


MATLAB applications for teaching Applied Thermodynamics: Thermodynamic cycles

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Abstract

The main objective of this study is to describe the teaching experience in an applied thermodynamics course, using MATLAB applications developed with MATLAB® App Designer. This course is compulsory for students in their sophomore year of the BSc in Chemical Engineering. MATLAB applications are developed to serve as tools for the teaching of thermodynamic cycles: steam and gas power, and vapor-compression refrigeration cycles. The computer applications are case-based problem generators, that is, based on chosen groups of initial variables, which values are randomly selected each time the MATLAB applications are run. Solutions of the cycle problems, which include thermodynamic cycles plotted in p - h , T - s , and p - v diagrams, and thermodynamic properties of each state of the cycle, are shown when students want to check their calculations. Moreover, the applications allow exporting initial data and solutions to an MS Excel file. The usability and learning experience of the applications were evaluated through anonymous surveys to students and the feedback of the academic staff involved in the course. The main problem, that the students referred, to was the utilization of the MATLAB applications that they considered it was not straightforward. The students believed that the utilization of these computer applications represented a significant improvement in teaching (70%) and expressed their interest in having similar materials in other degree courses (75%). After implementing the computer applications, the academic results showed an increase of ca. 16% in the pass rate.

KEYWORDS

applied thermodynamics, chemical engineering, e-learning, graduate-level education, MATLAB applications

1 | INTRODUCTION

The actual teaching model is no longer focused on traditional lectures but more on students, seeking their active participation in the teaching-learning processes [20]. In this scenario, the teacher must identify the

limitations of lecturing and provide useful materials and tools to students that are adapted to their specific needs. In addition, self-learning should be encouraged to facilitate the understanding and development of skills and the attainment of the learning outcomes corresponding to the subjects taught. Traditionally, lectures required

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a passive behavior of students in the classroom, and they must largely be able to learn unaided; therefore, there was a potential gap between the teaching and learning processes. This typically led to a low success rate, even more, notorious when many students enrolled per course, the content of the course syllabus was intensive (common during the freshman and sophomore years), and tough subjects.

The course on Applied Thermodynamics is one of those traditionally considered tough in the BSc in Chemical Engineering Degree at the Complutense University of Madrid (UCM). This is a compulsory course of six European credit transfer and accumulation system (ECTS) credits, taught in the second semester of the sophomore year of the degree, that is split into two blocks of three ECTS each: phase and chemical equilibrium and power and refrigeration thermodynamic cycles. The block dedicated to the study of thermodynamic cycles, called Thermotecnics, is currently the part of the subject with the worst academic results (each block is evaluated independently). One of the reasons why teachers believe that these low academic results occur is that the resolution of the proposed exercises is given during classes. This contributes to the fact that: the first stage of learning “Having the experience” does not occur directly in the students, but they are merely passive spectators [12]; students study the subject from the continuous repetition of these same exercises, getting to memorize them instead of deepening and acquiring the necessary skills to solve them by themselves. Thus, Stages 2 and 3 of the learning process, “reviewing the experience” and “drawing conclusions from the experience,” do not occur adequately. To solve this problem, other universities have selected a project-based learning methodology to improve student results of this Thermotecnics block [2]. However, this methodology was successful for a longer course, twice the number of credits (six ECTS), and with a much smaller number of enrolled students than at UCM (ca. 10 instead of more than 55 at UCM). Consequently, it does not seem a suitable solution due to the difficulty of its implementation at UCM.

As a first approach to change the teaching methodology and improve the learning outcomes, a case-based learning methodology was implemented in the workshops on Applied Thermodynamics on thermodynamic cycles [11]. The results were quite encouraging. Therefore, the design of computer applications that could motivate the self-learning of students and serve as an aid for lecturers was planned as part of a teaching innovation project. These applications would reinforce Stages 2 and 3 of the learning process [12]: “reviewing the experience” and

“drawing conclusions from the experience,” respectively. MATLAB applications were selected as promising teaching materials since earning, and understanding is more difficult than assimilating facts [12]. This selection was supported by a previous successful experience using notebooks as teaching tools [9], and taking into account that redesigned educational strategies based on computer-aided chemical engineering can integrate courses more efficiently and upgrade the use of computational tools in future courses [26]. Moreover, the benefits of using computer-assisted tools to improve student learning are widely tested, in particular in laboratories [5, 10, 28, 30], and e-learning teaching [1, 7, 8, 21, 22]; and computer savviness is among the top 10 skills chemical engineers [16].

The main goal of this work is to develop MATLAB applications for the teaching of thermodynamic cycles in a compulsory Applied Thermodynamics course year of the BSc in Chemical Engineering at UCM. These applications will aim to encourage self-learning as supporting material for the learning of the students and as an aid for teachers. The MATLAB applications were focused on the teaching of the Thermotecnics block of the Applied Thermodynamics course, specifically on the teaching of thermodynamic cycles of steam and gas power, as well as refrigeration cycles, which to our knowledge has not been done previously. The applications are case-based problem generators, that is, based on groups of unknown variables, which are calculated by students. In this type of problem generator, each time it is run, one of the available cases is randomly selected, and random values are assigned to the initial (known) variables set for the case. The selection of the more suitable software to be used to develop the computer applications, as well as the methodology followed in the design and implementation of the applications, is also described in this manuscript.

2 | SOFTWARE EMPLOYED: MATLAB AND COOLPROP LIBRARY

The selection of the software to be used in the design and development of computer applications, including a programming language and a package to calculate the thermal properties of the fluids in the thermodynamic cycles, is an essential task. The number of a priori available software that could be used to develop the computer applications mentioned in this work is quite large. Finally selected should be well-known by teachers and students, flexible and available, easy to learn and

highly used and recommended in engineering and teaching with large and easy access to documentation, also allowing the development of multiplatform applications (portable), and with GUI support. Moreover, the software must be free and/or licensed by UCM.

Under these requirements, only two possible programming languages came to our mind: MATLAB and Python [17, 27]. Both languages are well-known and extensively used in teaching. Other common features are that both are interpreted languages; recommended as easy learning languages; multiparadigm: supports object-oriented and procedural programming; includes versatile features such as a lot of available packages/toolboxes: for example, Tkinter and PySide6 (Qt) for Python, and *App Designer* in MATLAB; and both are portables. Furthermore, Python is free and can be called in MATLAB, and MATLAB is licensed at UCM.

Since both programming languages offer similar features, the reason for choosing one of them was the familiarity that students of the BSc in Chemical Engineering Degree have with its use. Specifically, through a six ECTS credits course on Applied Informatics (AI), taught during the fall semester of the freshman year of the degree, students learn to code in MATLAB, acquiring an intermediate level. Because of this, MATLAB was selected as the more suitable programming language for the development of computer applications.

A second software had to be used since the MATLAB applications require the calculation of the thermodynamic properties of the fluids used in the cycles to define their states and to plot p - h , T - s , and p - v diagrams and the cycles on these diagrams. In this case, CoolProp was the chosen software [4]. The CoolProp library offers several features that make it particularly recommended for its use as supporting software for teaching thermodynamics: it is open and free, which is not the case, for example, for other typical libraries such as REFPROP [15]; CoolProp can be used with some of the most widely used programming languages such as Python, MATLAB, C++ (the native language of the library), Mathematica, LabView, and so on; and finally, is also portable. Another benefit of this library is that it is quite well documented on the internet, including references for the scientific literature that support the equations of state (EOS) or thermodynamic methods used to calculate the properties of the selected fluid.

3 | METHODOLOGY

The methodology followed in the design of the MATLAB applications is shown in the following lines of action and was probed as suitable in previous works [9]:

- (1) Selection of knowledge and skills whose learning needs greater support and in which the MATLAB applications can contribute significantly to improve the learning outcomes of the course. The selection has been based on the accumulated experience of the teachers, as well as on the needs commented on by the students throughout the previous courses. Applied Thermodynamics is mostly subject in which 80% of the time is devoted to solving classroom exercises, which are mainly standard thermodynamic cycles of power and refrigeration. Therefore, all but one of the developed computer applications were problem generators for steam and gas power cycles and vapor-compression refrigeration cycles. A standalone MATLAB application was dedicated to reinforcing the handling of the traditional tables for the determination of the thermodynamic properties of water and steam; skillful use of tables and property diagrams is requisite for the Applied Thermodynamics course. However, students are strongly warned that solving these types of exercises requires a thorough background in theoretical thermodynamics, which is the remaining 20% of the syllabus of the course (typically neglected by students).
- (2) Design of the MATLAB applications was split into two tasks:
 - Features: the applications were programmed as case-based problem generators, that is, initial known variables of the exercise are grouped as cases, as well as unknown variables (in a previous publication, problem generators were classified into three categories: fixed problem generators, case-based problem generators, and random problem generators) [9]. Therefore, each time that the generator is run, a case is randomly selected, and random values are assigned to the initial variables of the case. This type of generator has as benefits a known and adaptable difficulty but requires in some cases support or guidance from the teacher since several solution sequences can be performed to obtain results.

The specific characteristics of the MATLAB applications designed to support and encourage the learning of thermodynamic cycles in the Applied Thermodynamics course include the graphic representation of the thermodynamic cycles in p - v , T - S , and p - h diagrams (previously, as aid, to obtain the results and the verification by the student of their resolution, or simultaneously with the obtaining of the tabulated results in the results tab). In addition, the results shown in the MATLAB application can be exported as an MS Excel file, together with the initial data (in different tabs), so that the student can try to

- solve the problem in different study sessions; the diagrams can also be exported as an image.
- Appearance: the graphical user interface (GUI) of the MATLAB applications was created using MATLAB App Designer [18]. This tool facilitated the development of the GUIs since it allows dragging and dropping components to arrange their layout. Moreover, the linkage between the GUI and the coding behavior of the application was simplified. The visual components included in the GUI were: text boxes, buttons, tabs, images, and graphics.
- (3) Dissemination of the MATLAB applications has been carried out using the learning managing system (LMS) Moodle. This is the platform implemented at UCM and students are familiar with it since they started their degree. In Moodle, the computer applications were hosted as such, that is, as executable compiled files, and as compressed MATLAB.m files; the compressed file includes the file with the executable class that generates the App Designer, as well as all the functions required by that class to run correctly. Other future options that are being evaluated and will be contrasted with the students are the hosting of the applications in MATLAB Drive or MATLAB Web App Server (not currently available at UCM). Learning how to install and use the MATLAB applications, although simple and even though the students had previously taken a compulsory course (1st semester, first year of Chemical Engineering) in which they were taught in depth how to use MATLAB, was reinforced with video tutorials. These video tutorials have been developed with OBS Studio [3].
 - (4) Evaluation of the usefulness of the developed MATLAB applications. Surveys were conducted among the students to assess the usefulness level of the applications. The surveys were designed in blocks of questions, so the difficulties encountered by the students in the installation and execution of the MATLAB applications could be evaluated, as well as their helpfulness and degree of satisfaction. Finally, the comments of the students on the materials hosted in Moodle provided further feedback on the computer applications.

4 | SYLLABUS AND LEARNING OUTCOMES

The Applied Thermodynamics course is structured in two blocks: phase and chemical equilibrium and power and refrigeration cycles. This work focuses on the second block, whose syllabus is as follows:

- *Lesson 1.* Thermodynamics of steam: Introduction. Compressed water. Wet steam. Saturated and superheated steam. Tables, correlations, and diagrams for thermodynamic properties of water/steam.
- *Lesson 2.* Exergetic analysis of systems: Concept of exergy. Exergy balances in closed systems. Exergy balances in open systems. The exergy efficiency of common equipment. Sankey and Grassmann diagrams.
- *Lesson 3.* Steam power cycles: Introduction. Operation of a thermal power plant. Simple ideal Rankine cycle. Ideal reheat Rankine cycle. Ideal regenerative Rankine cycle. Cogeneration systems.
- *Lesson 4.* Gas power cycles: Introduction. Brayton cycle. Modified Brayton cycles: with reheat, intercooling, and regeneration. Combined gas-vapor power cycles.
- *Lesson 5.* Refrigeration cycles: Introduction. Vapor-compression refrigeration cycle. Types of refrigerants: selection refrigerants. Cascade refrigeration systems. Multistage compression systems. Absorption refrigeration systems. Heat pump systems. Gas refrigeration cycles: Inverse Brayton cycle.

This syllabus is based on the classic applied thermodynamic reference books of Moran et al. [23] and Çengel et al. [6]. The developed MATLAB applications are designed as teaching tools that support the practical study (exercises) of Lessons 1, 3–5; the buildup of applications for Lesson 2 is still under consideration. Therefore, the MATLAB applications should be useful to help students reach the learning outcomes of those lessons, which mainly are:

- (1) Determine thermodynamic properties of steam, gases, and refrigerants using: traditional tables, thermodynamic diagrams (mainly T - s , p - v , and p - h) [14, 19, 25], software based on EOS and correlations, such as CoolProp [4], Termograf [31], XSteam [13], steamtables.com (online) [29], and so on.
- (2) Explain the basic principles of steam and gas power plants and refrigeration systems. Develop, analyze, and optimize thermodynamic models of steam power plants based on the simple ideal Rankine cycle and its modifications (reheat and regeneration), Brayton cycle and its modifications (intercooling, reheating, and regeneration), cogeneration and combined gas-vapor cycles, and refrigeration cycles:
 - o Sketching and understanding T - s , p - h , and p - v diagrams for thermodynamic cycles.
 - o Evaluating properties for the states of thermodynamic cycles.

- o Applying mass and energy balances for thermodynamic cycles.
- o Determining the performance of thermodynamic cycles: thermal efficiency, coefficient of performance (COP), net power output, and mass flow rates.
- o Optimizing thermodynamic cycles according to thermal efficiency/COP, economics, and environmental criteria.

5 | RESULTS: DEVELOPED MATLAB APPLICATIONS

As mentioned in Section 3, the MATLAB applications were mostly built for the study of thermodynamic cycles of power and refrigeration, and an initial standalone computer application was dedicated to enhancing the determination of thermodynamic properties of the cycles, using traditional methods such as tables and diagrams. Therefore, these were the developed applications classified according to the type of thermodynamic cycles:

- I. Thermodynamic properties of water and steam.
- II. Steam power cycles:
 - a. Simple Rankine cycle.
 - b. Reheat Rankine cycle.
 - c. Regenerative Rankine cycle.
- III. Gas power cycles:
 - a. Brayton cycle.
 - b. Brayton cycle with regeneration.
 - c. Brayton cycle with intercooling, reheating, and regeneration.
- IV. Vapor-compression refrigeration cycles:
 - a. Simple vapor-compression refrigeration cycle.
 - b. Cascade vapor-compression refrigeration cycle.
 - c. Multistage vapor-compression refrigeration cycle.

Below, some of the applications developed for each classification group are presented as examples, and their specific features focused on one or more of the learning outcomes of the subject will be described.

5.1 | Thermodynamic properties of water and steam

The application is designed to help students acquire the learning objective “Determine thermodynamic properties of steam... using traditional tables, thermodynamic diagrams” (Section 4). This application consists of a single panel without tabs (Figure 1a), unlike all other applications, in which students obtain

values of two thermodynamic properties corresponding to a random state of water once they push the button “run” (Figure 1b): compressed water, saturated water, wet steam, saturated steam, superheated steam, gas, and supercritical fluid.

The students must determine the unknown values of the other thermodynamic properties of the state using tables: saturated subcooled water and superheated steam tables sorted either by temperature or pressure [14]. They can also use thermodynamic diagrams to establish which tables to use. In this sense, the application includes a “Show diagrams” button that allows them to plot the thermodynamic state in p - h , T - s , and p - v diagrams (Figure 1c); therefore, they can use this button as an aid to know the water phase, that is, the right tables to be consulted to solve the problem.

The “Show results” button is used to display the solutions (Figure 1d) and view the state in the diagrams (as a filled colored circle) if the “Show diagrams” button was not pushed previously. In this way, students can check their solutions and their performance by using tables of thermodynamic properties with different degrees of difficulty, since the latter depends on the initial pair of properties, which may or may not be tabulated.

There is one exception contemplated in the application, which is the case of having either wet steam or a saturation state and the random initial values are temperature and pressure. In this case, students should be aware that the result is ambiguous, and the state cannot be determined from these two properties. The application displays as a result a sentence indicating this.

5.2 | Steam power cycles

The applications developed for the three steam power cycles, Section 5, were designed to achieve the learning outcomes mentioned in item two of Section 4. These applications have a graphical interface composed of a single panel and two tabs: Initial values (Figure 2a) and Results (Figures 2b,c) after running the application. This same structure will be followed in all the other applications presented in this work.

In the “Initial values” tab, after pressing the “Run” button, the values corresponding to the known variables of each exercise are shown, associated in each application to a case; the number of available cases depends on the thermodynamic cycle studied. As an example, in the application for a simple Rankine cycle (two possible cases) the values of the initial variables that can change after each run are:

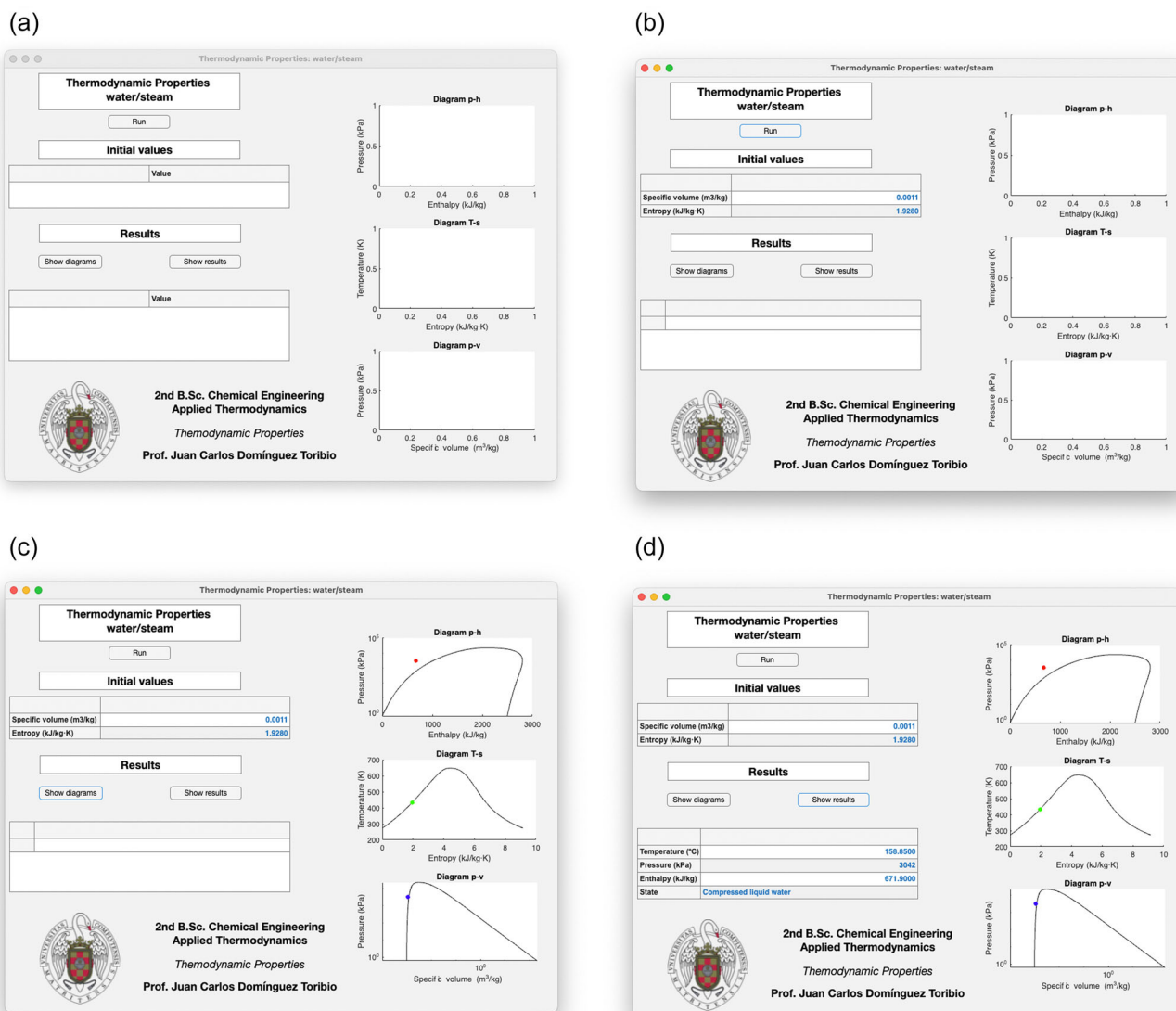


FIGURE 1 Thermodynamic properties application: (a) initial panel; (b) initial random values; (c) thermodynamic diagrams with the plotted state (filled colored circle); (d) panel with the result.

- Case 1: Pump inlet temperature and pressure, ratios in the pump and turbine, and turbine inlet temperature.
- Case 2: Pump inlet temperature and pressure, pressure ratios in the pump and turbine, and turbine outlet quality of the steam.

For each of these two cases, it can be given in turn:

- An isentropic compression and expansion, that is, an ideal simple Rankine cycle.
- An isentropic compression and an expansion with a random efficiency between 0.7 and 0.95.
- An isentropic expansion and compression with a random efficiency between 0.7 and 0.95.

- A compression and an expansion with random efficiencies between 0.7 and 0.95 (typically different values for each process).

The application checks that the generated initial values lead to a solution in which the turbine outlet quality of the steam is always comprised between 0.85 and 0.95; if this is not the case, the application generates new initial values, and these are not displayed until this requirement is satisfied (whether the quality of the steam is a known initial variable or not). The application with the initial values, once it has been run, is shown in Figure 2a.

Finally, students can view the sketches of the thermodynamic cycles in the p - h , T - s , and p - v diagrams,

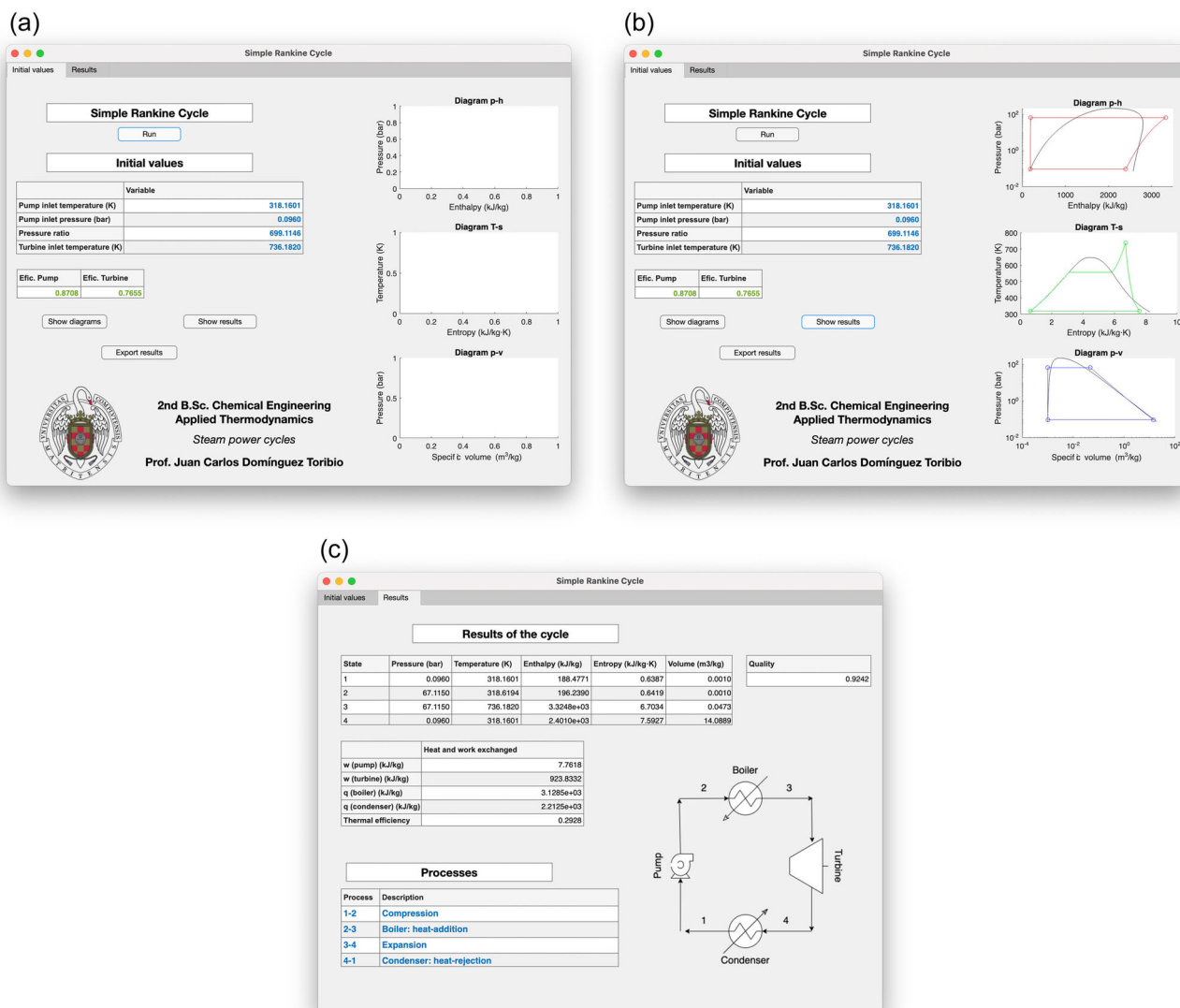


FIGURE 2 Simple ideal Rankine cycle application: (a) tab with the initial values obtained after running the application; (b) tab with the thermodynamic diagrams corresponding to the solved cycle (after pushing the “Show diagrams” button); (c) results tab with the thermodynamic properties of the cycle states, heats and works exchanged, and the thermal efficiency of the cycle.

Figure 2b, either by clicking on “Show diagrams” to help them solve the exercise, or, once they have finished the calculations, by pushing the “Show results” button, and checking them simultaneously with the results that are included in the “Results” tab (Figure 2c): the values of the thermodynamic properties for all the states of the cycle (pressure, temperature, enthalpy, entropy, specific volume and, if wet steam is obtained after an expansion process, the quality of the steam); the specific heat and work exchanged; and the thermal efficiency of the cycle. Furthermore, the applications for the study of thermodynamic cycles include the “Export results” button to export the values shown in the two tabs of the panel [24], creating an MS Excel book that includes two sheets, one for the data shown in the “Initial values” tab and other

for the data in the “Results” tab. This allows the students to have all the data of the exercise, initial and results, to ask questions to the teachers in case they have difficulties in solving it and/or do not get the correct solution.

5.3 | Gas power cycles

Figure 3a,c show the “Initial Values” and “Results” of an application coded for the study of gas power thermodynamic cycles after being run, specifically for a Brayton cycle with intercooling, reheating, and regeneration. The design of this application is like the other power and refrigeration cycles in terms of their appearance, as already mentioned. Thus, there is a button to run the



FIGURE 3 Brayton cycle with intercooling, reheating, and regeneration: (a) tab with the initial values obtained after running the application; (b) tab with the thermodynamic diagrams corresponding to the solved cycle (after pushing the “Show diagrams” button); (c) results tab with the thermodynamic properties of the cycle states, heats and works exchanged, and the thermal efficiency of the cycle.

application and display the initial values of the exercise (Figure 3a), another button to view the sketching of the cycle in the thermodynamic diagrams for air (Figure 3b), and a third button to show the results of the cycle (Figure 3c). The application also allows the export of the initial data and results generated in an MS Excel file by pushing the “Export results” button.

The specific features of the applications of the gas power cycle concerning the rest are:

- Initially, the applications set a reference state tabulated in the typically available tables for the thermodynamic properties of ideal air [6, 23]. Thus, by clicking on the “Show results” button, students obtain the thermodynamic properties for this

reference state. The reference state is randomly modified by pushing the “Change reference state” button (Figure 4a), and when they click to view the new results, students can observe the changes in the thermodynamic properties calculated for the modified reference state of the cycle (Figure 4b). In this way, students are aware that the specific heats and works, and the efficiency of the cycle remain constant, and are therefore independent of the reference state.

- Cold-air-standard properties are taken, that is, constant Cp and Cv.
- The initial value of Cp is random. It is assumed that air behaves as a diatomic ideal gas. Thus, Cp is equal to $5 \cdot R/2$, Cv is equal to $7 \cdot R/2$, and gamma is constant and

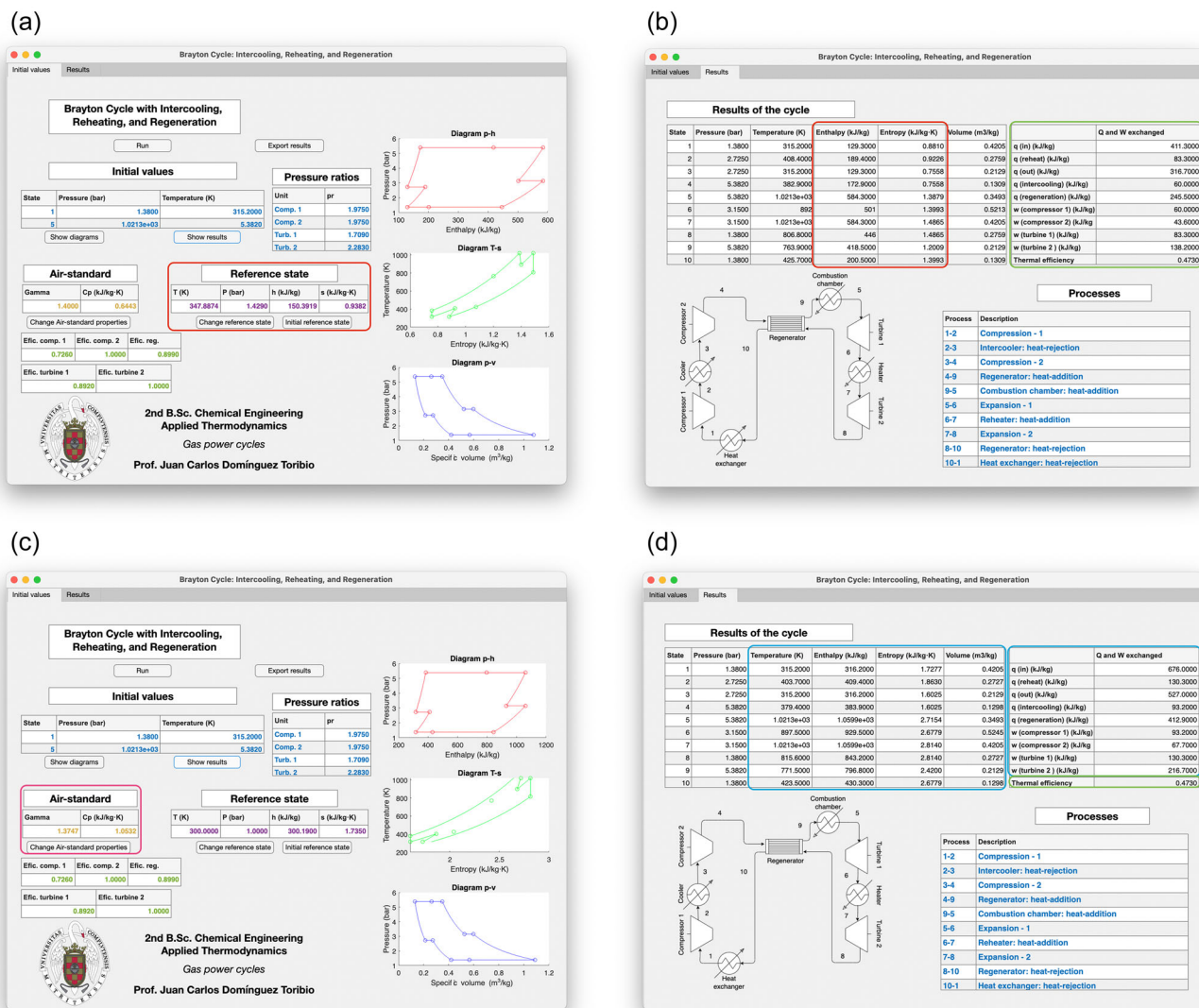


FIGURE 4 Brayton cycle with intercooling, reheating, and regeneration: (a) reference state randomly changes; (b) results for the new reference state: different enthalpies and entropies for each state and same heats, works, and thermal efficiency for the cycle; (c) air standard properties randomly changed (C_p and γ); (d) results for the new properties: different enthalpies and entropies for each state, as well as for heats, works, and thermal efficiency remains the same for the cycle.

equal to 1.4. Therefore, the variation of C_p is achieved by assigning a random value to the average molecular weight of air between 28 and 36 (assuming that it can be enriched or depleted in O_2), that is, the value of R (kJ/kg·K) changes and, likewise, so do C_p and C_v . By pressing the “Change Air-standard properties” button, the value of C_p and C_v becomes obtained by a linear fit of the tabulated data (h vs. T) for ideal air up to a temperature of ca. 1200 K (Figure 4c). By clicking again on the “Results” button, students can check how these are a function of the value of the cold-air-standard properties (Figure 4d). In this case, not only do the thermodynamic properties calculated for each state of the cycle change, but also the specific heat and

work exchanged and, therefore, the thermal efficiency of the cycle.

The specific characteristics of the applications for these cycles allow not only to study gas power thermodynamic cycles, but are also useful in reinforcing such basic and important concepts in the Applied Thermodynamics course as that both enthalpy and entropy are thermodynamic properties referenced to a randomly chosen state (usually a state tabulated or that simplifies the required calculations) and that C_p , C_v , and γ depend for a bimolecular ideal gas, as cold-air-standard is assumed to be, on the molecular weight of the gas, that is, on the “composition” of the air.

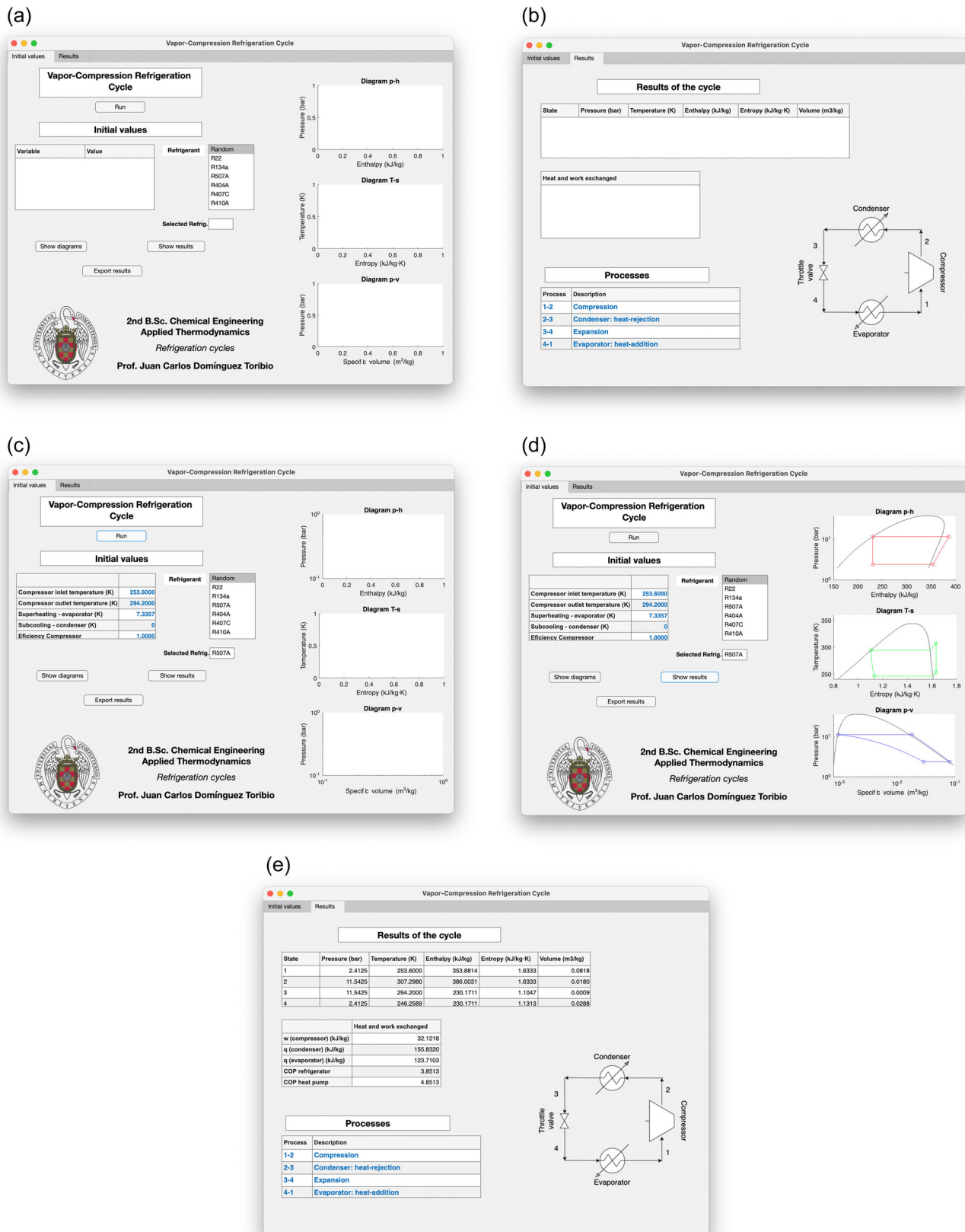


FIGURE 5 Simple vapor-compression refrigeration cycle: (a) initial tab; (b) results tab; (c) tab with the initial values obtained after running the application (random refrigerant); (d) tab with the thermodynamic diagrams corresponding to the solved cycle (after pushing the “Show diagrams” button); (e) results tab with the thermodynamic properties of the cycle states, heats and works exchanged, and the thermal efficiency of the cycle.

5.4 | Vapor-compression refrigeration cycles

These applications have a similar appearance to the rest designed for thermodynamic cycles (Figure 5). Given the similarities between gas refrigeration cycles and gas power cycles, only applications for vapor-compression refrigeration cycles were designed (at least so far). Although these cycles also share similarities with steam power cycles, they have their particularities.

The specific features of these applications for compressed steam refrigeration cycles are:

- Instead of calculating their thermal efficiency, the characteristic parameter of the cycles is their COP.- Multiple refrigerants can be used in the same cycle; in fact, the choice of refrigerant depending on the operating conditions can be considered a specific learning objective of this topic within the course. Six refrigerants are available to choose from in the applications: R22, R134a, R507A, R404A, R407C, and R410A. The application also allows the refrigerant selection to be random when executed (Random choice).
- The most common reference state has been taken for all refrigerants according to the International Institute of Refrigeration (IIR): 200 kJ/kg and 1 kJ/kg·K for the enthalpy and entropy of the refrigerant as a saturated liquid at 0°C, respectively.

- The application for refrigeration cascade cycles has different thermodynamic diagrams for each of the refrigerants used in the subcycles of high and low temperature, that is, six diagrams instead of the usual three.

6 | RESULTS: STUDENT SURVEY

The survey questions, based on previous work on notebooks [9], and the obtained results in the 2021/2022 academic year (57 students of the course Applied Thermodynamics) are shown in Table 1 and Figure 6, respectively.

In Block 1 (Questions 1–3), 10%–15% of the students did not answer the questions related to their performance with the software (downloading, installation, and operation). Eighty percent of the students reported that they were familiar with the applications developed with MATLAB. This can be explained because the students had a compulsory Applied Computer Science course in their freshman year and their knowledge of MATLAB was medium. Most of the students considered (57%) that the downloading and installation of these tools was straightforward, which was consistent given that they were very familiar with Moodle and the installation is quite simple. However, the handling of the applications seemed to be a handicap, since only 35% considered it simple. Therefore, add-ons must be developed that can

TABLE 1 Questions included in the survey.

Question 1	I am familiar with and have used the applications developed to support the learning of the subject
Question 2	Downloading and setting up the applications was straightforward
Question 3	The handling of the applications was easy
Question 4	I consider the use of these tools to be important for the understanding of the classes
Question 5	The use of similar applications is very useful in situations such as the one experienced during the COVID-19 pandemic.
Question 6	The use of the applications of problems improved my understanding of the problems of the course
Question 7	The use of the problem applications improved my problem-solving skills
Question 8	I consider that the use of these tools represents a significant improvement in teaching.
Question 9	I believe that the use of these tools helped me to improve the results obtained in the course
Question 10	I consider that these applications helped to reduce the study time dedicated to the course to achieve my objectives (grades)
Question 11	I consider the number of applications available is adequate
Question 12	The use of the applications has improved my competences beyond those of the course
Question 13	I would like to have more similar tools in the future in other similar courses
Question 14	How do you rate the effort made by the academic staff to develop the applications?

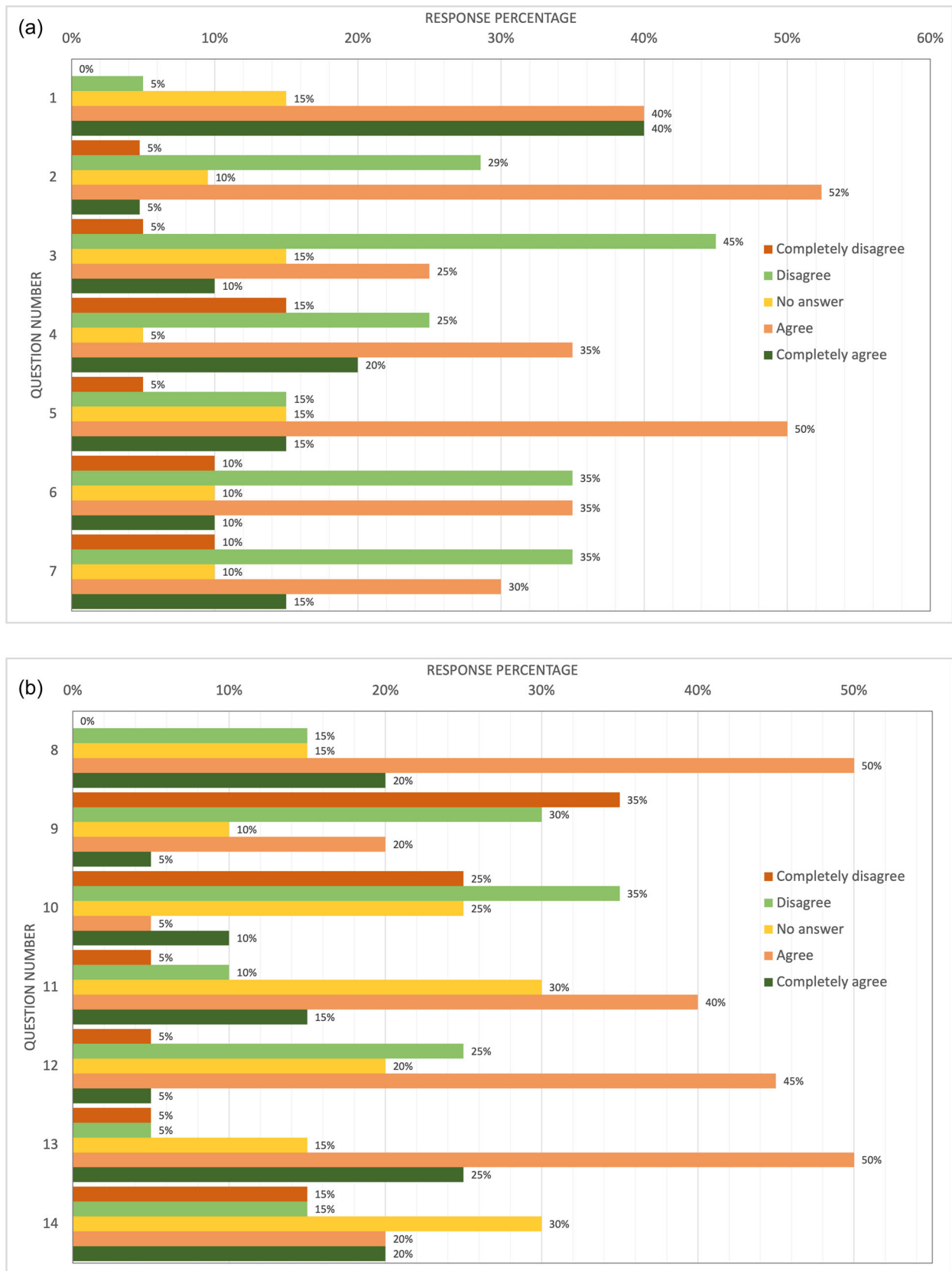


FIGURE 6 Survey results (a) questions 1–7 and (b) questions 8–14: student’s evaluation of the generators.

help students in this task, as was done by developing video tutorials, also hosted in the LMS. Finally, it was found that, once these obstacles were overcome, most of the students had no difficulty in handling the applications.

Block 2 of questions is intended to evaluate the perception of the students, that is, their degree of satisfaction with the applications. The answers to Questions 4, 6, and 7 showed similar results: opinions on the importance of the applications in terms of improving their performance throughout the course were divided practically 50/50 among the students who answered the questions. However, in a situation like a lockdown during the COVID-19 pandemic, the perception of the usefulness of the applications rises to 65%, whereas only 20% still do not consider them useful even in this scenario.

The results obtained in Questions 8 and 12 seemed to be inconsistent with those of Questions 9 and 10. Students valued the applications positively as they considered that they represented a teaching improvement and improved their skills throughout the course (70% and 50% for Questions 8 and 12, respectively). However, they indicated that the applications were not useful either in improving their grades or in reducing the study time required to pass the course (65% and 60% of negative opinions for Questions 9 and 10, respectively).

Finally, the number of applications available appeared adequate to the majority who answered Question 11 (50%). A large majority would like to have similar applications available in future courses.

The evaluation of the learning outcomes of the course was carried out by a final exam (70% of the overall marks) in a computer classroom where the students had to solve the proposed exercises using MS Excel together with the CoolProp Excel plug-in. Also, during the course, the students must resolve and hand in two assignments (30% of the overall marks) where the students must show their skills in the resolution of complex thermodynamic cycles.

Regarding academic results, the applications were included as teaching materials during the 2021–2022 academic year, with a pass rate of 45.8%. Although this is a low rate, in fact, the lowest of all the courses offered in the sophomore year of the BSc in Chemical Engineering that year, it represents an increase of 15.8% with respect to the rate obtained by the students in the previous academic year (2021–2022), which was ca. 30%; similar to the rate obtained by one of the cohorts of the enrolled students in the course of the Fluid Mechanics (also offered during the

sophomore year of the Degree). Therefore, the implementation of the MATLAB applications had a notable impact on the obtained academic results, and in successive years this improvement is expected to continue increasing, although more slowly.

The results achieved were very good, considering student satisfaction, the improvement in academic rates, and the fact that this was the first year in which computer applications were implemented as teaching tools. However, beyond the results of the surveys, in our experience, the teachers need to consider aspects such as:

- From the point of view of students who pass the course, the use of computer applications is successful. However, it is unclear to what extent it may affect the increase in average grades and improvement in the higher-grade range.
- Students doubt that the tools mean a decrease in study time to achieve their goals. In this sense, although we believe that the question is well stated, it is difficult to evaluate the results given that: either it is assumed that the objective of any student is always to obtain the best possible grades, or the goal is a variable that is difficult to assess given that it can vary from passing the course, to get the highest mark, and even achieving a grade that is “acceptable” for the student and has more free time for other activities or courses.
- The handling of the applications seems to be the biggest problem for the students. In our case, the time available is too short to be able to complete the syllabus and teach in detail how the applications must be run/used, and the material provided (videos, examples, etc.) does not seem to be sufficient. This problem was already the major handicap in a previous publication using notebooks instead of applications. In our experience, perhaps the only possibility to solve it is to plan extra workshops dedicated to demonstrating their use and solving possible doubts that may arise on the part of the students. In this sense, we believe that the coding of individual computer applications for each type of cycle was a good decision, since making a single application covering all cycles would have increased this key difficulty.

7 | CONCLUSIONS

In this work, some applications were developed using MATLAB software, to promote self-learning and facilitate the understanding of exercises related

to the study of thermodynamic cycles that are part of the syllabus taught in a course on Applied Thermodynamics. The applications were classified according to the type of thermodynamic cycles; thus, they shared common characteristics and included specific features of each type of cycle: steam and gas power cycles, and vapor-compressed refrigeration cycles. These applications were designed as case-based tools so that the resolution of the problems presented was in accordance with the difficulty required to pass the course. The results obtained through surveys identified weaknesses in the installation and running of the applications, as well as ambiguous results since the answers of the students were incoherent in some cases. Either way, most of the students wished to have similar tools available in other courses within the BSc in Chemical Engineering at UCM. Finally, the academic results of the course showed an increase of 15% in the pass ratio.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The software that is presented in this manuscript is available at <https://github.com/JuanCDT/MATLAB-APPS-Thermodynamic-Cycles>. To express further interest, please contact Prof. Juan Carlos Domínguez (jucdomin@ucm.es) at Complutense University of Madrid (Spain).

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