the 'others' category. The overall outcomes from the two questions are summarized here.

Table 5. A selection of representative comments from students to the two open-ended questions.

Comment on how Clausius can impact your learning.	**Provide any other comments or suggestions with regards to Clausius.**
In our class we had not covered enthalpy, which would have helped my learning experience. However, I still felt like I was learning from Clausius.	It would be great if the user was able to lock in on a certain parameter or even be able to type in that parameter. For example, it would be very helpful if you could type in 100 KPa and then the app locks you in on that constant pressure line so you can examine other properties at that constant pressure.
It is great for seeing trends and becoming more comfortable and familiar with concepts.	Having the option to choose what type of graph you view would be very nice. Adding in a feature to search/pinpoint a specific coordinate on the graph. and maybe allowing a method for snapping the pointer onto any of the lines of constant what ever.
Allows for user to see how variables affect each other in water. It is very interesting.	It is a great app to use if you quickly need a value on the graph without having to do any calculations, but I don't think it is a good learning tool for students.
Fun and interactive chart. Much more attention grabbing and visually appealing than paper graphs.	Being able to type in specific values and have it plot points.
Much less time focusing on tables and interpolation and more on understanding content.	Being able to interact with the graphs are helpful.

When asked how the app can impact their learning, majority of the students (approximately 40%) indicated how ‘easy’ Clausius was to use and how ‘fast’ they were able to retrieve properties. Most notably, 22% recognized how Clausius can enable learning the relationships between properties; while 13% praised its ability to help ‘visualize’ the property charts and their inter-dependence. The rest of the students noted a range of unique or less popular responses (labeled as ‘others’ in Table 4). Some of the ‘other’ responses included: Clausius’ ability to eliminate tedious interpolation, Clausius being great tool for eliminating the dependence on the steam tables, and few that countered by their concerns of becoming too dependent on the app instead. A number of students from the control section felt uncomfortable to judge the app’s impact without trying the apps themselves. Overall, these responses supported the design philosophy and confirmed the outcomes of the impact study from student’s perspective.

In response to the second open-ended question requesting general comments and suggestions, the most common response (over 26% responses) was the request to allow numeric input of the given properties to quickly arrive at the desired state properties (skipping the chart entirely). 11% of the students felt it would be useful to add a ‘property lock’ feature to hold desired properties constant as they scanned the chart for exploring isothermal, isobaric, or isentropic lines - a further indication of deep engagement with Clausius. 14% of the students surveyed simply stated how they liked the app and the concept behind it and did not have any further suggestions. Few students noted the inherent inaccuracies associated with using one’s finger to locate a state; some even requesting the ability to zoom or providing additional control interface to mitigate this issue (using a stylus or directional-pad common to game-consul controllers). Some of the less popular suggestions included adding more substances, ability to select units, and increasing the visibility of the target to locate a state. Students also frequently inquired if they will be permitted to use the app during tests. Naturally, few students also requested Clausius to be made available on alternative platforms (other than Apple’s iOS).

Based on these responses, we can attempt to arrive at some general conclusions and address the common requests. Noting the high number of participants reporting how ‘easy’ and ‘fast’ Clausius was to use, is a strong endorsement for this approach. Remember, no instructions were provided prior to its use; students intuitively began using it. The survey also suggested students generally liked using the app and thought it would help their understanding of the thermodynamic properties. Indeed, as demonstrated by the impact study, Clausius certainly has the potential to become a very useful learning tool for the thermodynamic property trends. Students however did express the desire to extract all the state properties simply by supplying the available state information. While such a feature can be very useful, we feel it would take away Clausius’ ability to reinforce property trends by the way of interacting with the charts. Besides, there are existing apps that supply such information (e.g., NIST web database of properties). We also believe this desire to arrive at an ‘accurate’ answer stems from the use of tables that afford precision but do not necessarily aid learning. From a pedagogical stand point, precision is not required to convey thermodynamic concepts or, for that matter, to solve thermodynamic problems. In fact, Clausius reinforces concepts without emphasis on precision similar to how Psychrometric charts, Drag coefficient charts, or the Moody Diagrams are used to solve HVAC, external flow drag, and pipe-flow problems, respectively. We recognize, for advanced or optimization-focused power cycle questions, precision may be necessary and existing applications are sufficiently adequate. However, at the early stage when students are just getting acquainted with thermodynamics, tabulated values do little to drive the conceptual understanding. As a result, we propose making property charts central to thermodynamics instruction, and eliminating the practice of teaching property tables. This new practice when augmented by applications such as Clausius, can engage students at a much deeper level.

Conclusion

The Clausius app provides a radically new way to introduce students to the thermodynamic properties of water. Rather than relying on printed tables, Clausius invites students to interact with thermodynamics properties with their fingers and experience how these properties change as they move their fingers across. To demonstrate the effectiveness of using Clausius, an impact study involving 175 students across two campuses was conducted. The study concluded that the students who used Clausius to explore thermodynamics properties of water retained the property trends better than the students who relied on traditional printed steam tables. When surveyed, students overwhelmingly preferred using Clausius app over the steam tables for its ease of use and how rapidly they can retrieve properties. Students also recognized Clausius' ability to demonstrate property trends and to visualize the property relationships. Clausius provides an opportunity to shift our pedagogy from teaching how to read property tables to teaching how properties relate to one another and how they evolve, simply by asking students to 'touch' them.

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