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Computer Simulations Developed to Improve Understanding of Thermodynamic Principles

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Dr. Alexander has 10 years of industry work experience most of which as CEO of IVUS Energy Innovations – a technology start-up company that he and three partners formed around unique fast changing technology. As CEO, he raised over $2 million in equity financing, secured a worldwide license agreement, and managed the commercialization and launch of the industry's first 90-second rechargeable flashlight. In addition he is co-inventor on four U.S. patents and has presented numerous times at advanced energy technology conferences in the areas of business and technology development.

Computer Simulations Developed to Improve Understanding of Thermodynamic Principles

This paper describes the design, development and pilot implementation of computer simulations created to support student learning in a first semester course on thermodynamics. This project was sponsored by the Course Redesign with Technology program through the California State University Chancellor's Office. The focus of the computer simulations was to be engaging, relatively simple, and scientifically accurate. They were developed within the Matlab® environment using relatively simple geometric shapes, lines and colors specifically designed to coincide with the simple systems described in an introductory thermodynamics course and to avoid elaborate designs that might distract or obscure important and relevant concepts. Each module emphasized a common thermodynamic principle or concept and provided an opportunity for users to adjust a limited number of inputs and immediately observe a resulting change. The modules included concepts in material density, simple compressible systems, and 2-D property diagrams. Feedback was collected from students self-reporting their experiences and impressions. Thirty-three students completed the questionnaire after using the 2-D properties module while only ten and seven responses were collected for the simple compressible system and density modules, respectively. Based on student feedback using the 2-D properties module, 15 of 32 respondents reported that their understanding of the thermodynamic principles improved and 29 of 33 students reported that they would use the 2-D module again for other classes or applications. Four of ten respondents reported that after using the simple compressible system module their learning improved and all students reported that they would or might use the simple compressible system module in the future. Only one student reported that their understanding of the material improved and 4 of 6 reported that they would not use the module in the future, which indicates that this module was either too simplistic or was introduced too late in the semester. The positive student responses for using the 2-D property and simple compressible system modules provides preliminary support that the computer simulations supported student learning.

Introduction

Thermodynamics presents students with new terminology and concepts that are often counter-intuitive and difficult to visualize and conceptualize. Additionally, the mathematics is abstract and has its roots in inequalities and statistical probabilities as opposed to direct, predictable events and phenomena such as kinematics and kinetics. Without sufficient time on task and opportunities to visual and ponder concepts, students can develop weak understanding of the fundamentals and have difficulty applying their understanding to the analysis of a thermodynamic system. Traditional textbooks and classroom lectures are insufficient in and of themselves for students to master thermodynamics concepts. For these reasons and the portability and accessibility of software, computer modules were selected as a potentially engaging way to provide students with enhanced learning opportunities.

Bloom's revised taxonomy categorizes learning into two dimensions, knowledge and cognitive processes (Anderson and Krathwohl 2001). The knowledge dimension consists of factual, conceptual, procedural, and metacognitive dimensions in a hierarchical structure where learning processes begin with factual knowledge acquisition and continue toward meta-cognitive knowledge, which is the awareness and understanding of one’s self in relation to one’s understanding. Similarly, learning evolves along the cognitive process dimension from the lowest order process of remembering to the highest order process of creating. While the learning process is fluid and not restricted to moving along a multidimensional hierarchical path, learning progresses optimally when it flows from lower level dimensions of knowledge and cognitive processes toward to higher levels, ultimately reaching the level of creating something new from ones knowledge and understanding. Designing computer simulation modules that support students in the progression from lower level skills to higher level skills as identified and described by Anderson and Krathwohl (2001) was a significant design consideration for the thermodynamic modules.

Recognizing that different students learn in different ways (Felder and Spurlin 2005, Felder and Silerverman 1998), the modules were designed to provide opportunities to test hypothesis, predict outcomes, and/or experiment different inputs and immediately see results in a safe and interactive environment.

Course History/Background

Thermodynamics is a core building block of engineering and spans most science and engineering disciplines. It is required for mechanical and civil engineering students at California State University, Chico (CSUC). For mechanical engineering students, thermodynamics is often the starting point in a series of courses in the thermal sciences, a core area of focus in mechanical engineering. Students typically take the course after the second semester of engineering physics. For civil engineering students, thermodynamics is a terminal course and often put off until late in a student's academic program. Prerequisites include successful completion of the first semester of calculus and calculus-based physics.

High Demand / Low Success Issues

Thermodynamics class sizes have grown over the past several years from about 30 to 40 students per class to approximately 60 to 70 as a result of lower budgets and pressure to teach more students with fewer resources. With current class sizes at approximately 65, it is very difficult to provide personalized and directed content to each student. The delivery of content also becomes more structured in order to process the high number of enrolled students. Instruction becomes less individual and more formal. This can lead to students withdrawing from the course mentally and emotionally. With thermodynamics, if one is not actively engaged and continually challenging oneself to understand the material, comprehension can be quickly lost.

There tends to be few students that perform at a high level, earning As on assignments and exams and steadily devoting the necessary time to understand the material, while a large student population hovers around the C range, exhibiting average comprehension and devoting just enough time to stay above the D, F, or W (DFW) level. Unfortunately, with large class sizes, the difference between earning a C and a D, F, or W can be slight because of the lack of connection and engagement.

Matlab®-based Computer Modules

As a way to provide students with additional learning opportunities without significantly increasing instructor workload, computer simulation modules were developed. These modules were designed, developed and implemented by the author. Thermodynamics concepts were reviewed including concept inventories from Midkiff et al. (2001) and Jorion et al. (2013). Additionally, techniques from Tobin (2014) were reviewed in an effort to support universal design and accessibility. Matlab was selected as the software platform. It is taught in many courses in the mechanical engineering curriculum including mechanics of materials, mechanical design, and numerical methods. Students already have some familiarity with it, and it is widely used in industry and research and development.

Interactive examples of thermodynamic concepts were developed to provide the learner with the opportunity to progress along the cognitive process dimension from low to high level abilities within the conceptual knowledge dimension. To be most effective, learners would need to have mastered the factual knowledge dimension of the material that is presented in the module. In other words, a student using the computer modules would gain the most benefit if they learned the terminology of thermodynamics first. However, not understanding the terminology first would not prevent the user from experiencing the modules and potentially developing some degree of understanding.

The interface of each module was designed to be relatively simple. The user could relatively easily identify the key parameters and manipulate the available inputs without needing separate instructions or directions. A student-user could quickly begin interacting with the module and visually experience how changing inputs to the system dynamically changes the outputs.

A module on density was the first one provided to the students. It was introduced approximately halfway through the semester. Figure 1 depicts the density module interface. The user can change the acceleration due to gravity, the object's mass or volume, and fluid density. Pressing the "Will it float?" button calculates the objects specific gravity, specific weight, displaced volume of the fluid, and resulting mass and weight of the displaced fluid. Feedback is provided through displaying the object floating, sinking, or neutrally buoyant in the fluid with corresponding numerical results. Students can adjust the fluid density while keeping all other inputs constant and determine at which point the object sinks or floats.

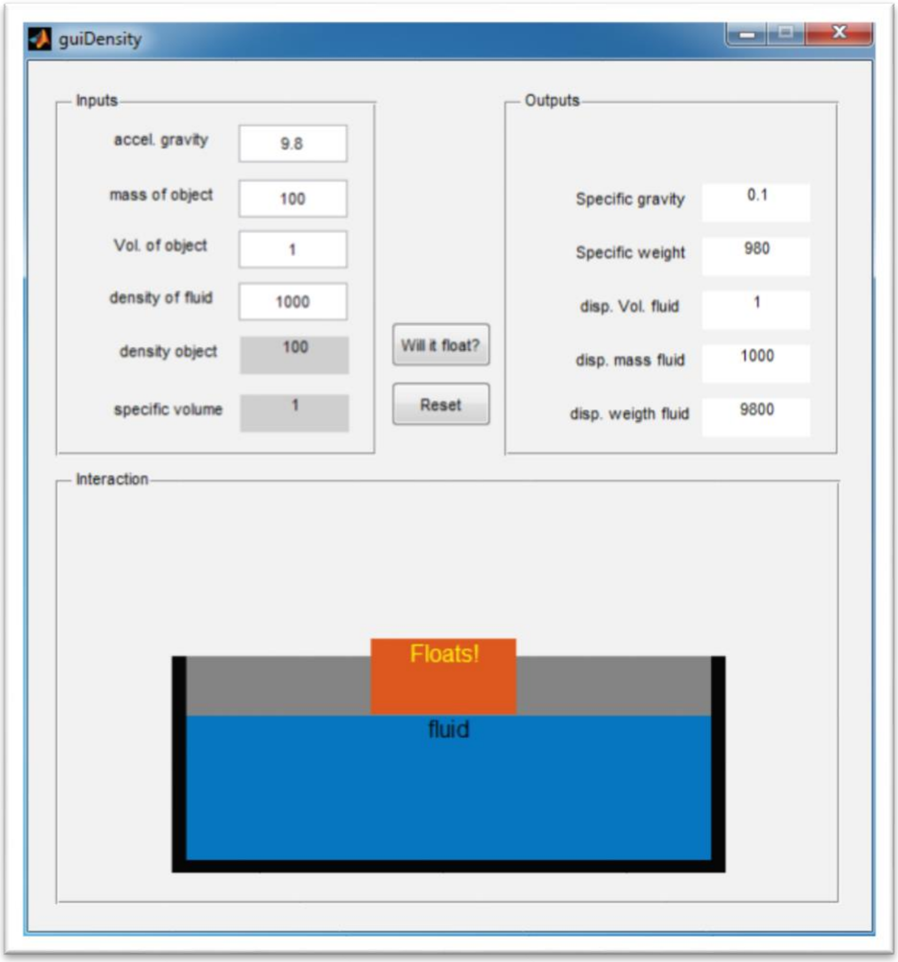

Figure 1. Density thermodynamics module

The second module that was introduced to the students was a piston/cylinder module. It included a brief description of the module as well as prompts for the students to encourage exploration of the physics related to how the piston/cylinder behaves under different physical situations. The user is restricted from being able to change one of the four initial states. By selecting the radio button in the *Initial States* window, the corresponding variable is restricted from being accessed. This way, the user is able to set three input parameters that specify the initial state of the contents of the cylinder, in this case, air. The final state is determined as a percentage of the initial state's total volume. Once the final percentage of initial volume is set and the user presses the enter key, the module immediately recalculates the final state and plots a polytropic path from the initial state to the final state. Labels at both ends of the process path or curve are indicated as either initial or final. A final percentage less than 100 percent results in the compression of the air and a percentage greater than 100 percent depicts the expansion of air. Figure 2 shows a compression process and Fig. 3 depicts an expansion process.

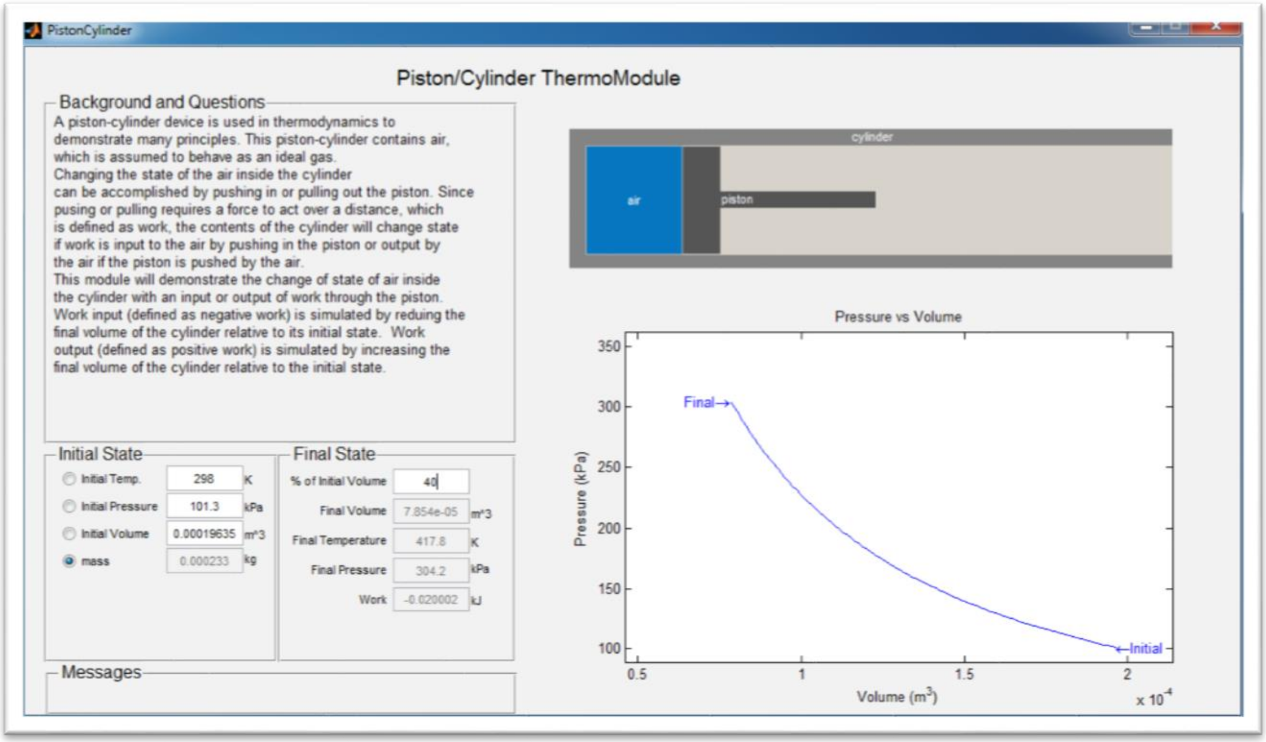

Figure 2. Piston/cylinder thermodynamics module depicting a compression process.

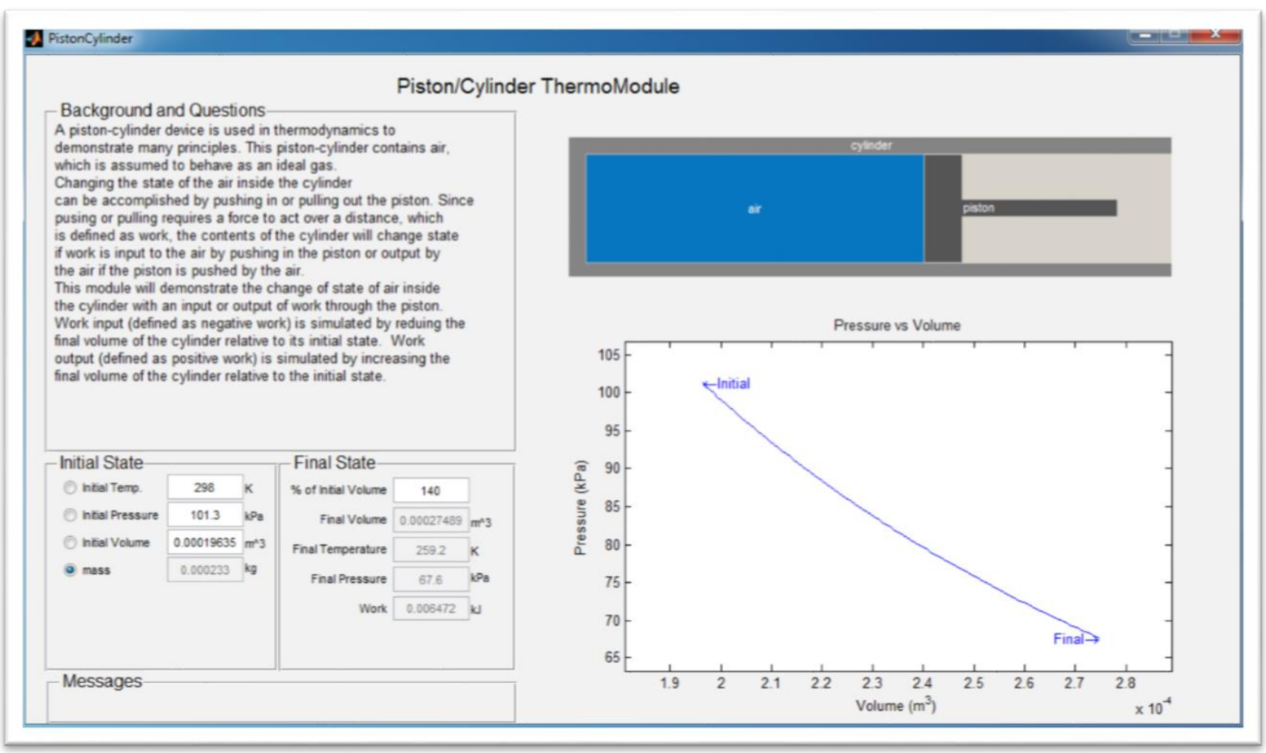

Figure 3. Piston/cylinder thermodynamics module depicting an expansion process.

The third module that was developed and presented to students was designed to give a visual and dynamic representation of how properties change while following a constant property line through a phase/property diagram. Four 2-D axes plot pressure as functions of specific volume and specific enthalpy and temperature as functions of specific volume and entropy. Overlaid on each plot are saturation lines delineating liquid, liquid-vapor mixture, and vapor phases. Three types of iso-lines are available to the user, isothermal, isobaric, and isochoric. The user inputs the numerical value for a constant temperature, pressure, or volume and the corresponding iso-line is plotted in all four axes.

While plotting material properties is not new nor novel, this module was designed to progress students through several dimensions of knowledge and cognitive processes. Lower order thinking skills are developed and reinforced by recognizing properties of water by inputting different states of pressure, temperature and/or volume. Following an iso-line through its various phases, students interpret, contrast, compare, and predict how other properties change along the same path by analyzing the paths on all four axes. See Fig. 4 showing the constant temperature of 300 °C. From the axes showing temperature as a function of specific volume, it can be seen that the specific volume increases as one follows the constant temperature line from left to right, i.e. from a liquid to a vapor. The constant temperature line also appears as a horizontal line in the pressure as a function of specific volume plot.

Higher level thinking can be developed as additional iso-lines are plotted. For example, constant pressure lines could be added to the existing axes and used to predict where the lines will intersect. A student would be able to analyze and distinguish points of intersection as well as bounds on properties or phases by evaluating the various graphs. Plotting is nearly instantaneous and any value can be selected and quickly plotted and quickly erased allowing many multiple scenarios to be viewed and analyzed. Figure 5 shows two constant pressure lines of 101 kPa and 1,000 kPa intersecting the constant temperature line of 300 °C. Viewing the module's output statically in the figures provided does not adequately convey the dynamic aspect of being able to select a property value and almost instantly watch a line being drawn across all four axes.

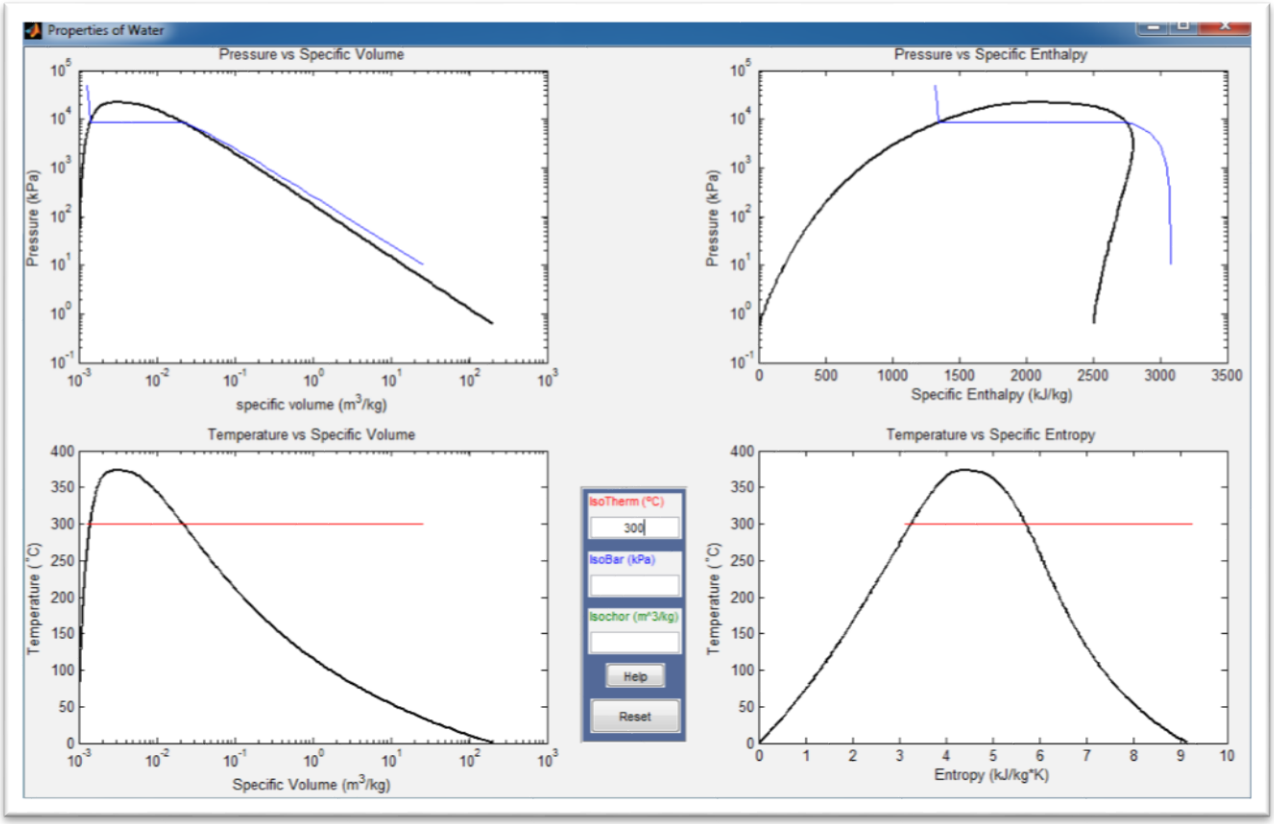

Figure 4. Isothermal line at 300 °C.

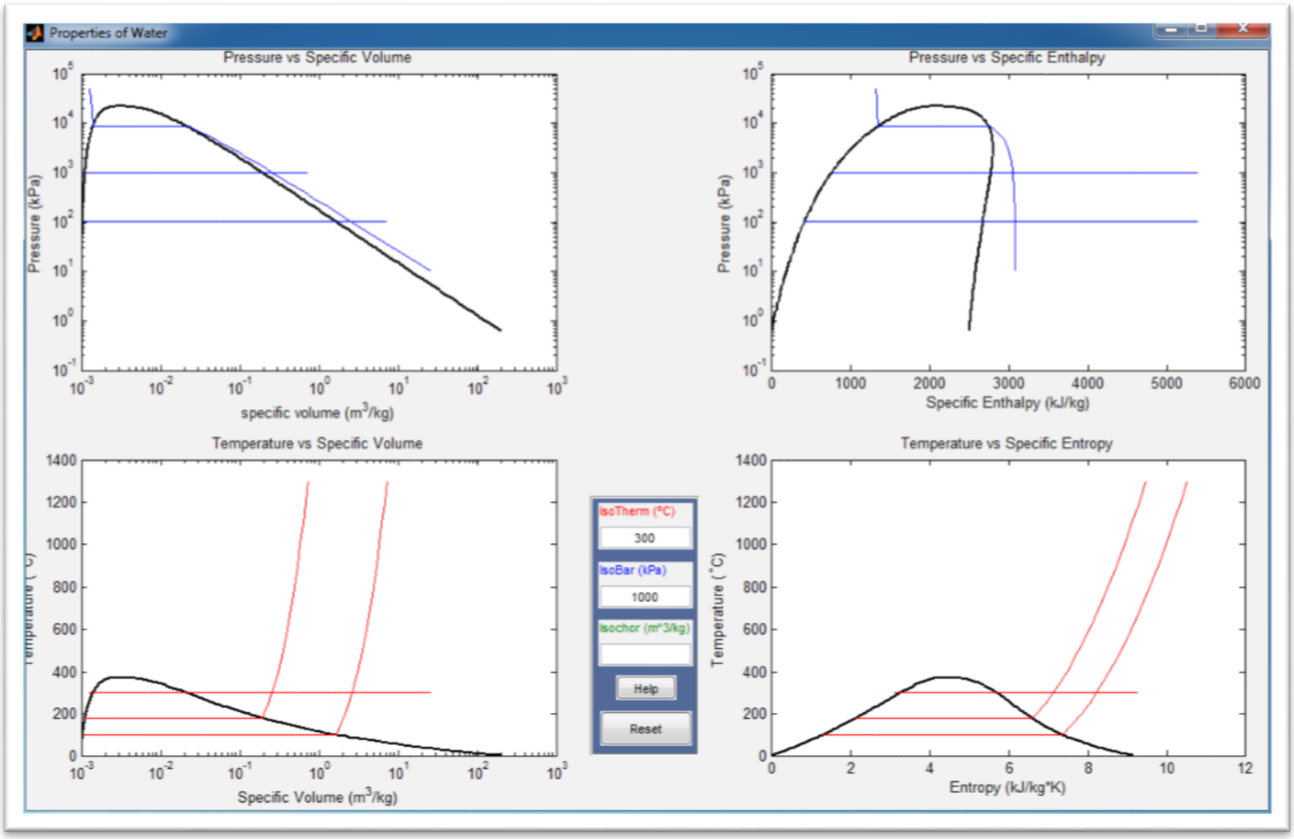

Figure 5. Isobaric lines at 101 kPa and 1,000 kPa intersecting the isothermal line of 300 °C.

Implementation

Three modules were introduced throughout the semester accompanied by an online questionnaire. The modules were made available to students to download from the course learning management system (LMS) after the module's content was presented in class lectures or activities. To incentivize all students to use the modules, extra credit homework points were given for each questionnaire that was completed with feedback. The questionnaire was implemented through the LMS. Student feedback and the number of questionnaires completed by each student was collected anonymously. Table 1 lists all the questions that were asked. Space was provided in the questionnaire for long responses.

Table 1. Questions asked of all students after using the modules.

QUESTION 1: What module are you evaluating? ○ Density ○ Piston/Cylinder ○ Iso-lines ○ Other QUESTION 2: Describe the fundamental engineering principle(s) that is/are being demonstrated in the module. QUESTION 3: Prior to using the module, I fully understood the engineering principles that are demonstrated in the module. ○ Strongly Agree ○ Agree ○ Neither Agree nor Disagree ○ Disagree ○ Strongly Disagree ○ Not Applicable	QUESTION 4: Because of using the module, I now have a significantly better understanding of the engineering principles that are demonstrated in the module. ○ Strongly Agree ○ Agree ○ Neither Agree nor Disagree ○ Disagree ○ Strongly Disagree ○ Not Applicable QUESTION 5: Would you likely use this module again to study these engineering principles? If so, why. If not, why not. QUESTION 6: How could the module be improved to increase your level of understanding of the engineering principles? QUESTION 7: What module would you like to see developed?

Results

Three modules were developed and provided to the class throughout the semester. Students were able to interact with the computer simulations and observe the concepts dynamically as various inputs were modified resulting in changes to the outputs, which were displayed dynamically to the screen. Feedback was collected from students after using each module.

The following feedback was collected on the Piston-Cylinder Module in response to Question 5 in Table 1.

> *"This was my first time using Matlab, It took me a while to figure out the interface. A suggestion would be to integrate these modules into the course earlier on so those who have no experience with Matlab may gain some, along with learning more engineering principles from these modules."*
>
> *"hmm. I don't know..."*
>
> *"Maybe. It was difficult to load up"*
>
> *"yes i would because it gives a good visual representation and graph. when you change your numbers you can see what is going on."*
>
> *"Yes this module was very helpful in increasing my understanding"*
>
> *"Yes, I like being able to visually see the changes that occur based on the variables I put in and the graph that's shown. Although it can all be calculated by hand, I find seeing it and being able to play with the numbers much more satisfying."*
>
> *"I would consider using this module again, mainly for the process diagram. It provides a good visual for a polytropic process path."*

"Yes, I would. The graph and piston cylinder graphic make it easier to understand how changing one property has an overall effect on the system."

"I am a visual learner and having the ability to change one thing and seeing the effects of it, you get a better grasp of a concept."

The following includes all the feedback collected from the Density Module in response to Question 5 in Table 1.

"I do not think I will use module again because these relationships are described with equations."

"Definitely, this module is going to assist me in a variety of my classes in the future along with my career in civil engineering. I will be taking water resources, concrete design and a few other classes that deal with physics which this module can assist in."

"I probably wouldn't use this one specifically. I would probably use the other ones more than this one."

"Yes, this could be very handy when in the design phase of a prototype of some sort. It is very convenient to be able to pull up a module and input the information you have in order to find out what you need to know at the click of a button, instead of having to do tedius calculation as well as refresher research."

"no because it was too hard to set up."

"I only remember that the module was not much help at the point in the semester when I finally got around to using it, and was not quite as interesting as the other modules."

"It would be nice to have this module as a sanity check for future problems."

Students were asked to self-assess their understanding of the conceptual material presented in the modules before and after using the modules. These are Questions 3 and 4 in Table 1 with five options for answers ranging from strongly disagreeing to strongly agreeing to fully understanding the material. The results are given in Figures 6, 7, and 8. The outlined columns represent student responses prior to using the module whereas the shaded columns are student responses after using the module. Responses before and after using the density module indicate that overall conceptual understanding did not improve as seen in Fig. 6. However, of the 7 responses, 3 did not change after using the module. Two respondents indicated that after using the module they neither agreed nor disagreed that they fully understood the material, indicating no change in their understanding after using the modules. One respondent indicated that their understanding improved and one indicated that their understanding degraded.

Before and after using the piston/cylinder module, four out of ten students indicated that they improved their understanding of the material whereas the same number reported no change in understanding, and two reported that they strongly agreed to fully understanding the material prior to using the module and there was no change in understanding afterward.

Figure 8 shows the results from 33 students that used the Iso-lines module. Fifteen of 32 respondents indicated that they increased their level of understanding after using the module whereas 12 respondents indicated no change in understanding. Of the remaining 5 respondents, 4 agreed or strongly agreed that they fully understood the material prior to using the module and after using the module, they indicated that they neither agreed nor disagreed that they fully understood the material. Only one respondent indicated that they did not agree nor disagree to fully understanding the material prior to using the module and after using the module they disagreed that they fully understood the material.

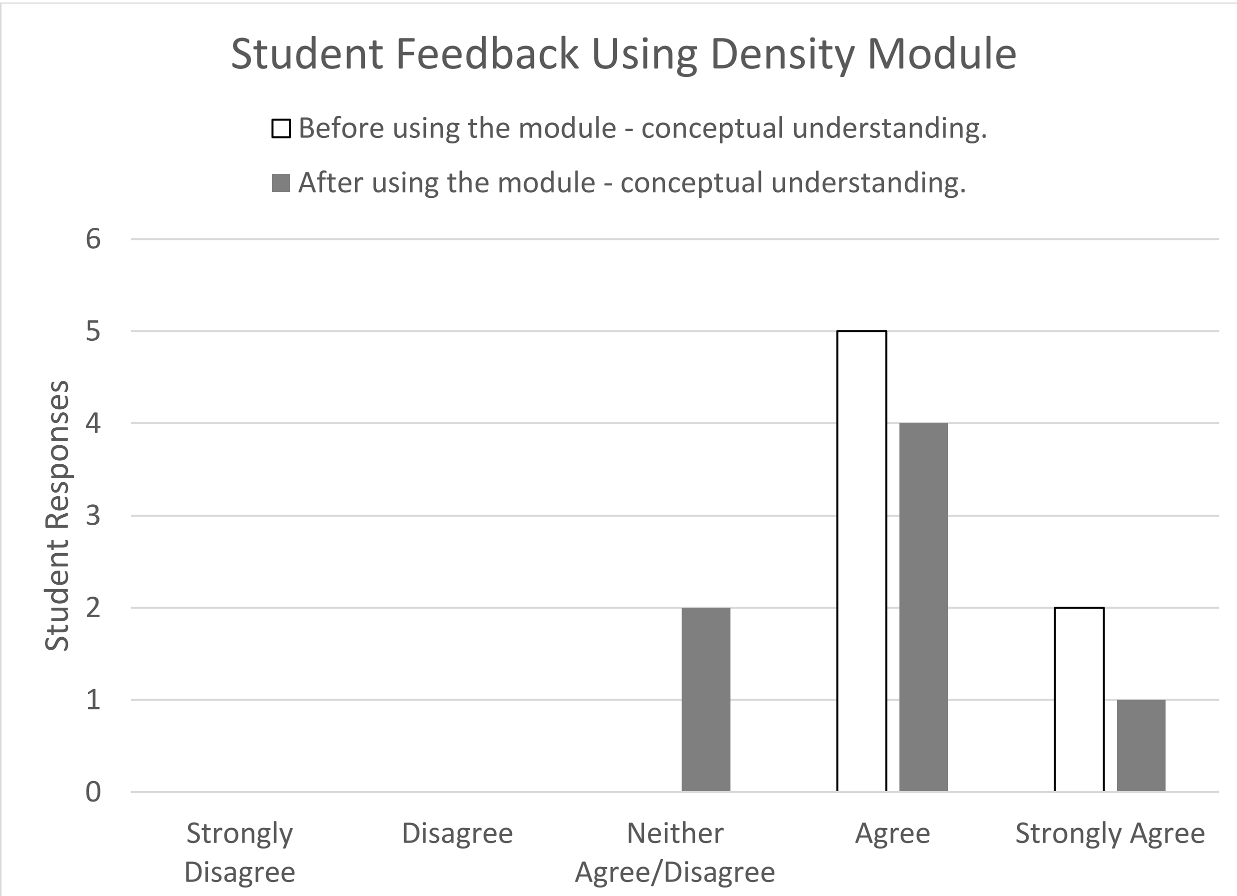

Figure 6. Student feedback self-assessing conceptual understanding before and after using the module on density.

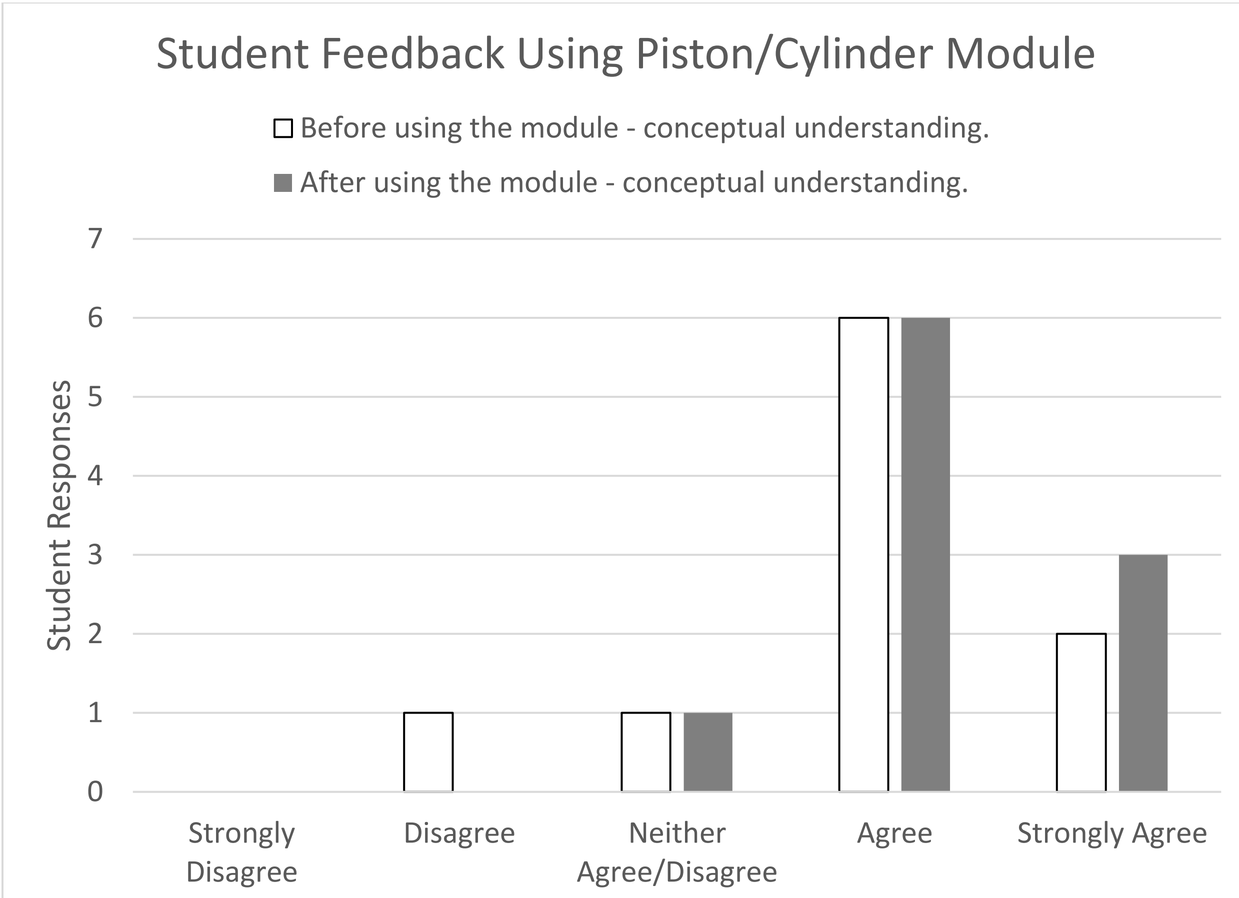

Figure 7. Student feedback self-assessing conceptual understanding before and after using the module on the piston/cylinder.

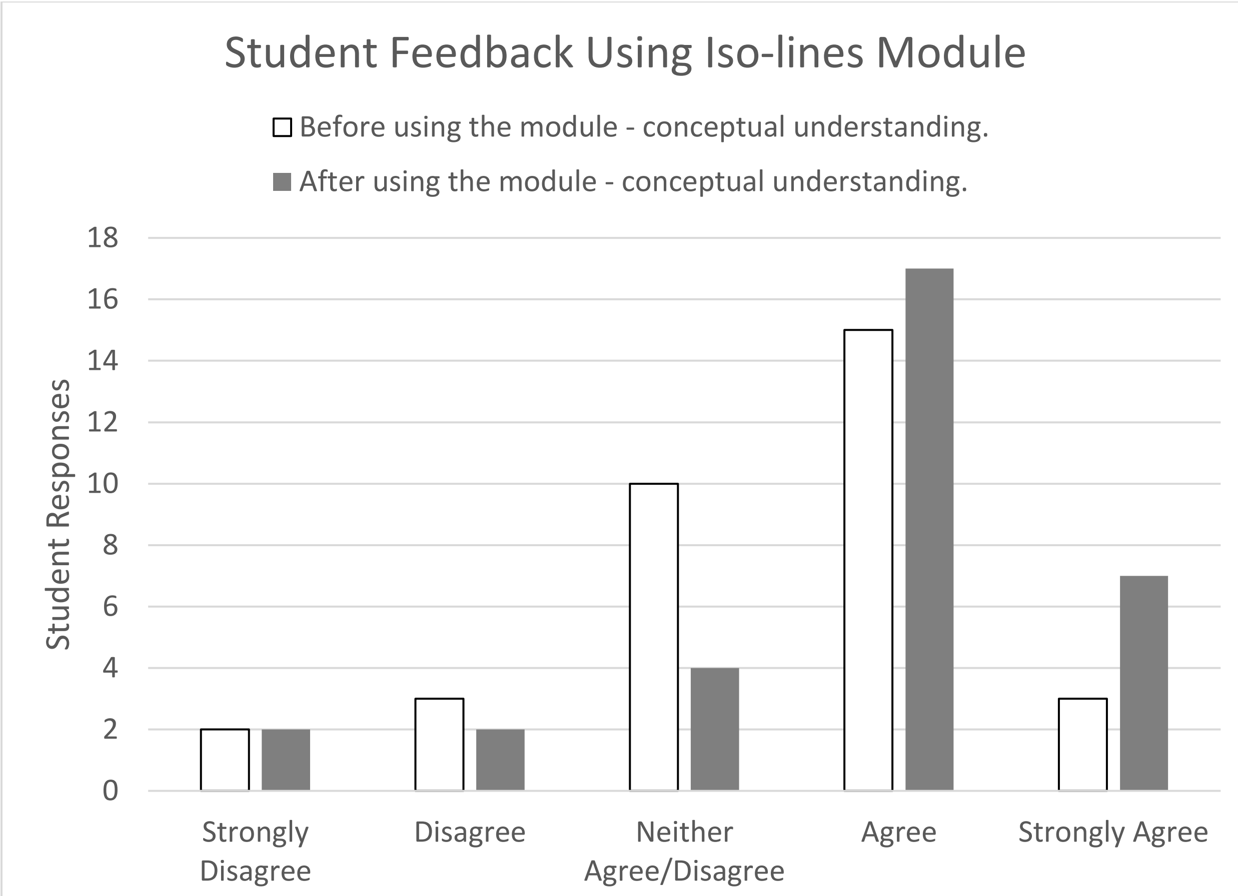

Figure 8. Student feedback self-assessing conceptual understanding before and after using the module on iso-lines and phases of water.

Discussion

The goals of this project were to engage students in learning principles of thermodynamics through scientifically accurate and relatively simple computer simulations. Three thermodynamics modules were developed and given to students taking a first course in thermodynamics. Feedback was collected and used to evaluate the effectiveness of the modules. The results of the feedback can be categorized into two areas (1) student engagement and (2) module effectiveness. Answers to question 5 asking students whether they would use the module in the future were mostly positive. In aggregate, 33 out of 49 students indicated that they would use the module in the future, 10 said that they would not use the module, and 6 indicated that they might use the module or their response did not definitively indicate one way or the other. Using question 5 as an indication of the level of engagement to learning thermodynamics, a majority of students were engaged in using the module and would use it again in the future.

Questions 3 and 4 were used to determine if the modules were of value for students learning thermodynamics based on student self-assessed understanding of the material before and after using a module. Tabulated results of these questions are presented in Figures 6, 7, and 8. The modules were considered to add value to student learning if student perceived level of understanding increased by at least one score, e.g. from neither agree/disagree to agree or from agree to strongly agree. The number of students that increased their perceived understanding of the material was 1 of 7, 4 of 10, and 15 of 32 for the density, piston/cylinder, and iso-lines modules, respectively. The number of students that indicated that they would use the module again in the future was 2 of 7, 6 of 9, and 28 of 33 for the density, piston/cylinder, and iso-lines modules, respectively. Students' perceived value of the density module was less regarded as compared to the piston/cylinder and iso-lines modules. The density module was delivered to students later in the semester than intended, which is believed to be a reason why it was not as well received as the other two modules. It is also the simplest of the three modules and does not provide significantly different information to the user than what one would get from solving a relatively simple calculation. Units were not presented in the density module to encourage students to verify units themselves. Also, without units the density module could be used to solve problems in either SI or FPS system without changing the program's code. The feedback was instructive for better understanding the appropriate level of complexity of modules for future development.

One of the biggest challenges that the students encountered based on their responses to Question 6 in Table 1 was with using Matlab. Unfortunately, Matlab was only available in one or two computer labs or via VSL or an educational version could be purchased online for $99. Using VSL was problematic and many students were reluctant to purchase the educational version. Also, Matlab is not always used in civil engineering courses, so there is wide ranging interests and motivations for using it. Students that were not exposed to Matlab were reluctant to use it and struggled with the modules. The modules were designed to be standalone applications that required very little knowledge of or experience with Matlab, however just finding a workstation running Matlab or logging into VSL was challenging for many students. Instructions were provided online through the course LMS with additional links to Lynda.com and the campus information technology services, however, students still struggled getting Matlab to work effectively.

Developing the computer modules took a long time. Each module took approximately 50 to 70 hours to develop. Most of this time was spent designing the user interface and creating the appropriate controls to the inputs that minimized inadvertent errors by the user while still allowing flexibility to explore various input settings or ranges. In addition to the development time, deciding on what type of module to develop took careful consideration. The module needed to demonstrate dynamically a thermodynamic principle but not be too complex so that one could focus attention on the concepts. But a module that was too simplistic could result in an unimpressive and unengaging experience as seemed to be the case with the density module.

Overall, the student experience was positive. Students spent time using the modules and were presented with a visually dynamic interface that provided an opportunity to explore complex thermodynamic principles in a safe and low stakes environment. The modules are being used by other faculty and students with more feedback being collected and analyzed for future improvement. For additional information and to use the modules, contact the author.

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