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Enhancing Student Understanding of Thermodynamic Principles Through 3D Visualization

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Abstract

Many engineering students struggle to develop three-dimensional visualization skills. Such visualization plays a key role in a variety of undergraduate courses, including thermodynamics. The pressure-volume-temperature (P-v-T) surface is a foundational concept in the discipline. It provides a visual representation of the relationship between the three physical properties and serves as the cornerstone for understanding simple compressible systems. This study investigates whether utilizing three-dimensional P-v-T surface models in instruction makes the content more accessible to engineering students.

Participants in this investigation came from a flipped-classroom undergraduate thermodynamics course. Volunteers are divided into two groups. The control group receives the standard video instruction on P-v-T surfaces using traditional two-dimensional illustrations. The test group is presented with a video lecture featuring rotating three-dimensional figures. Aside from the P-v-T visualization techniques, the content between the two lectures remains the same. Following completion of the lesson, students in both groups complete a multiple-choice online survey to assess their understanding of key concepts.

While students who received the modified lesson had a higher average score on the post-lesson assessment than those who did not, there is not sufficient evidence to establish a statistically significant difference between the two groups. Students in the test group performed better on four out of the five survey questions as well, but once again statistical significance is not observed. A larger sample size is required to more rigorously assess the efficacy of the visualization techniques. Even so, the increasing accessibility of three-dimensional visualization

software makes the models implemented in this study a viable option for undergraduate thermodynamics educators.

Introduction

Three-dimensional (3D) visualization is an important skill in engineering. The ability to map two-dimensional (2D) images to a mental 3D representation allows engineers to think critically about the world around them and make informed decisions. Unfortunately, many students who enter collegiate engineering programs lack strong visualization skills, opting instead to adopt trial-and-error approaches to spatial reasoning[1]. This issue can be especially acute for new female students, who on average score lower on visualization assessments than their male counterparts due in large part to differing background experiences[2]. A large body of work has sought to quantify and address student challenges with visualization, including the international investigation of Leopold, Gorska, and Sorby[3] considering students from Germany, Poland, and the United States, and the decade-long efforts conducted by Michigan Technical University and its partners assessing the impacts of an introductory visualization course[4,5]. Both of these groups observed improvement among student abilities such as mental rotation and cutting visualization as the result of classroom intervention. Other investigators have found success deploying augmented reality approaches in visualization courses as well[6,7].

At the same time that students struggle with 3D visualization, many find thermodynamics to be among the most difficult undergraduate engineering courses. Foundational concepts from throughout the discipline consistently cause trouble for students[8], and a multitude of surveying techniques have been developed to assess these shortcomings[9]. Educators have responded with a variety of approaches to make thermodynamics more accessible[10]. While tools like Engineering Equation Solver[11] make solving mathematical problems more approachable, a popular subcategory of this research concerns the deployment of 2D visualization tools. Approaches include online textbooks with animations[12] and applets used to present fundamental problems[13,14]. While these interventions bolster student retention and engagement with course material, they can also fall short in depicting concepts completely. One foundational concept in any thermodynamics course is the interrelatedness of the properties of a pure substance – specifically pressure, specific volume, and temperature. The relationship between these three properties can be represented by a 3D surface (known as the P-v-T surface), a construct which can be difficult for students to visualize and interpret based simply on 2D depictions. This concept, of interconnectedness between the properties, is a fundamental idea for assessing simple compressible systems in thermodynamics.

While much of the research on student visualization has focused on new students and introductory courses, Bairaktarova et al.[15] observed comparable visualization skills across all undergraduate levels. This evidence suggests that, even in upper-level courses such as thermodynamics, visualization practices can be impactful on developing students' comprehension of spatial topics. Pfotenhauer and Gagnon[16] first proposed the usage of real-time 3D models of the P-v-T surface as part of a supplemental computer game to improve student understanding of the construct. This work was further expanded into a full virtual reality experience, where students were able to observe a simple piston-cylinder system and P-v-T surface through a virtual reality headset[17]. Here the authors reported high levels of satisfaction and engagement among students, with many citing improved understanding of the 3D surface and its usage in the course. 3D models have been deployed in other related fields as well, specifically in chemistry, where 3D printed energy surfaces[18] and other visual aids[19] have been developed. This work seeks to evaluate the efficacy of 3D visualization technologies within the context of a standard, flipped-classroom undergraduate thermodynamics course. Students provided with a rotating P-v-T surface as a part of their curriculum are assessed, alongside peers with standard content, to determine whether the intervention improves content understanding and retention.

Methods

The defining materials utilized in this research are 3D renderings of a P-v-T surface. Two P-v-T models are utilized. The first features all three basic phases of matter (solid, liquid, and vapor), and is used to convey the differences between the three[20]. Due to the prevalence of the liquid and vapor states of matter in standard thermodynamic coursework, a surface featuring these two phases and the liquid-vapor dome between them was generated for use with more in-depth concepts. Water was chosen as the substance from which to obtain the thermodynamic properties necessary to construct the surface as a result of its ubiquity in both instruction and real-world applications. The generated surface is shown in Figure 1. The MATLAB X Steam function[21] was used to map combinations of pressure (P), specific volume (v), and temperature (T) for water across the intervals of 200 K to 400 K and 15.55 bar to 215.53 bar. The specific volume axis is represented by a logarithmic scale, and each axis is further scaled independently to generate a surface that fits within a roughly cube-shaped volume. An STL mesh file was generated based on the coordinates generated via X Steam, and the model was further refined in solid modeling software to add axis and phase labels.

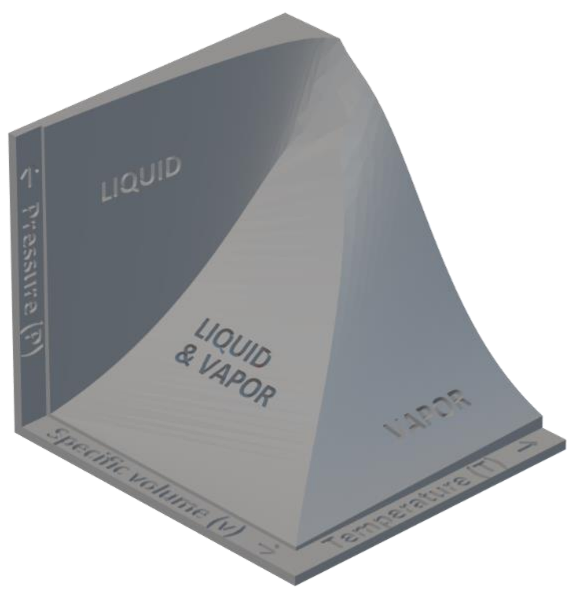

Figure 1: The generated P-v-T 3D model.

The study itself is implemented in one section of undergraduate thermodynamics taught at a major Midwestern university. The course employs a flipped-classroom approach, with students viewing lecture videos on the university's online platform prior to each class meeting. Students enrolled in the course are invited to participate in the study on a voluntary basis, with extra credit offered to students who complete the study materials even if they choose not to opt into having any data collected from their activities. Consenting participants are randomly divided into two groups: a control group, who view the standard course content relating to the P-v-T surface and accompanying concepts, and the test group, who receive content containing a rotating, 3D P-v-T surface. 24 students participated in the study, with 9 students in the control group and 15 students in the test group.

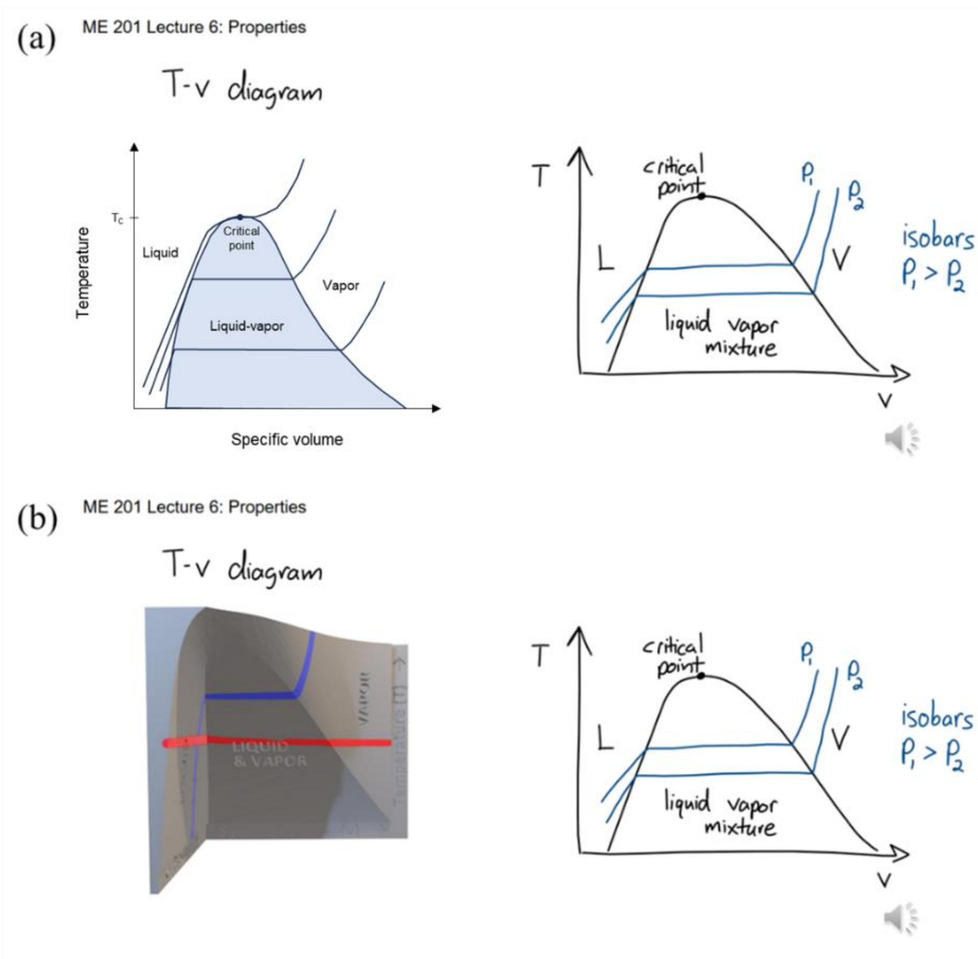

Figure 2: A comparison between visual lecture content for (a) the standard lecture (control), and (b) the modified lecture (test)

The procedure for participants features two distinct components: a video lesson and a follow-up assessment. Both are deployed on the course website, as the platform can host both video and quiz content. The lecture videos for both groups, control and test, feature the same general script, with minor deviations between the two occurring only to better explain the 2D or 3D depictions. Topics covered include the relationship between properties and phases, the P-v-T surface, phase transitions, and P-T, P-v, T-v diagrams. A snapshot of content from each video lecture is depicted in Figure 2. While both lectures feature a hand-drawn T-v surface, the standard lecture of Figure 2a features a typical illustration similar to those found in the course textbook [22] and the modified lecture of Figure 2b contains a rotated P-v-T surface. The surface is animated to rotate throughout the lecture as needed, providing students with a clear visualization of the object.

Students attempt the follow-up assessment upon completion of the lecture material. This assessment consists of five multiple choice questions. Among these questions, two ask students to select the best answer based on their interpretation of a provided 2D diagram. For the other three, students are provided a verbal prompt and tasked with selecting the best 2D diagram that satisfies the prompt. The complete questionnaire can be found in the Appendix. Students in both groups receive the same questions, and all data is anonymized prior to analysis.

Results and Discussion

Average overall scores for the test and control groups are shown in Figure 3. The error bars represent one standard error on each side of the average value. The average score for the modified lesson group is 3.53 ± 1.13, and the score for the standard lesson group is 3.33 ± 1.22. While the modified group scored higher on average, a two-sample t-test between the groups yields a p-value of 0.687 – considerably higher than the standard value of 0.05 required to suggest a significant difference between the two groups. As such, evidence is insufficient to statistically confirm that the 3D visualization tool used has a positive impact on student performance.

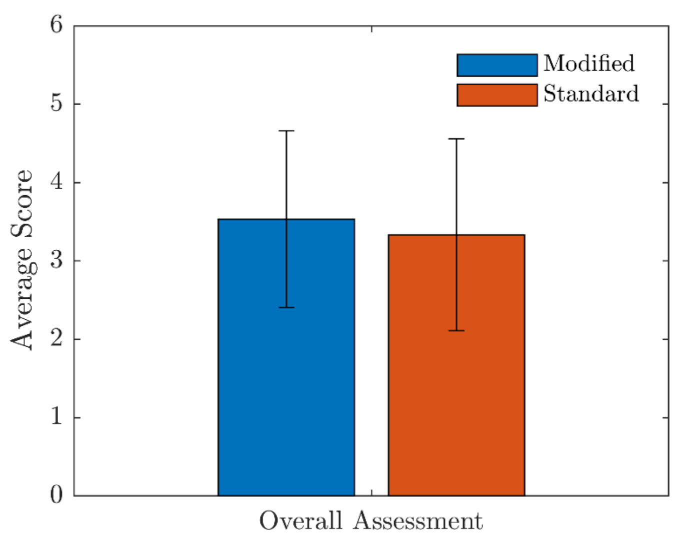

Figure 3: Comparison between the average overall scores for the modified and standard instructions

Further details concerning study results are depicted in Figure 4. Here, the average score for each assessment question is compared between the two groups, with error bars again showing deviation from the average score. Students receiving the modified lesson scored higher than their peers on four out of the five assessment questions in the control group, but once again two-sample t-tests for each question do not yield sufficiently low p-values to confirm statistically significant improvements. Tabulated data, including p-values for each question, are listed in Table 1.

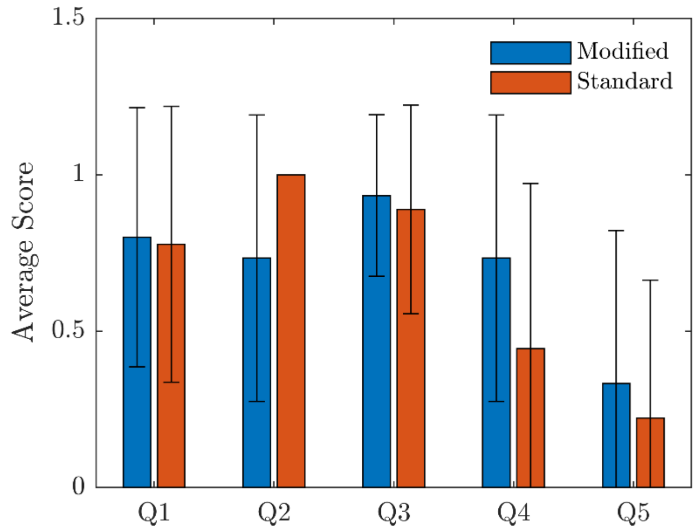

Figure 4: Comparison between the modified and standard groups for the five individual assessment questions

Table 1: Average scores and p-values from the follow-up assessments

	Q1	Q2	Q3	Q4	Q5	Overall
Standard	0.78 ± 0.44	1	0.89 ± 0.33	0.44 ± 0.53	0.22 ± 0.44	3.33 ± 1.22
Modified	0.80 ± 0.41	0.73 ± 0.46	0.93 ± 0.26	0.73 ± 0.46	0.33 ± 0.49	3.53 ± 1.13
p-value	0.902	0.0973	0.718	0.171	0.582	0.687

Conclusions

The results of this study cannot confirm a statistically significant improvement in student performance based on the use of three-dimensional visualization of the P-v-T surface during instruction. Even so, higher average scores among students who received the modified instruction suggest that further investigation may be worthwhile. One major limitation of this study is its size – only 24 students participated in the investigation, far fewer than would be preferred for determining statistical significance. Broader participation is required to limit the impacts of randomness and sampling bias. Besides surveying too small a student population, this study also does not quantify the effectiveness of the intervention specifically for women in engineering, missing the opportunity to evaluate whether the technique could lead to more equitable outcomes in the classroom. Future work will attempt to address these limitations of the current study to provide better insights into how to improve thermodynamics education.

While the rotatable P-v-T surface is presented in a flipped-classroom lecture format in this study, it can easily be deployed in a wide array of educational settings. In the most technical case, the 3D model is an ideal candidate for immersive virtual environments such as Marquette

University's MARquette Visualization Lab (MARVL), which provides a room-sized virtual reality classroom for interacting with 3D models[23]. The virtual reality headset approach of Pfotenhauer[17] could further offer students an individualized opportunity to explore the P-v-T surface. Due to the ubiquity of smartphones, augmented reality apps also offer a lower cost alternative that is more accessible to a wider audience of students, as Bell et al.[6,7] explored. Even in the case of simply replicating the lecture-based approach of this study, most modern computers come prepackaged with some form of 3D-viewing software. Users with little to no technical knowledge in computer modeling can access and interact with 3D renderings, such as the P-v-T surface implemented here, with relative ease. A final avenue of deployment could be producing and distributing 3D printed models to students to provide a tangible, tactile representation that rendering-based approaches are unable to capture. All of the modeling resources utilized in this work are open source as well, providing further accessibility for educators. With so many different implementation options, the interactive model of this study can be flexibly applied to a variety of different learning environments.

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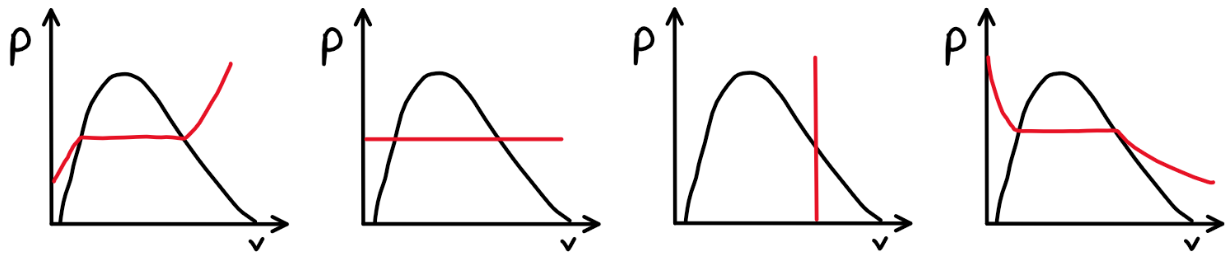
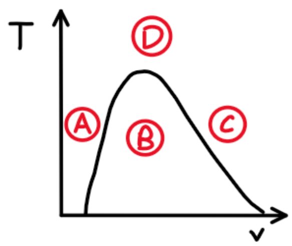
Appendix: Questions featured on the follow-up assessment

Q1.) Which illustration shows an isotherm on a P-v diagram?



(a) **(b)** **(c)** **(d)**

Q2.) Which point on the T-v diagram is a liquid-vapor mixture?



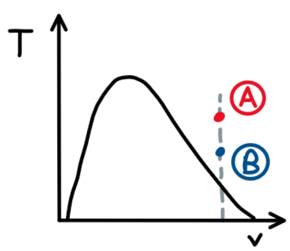
(a) Point A

(b) Point B

(c) Point C

(d) Point D

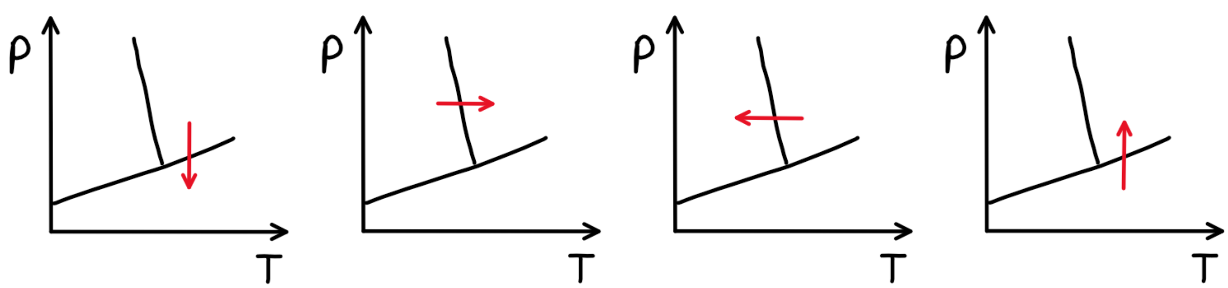
Q3.) Two points are shown on a T-v diagram. The points have the same specific volume. Which point has a higher pressure?



(a) Point A

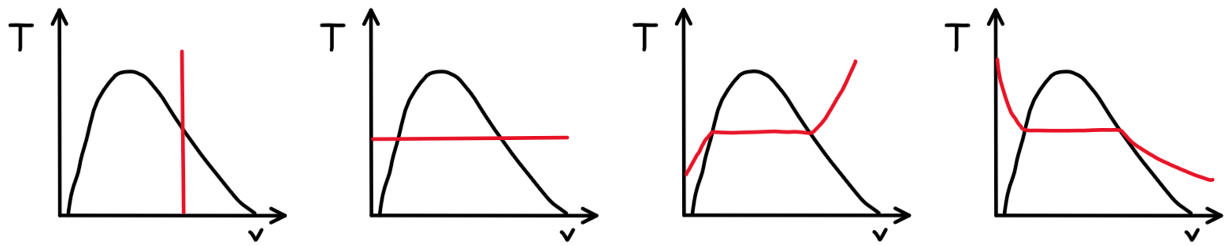
(b) Point B

Q4.) Which P-T diagram shows a process that features evaporation? Arrows depict the direction of each process.



(a) **(b)** **(c)** **(d)**

Q5.) Which illustration shows an isotherm on a T-v diagram?



(a) **(b)** **(c)** **(d)**

Answers to all: d, b, a, a, b