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Software for simulating thermodynamic states of water in a cylinder-piston system

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Abstract. With the advancement of digital technologies and the growing demand for interactive didactic resources in engineering education, the development of computational tools that facilitate the understanding of complex physical phenomena has become increasingly relevant. In this context, this work describes the development of an interactive web application, developed with the Python programming language and the Django framework, aimed at visualizing and analyzing the thermodynamic states of a cylinder-piston system with water. The main objective is to provide an accessible, efficient and didactic computational tool for teaching and learning fundamental thermodynamics concepts. The platform is designed to simulate, graphically and interactively, the states of compressed liquid, superheated vapor and the liquid-vapor phase mixing region (saturation), allowing the user to explore different thermodynamic processes by manipulating specific variables. The application enables them to select known properties, such as temperature, pressure, specific volume, internal energy, enthalpy and entropy or quality (title), allowing the input of their respective values to determine the thermodynamic state of the water. The backend determines the water's state based on the information provided by the user, using thermodynamic tables that have been previously structured and adapted to Python to identify the phase and calculate the other properties of the substance. The frontend, developed with the Processing.js library, offers a dynamic graphical visualization that simulates, in real time, the piston's position and the behavior of the substance inside the cylinder according to the user's input. The adopted methodology stands out for the integrating computational algorithms, an interactive graphical interface and the use of open-source technologies, resulting in a flexible solution. Tests carried out demonstrate that the tool contributes significantly to the understanding of abstract concepts through intuitive visual simulations. In this way, the application presents itself as a valuable resource to support teaching and deepening knowledge in thermodynamics, highlighting the role of computational methods in the development of innovative educational solutions.

Keywords: thermodynamics, software, simulation, cylinder-piston.

1 Introduction

The use of digital technologies in education has significantly transformed teaching methodologies in engineering. With the advancement of interactive and accessible computational tools, new possibilities have emerged to enhance the learning process. Belisário et al. [1] highlight the importance of these technologies, especially in traditionally challenging subjects such as Thermodynamics. In the same context, Boghi et al. [2] emphasize the main obstacles faced in teaching Thermodynamics and point out that the integration of simulations, real-time graphical visualizations and interactive virtual environments has proven to be an effective strategy for fostering the understanding of abstract concepts. This approach provides a more dynamic, active, and meaningful learning experience.

Within this scenario, Belisário et al. [1] emphasize that engineering education has greatly benefited from the incorporation of technological solutions, which bring students closer to real-world situations through the use of computational models. Such tools enable virtual experimentation, manipulation of variables and direct

observation of physical effects, promoting more active learning and enhancing student autonomy. Complementing this perspective, Lopes et al. [3] note that the use of open-source platforms and accessible programming languages, such as Python and JavaScript, supports the democratization of knowledge and contributes to the development of essential digital skills for the formation of the modern engineer.

In the work of Boghi et al. [2], it is highlighted that among the various topics covered in Thermodynamics, the study of the behavior of pure substances in different physical states, such as compressed liquid, saturated phase mixtures and superheated vapor, represents an area of high conceptual complexity. In this context, Borgnakke and Sonntag [4] present the cylinder-piston model as a widely used didactic resource, as it allows for a simplified representation of typical thermodynamic processes such as compression, expansion, heating and cooling.

Based on this, the present work introduces the development of an interactive web application aimed at simulating the thermodynamic states of water in a cylinder-piston system. The tool was implemented using the Python programming language with the Django framework for the backend, responsible for data handling and thermodynamic calculations, and JavaScript with HTML for the frontend, enabling the creation of a responsive graphical interface that visually and interactively represents the behavior of the substance within the system.

The objective is to offer an accessible, didactic and efficient educational solution that supports the teaching and learning of fundamental thermodynamics concepts. The proposed solution combines scientific rigor, interactivity and open-source technologies, reinforcing the role of digital innovation in preparing engineers to face the challenges of contemporary engineering.

2 Methodology

The development of the web application followed an integrated approach combining programming, computational modeling and graphical visualization, with the goal of creating an interactive and didactic tool for the study of thermodynamics. The adopted methodology comprises four main stages: theoretical framework review, structuring of thermodynamic tables, implementation of the backend and development of the graphical interface on the frontend.

The system implemented is a closed cylinder-piston assembly containing 1.0 kg of water, with its functionalities limited to states between the compressed liquid and superheated vapor phases, according to the data available in the thermodynamic tables used as the database. The solid phase was not included in the functionalities of the program.

2.1 Theoretical Framework Review and Structuring of Properties

The development of the application began with a literature review based on classical thermodynamics references, with emphasis on Borgnakke and Sonntag [4]. The goal of this stage was to gather the fundamental concepts of the discipline and identify the essential properties required to characterize the thermodynamic states of water. The theoretical review provided a deeper understanding of the interrelationships among the properties of the substance and the physical conditions imposed by the system, with a focus on the cylinder-piston model, which is widely used in thermodynamics education and analysis.

Based on this framework, the most relevant properties for computational modeling were selected: pressure (p), temperature (T), specific volume (v), specific internal energy (u), specific enthalpy (h), specific entropy (s), and quality (x), the latter being applicable exclusively to the liquid-vapor mixture region. The property tables extracted from Borgnakke and Sonntag [4] were organized and converted into data structures compatible with the Python programming language, enabling their efficient use in the application's backend.

Additionally, saturation conditions, phase boundaries and criteria for determining the state of the substance from known property combinations were studied. This theoretical foundation was essential for implementing the interpolation and lookup algorithms that allow the calculation of the remaining properties based on the values entered by the user, ensuring accuracy and consistency with thermodynamic principles.

2.2 Backend Development

The backend of the application was developed in the Python programming language using the Django framework, which provides a modular and robust architecture for managing routes, forms, sessions and data handling. This layer of the system is responsible for processing the information provided by the user through the web interface, performing the necessary thermodynamic calculations and accurately returning the properties corresponding to the state of the substance.

Based on the known properties entered by the user (in accordance with the state postulate), the implemented algorithm determines the phase of water (compressed liquid, saturated liquid, vapor ou liquid-vapor mixture, or superheated vapor) using saturation criteria as a classification parameter. Based on this identification, the system performs either direct searches or linear interpolation in property tables organized into data structures compatible with the Python language.

To ensure the reliability of the results, validation mechanisms were implemented to verify the physical consistency of the input data, preventing the processing of values outside the limits of the reference tables used as the system's database.

2.3 Frontend Development

The graphical user interface of the application was developed using JavaScript integrated with HTML, supported by the Processing.js library for creating dynamic and interactive visualizations. This layer of the system was designed to provide an intuitive and responsive user experience, allowing the input of thermodynamic property values through simple and accessible forms.

After submitting the data, the interface displays a visual simulation of the behavior of water inside the cylinder, including the movement of the piston, which adjusts according to the volume calculated for the determined thermodynamic state. This dynamic graphical representation is essential to facilitate understanding of the physical processes involved, such as phase changes and volumetric variations associated with different states of the substance.

Furthermore, the interface was developed to ensure compatibility with major web browsers, enabling access to the application without the need for additional installations. The use of the Processing.js library allows for the creation of smooth animations and visual elements that enrich the educational experience, making abstract concepts more concrete and accessible. In this way, the interactive visualization not only assists in assimilating theoretical content but also encourages autonomous experimentation and exploration of thermodynamic phenomena by the user.

3 Results and Discussion

The developed application was tested through various representative simulations of thermodynamic transformations in the cylinder-piston system containing water. The tests involved variations in properties such as pressure, temperature, volume and quality, aiming to verify the accuracy of the backend calculations and the fidelity of the graphical visualization on the frontend.

Figure 1 shows the conceptual design of the cylinder-piston system used as the basis for the computational simulation, indicating the thermodynamic variables involved, such as pressure, volume, and temperature, as well as the possible phases of water inside the cylinder.

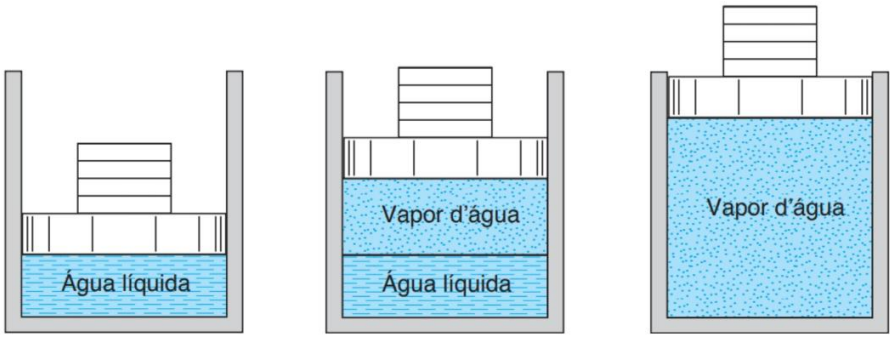


Figure 1. Diagram of the cylinder-piston system and phases of water

Figure 2 shows the graphical interface of the application, which interactively simulates the behavior of the water phases in a cylinder-piston system according to the thermodynamic properties provided by the user. The height of the piston is adjusted based on the calculated volume, and the coloring of the fluid inside the cylinder indicates the phase of the substance: liquid, mixture or vapor. This visual representation significantly contributes to the understanding of the effects of compression, expansion and phase change, making abstract concepts more tangible in the context of thermodynamics education.

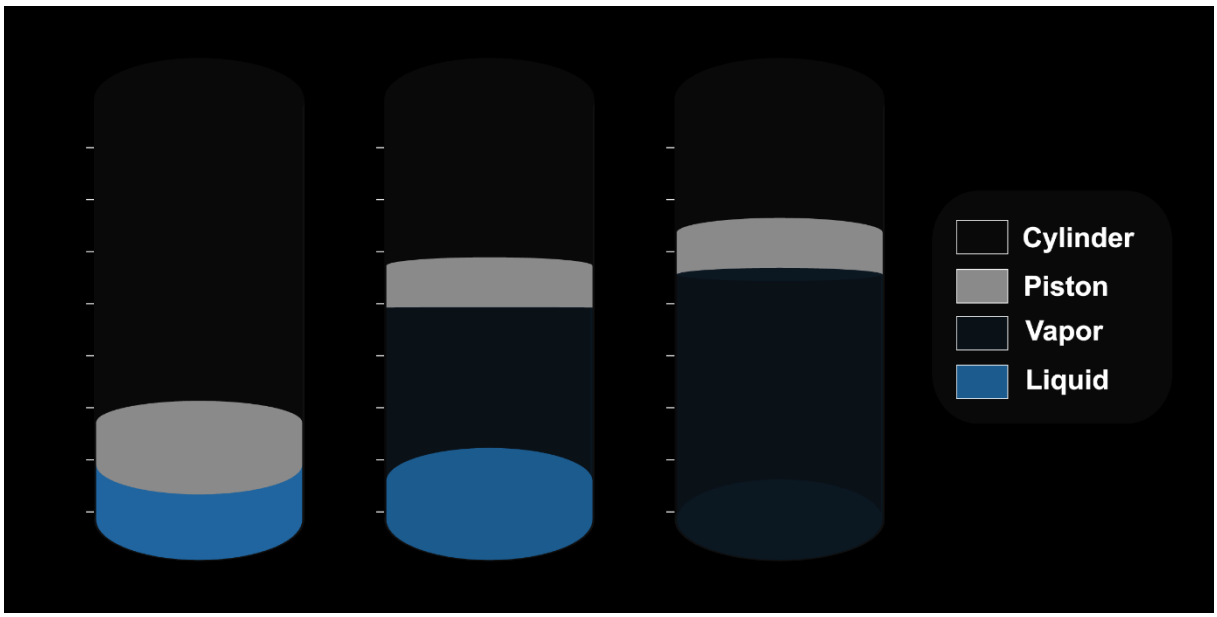


Figure 2. Graphical simulation of the states of water in the cylinder-piston

The structure of the thermodynamic data input forms, illustrated in Figure 3, was designed to provide a simple and efficient user experience. The user can select known properties, such as temperature, pressure, specific volume, specific internal energy, specific enthalpy, specific entropy or quality, through interactive menus and enter the corresponding values in clearly defined fields. The interface includes automatic data validation, preventing entries outside the table limits and ensuring calculation consistency. This organization directly contributes to the tool's applicability in educational environments, allowing students to explore different thermodynamic scenarios quickly, safely, and autonomously.

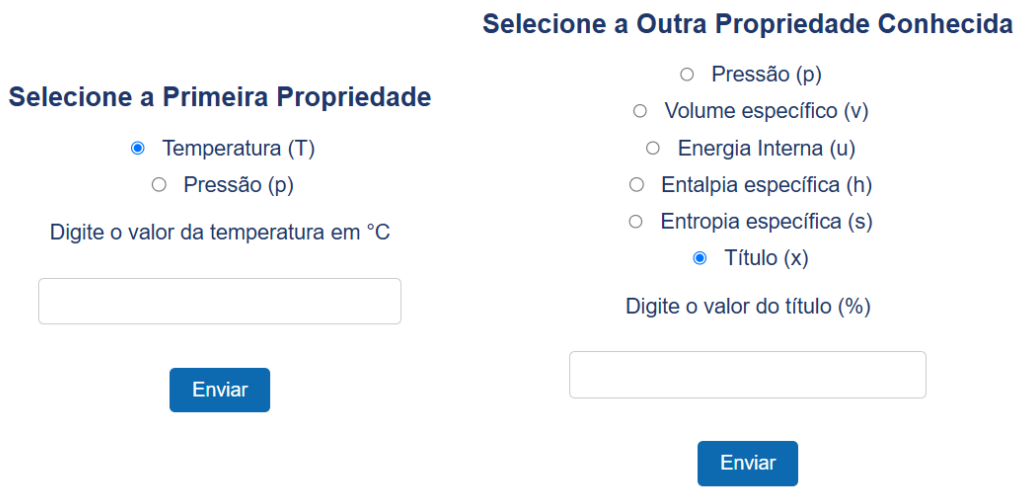


Figure 3. Form for inputting thermodynamic properties into the system

3.1 Simulation Example

To demonstrate the functionality of the application, a simulation was performed with two known properties: pressure of 100 kPa and temperature of 20 °C. Figures 4 and 5 illustrate the initial stage of the simulation, where the user selects these properties through the previously shown form, facilitating the definition of the thermodynamic state of the substance.

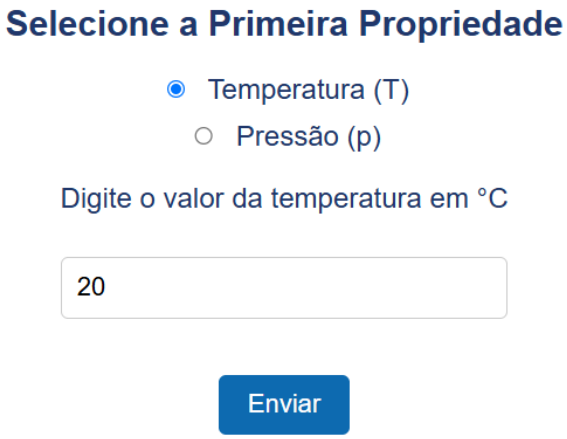


Figure 4. Form for selecting the first known property

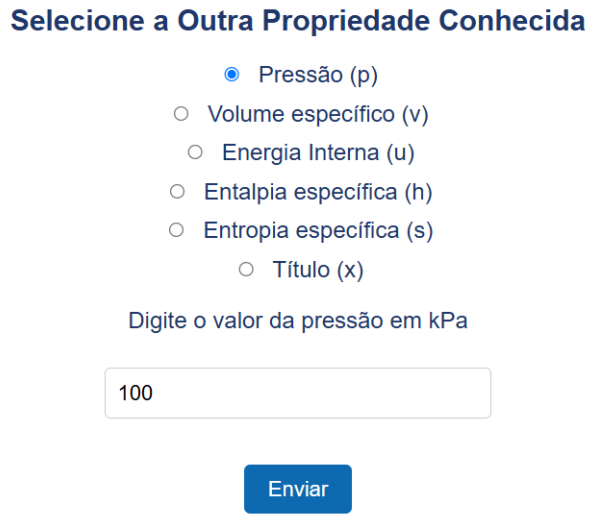


Figure 5. Form for selecting the second known property

Based on these values, the system determined the remaining thermodynamic properties through interpolation in the previously structured tables. The graphical interface represented the fluid with a bluish and opaque coloration, indicating the presence of compressed liquid, and automatically adjusted the height of the piston according to the calculated volume. This simulation highlights the educational nature of the tool, allowing the correlation between numerical data and the visual representation of the physical process. Figure 6 shows the results obtained by the software, along with the graphical visualization of the cylinder-piston assembly.

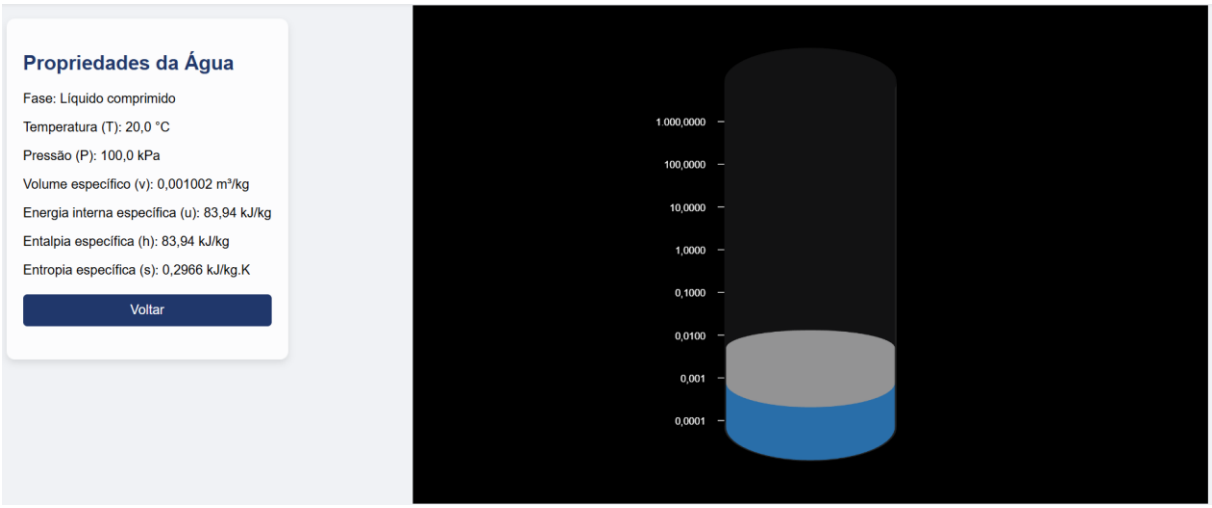


Figure 6. Display of the calculated results for the selected thermodynamic state

4 Conclusions

This work presented the development of an interactive web application aimed at simulating the thermodynamic states of water in a cylinder-piston system, integrating precise thermodynamic calculations with dynamic graphical visualizations. Validation against established table data confirmed the accuracy of the computational model, while the intuitive interface proved to be highly suitable for educational purposes. The tool stands out as a relevant support resource for teaching complex thermodynamics concepts, promoting a more visual, interactive and accessible learning experience.

The results demonstrated that the system is capable of accurately identifying the thermodynamic states of water, correctly applying saturation criteria and efficiently performing interpolations between tabulated data. The application maintained consistency even under conditions near the limits of the tables, evidencing the robustness of the implemented algorithms. The graphical interface and input forms ensure smooth user interaction, facilitating experimentation and visualization of processes such as phase changes, expansion, and compression.

Overall, the application proved to be an effective teaching tool with great potential to enrich thermodynamics education in academic contexts. As future prospects, the expansion of the tool to simulate other fluids and the incorporation of complete thermodynamic cycles and processes are highlighted. Additionally, systematic educational assessments are recommended to measure the application's impact on the learning process.

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