



Research article

Development of a new educational package based on e-learning to study engineering thermodynamics process: combustion, energy and entropy analysis

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ABSTRACT

This paper presents a new educational package based on e-learning called TermolabUA integrated by three programs, which are VOLCONTROL focused on the analysis of steady-state flow devices, CarnotCycle aimed to analyze reversible and irreversible processes, and CombustionUA to study combustion processes. The educational package was designed for both, to promote significant learning on some thermodynamic topics in undergraduate students, and to help the student to reach the cognitive competencies of interpreting, arguing and proposing, and interacting with the different graphical user interfaces to solve relevant cases studies. Also, the teaching-learning activity helps them to understand the influence of a specific variable on the energy and entropy behavior of the selected systems, which is traditionally studied manually in a classroom. The results of the t-Student tests showed that the average grades obtained by the students in the problems using the software were higher than the average grade without using the software. The estimate for the average grade difference was 0.56 with a P-value = 3.31E-13 for Problem 1 and 0.631 with a P-value = 3.31E-13 for Problem 2 in the Workshop- VOLCONTROL. Similar results were obtained for the problems reported in the CarnotCycle and CombustionUA Workshop with an estimate for average grade differences and P-values lower than 0.79 and 0.05, respectively. It means that the new software package significantly improved the learning skills of the students.

1. Introduction

Generally, people that work in the industry of chemical and petrochemical processes need workers highly trained in thermodynamics. People with that training have excellent troubleshooting skills that help them to solve many problems in a highly effective way. To acquire this skill, it is necessary to have exceptional preparation in their thermodynamics courses, as well as in the engineering laboratory practices because it provides students real manipulation of instruments and devices, allowing them to have both experiences, theory, and practice. Although laboratories are one of the best ways of teaching, they have some disadvantages, such as the cost of their creation as well as their maintenance [1]. Due to technological advancement, the use of computational tools for simulation of industrial processes is an exciting alternative to complement the theoretical classes in a classroom. It has been found that the

implementation of process simulations increases the interest of students and their motivation [2].

The teaching of thermodynamics has made significant progress moving from the traditional theoretical method to the use of computer technology, allowing the student to have higher participation in the development of classes [3, 4]. Ahmet Gurses [5], determined that students trained through interactive teaching obtained significantly higher performance than through the traditional training method. This trend is driven by the growing interest of students in e-learning systems, which are web-based learning systems, computers, and everything related to virtual learning that includes technologies and information systems either online or offline [6]. The implementation of this type of knowledge provides many benefits to students promoting better education [7, 8]. However, this new way of learning has a significant challenge in

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measuring its quality level, because there is no reference base to evaluate electronic learning systems [9, 10].

There are two essential aspects when evaluating the quality of e-learning systems; these are the pedagogical and the technical issues, which are related to measuring the level of quality of this type of e-learning systems [11, 12, 13, 14]. Besides, the opinion of the institutions, teachers, students, and software designers [15, 16, 17, 18] is considered in the evaluation. Vladimir Nikolic [19] did a survey to determine the primary indicator that measures the quality of e-learning systems considering the two main perspectives, pedagogical and technical. He used different criteria such as the learning environment, efficiency, performance, reliability, functionality, usability, interaction, services, customization, learning activities, access, cost, technology, content, among others [20, 21]. Nicolic [19] found that content was the crucial quality factor for e-learning systems and that the main disadvantage when analyzing quality models was the absence of model validation. Eldin Wee Chuan Lim [22] developed software of design within the Technology Enhanced Learning (TEL) to facilitate learning through a repeated practice approach by Chemical Engineering students who work with a central module called Fluid- Solid Systems. He determined that the students that use the software with higher frequency during the semester obtained better results in the final exam. It is related to the significant number of variables used when studying or simulating a chemical or mechanical process, which affects the student motivation to obtain the specific competences of the class. The mood of the students is critical to absorb a considerable amount of vital information [23] Novel engineering software is being implemented in engineering classes to help in the solution of this problem.

Samuel Cartaxo [24] developed free educational software to teach transient analysis of shell and tube heat exchangers to undergraduate students. He concluded that the use of the program improves the student performance on engineering classes, as it allows students to practice heat exchanger analysis avoiding tedious, repetitive calculations. Currently, there is a substantial increase in the development of computer applications that seek to facilitate and promote engineering education [25, 26, 27, 28, 29, 30].

The arrival of ICTs has radically changed the landscape of education; its evolution in recent years has boosted the innovation and creativity of students, encouraging the development of computational tools. They are more frequently used in different areas of engineering, propagating the advantages of process simulation in student learning.

The ICT's have allowed the introduction of e-learning, giving students the possibility of non-face-to-face learning, motivating a self-taught training, and therefore helping the "Lifelong Learning." It was possible because the ICTs were able to work with some of the basic postulates of the classical educational theories such as behaviorism, cognitivism, constructivism, and socio-constructivism. Behaviorism seeks to achieve the appropriate response of students to the stimulus; cognitivism pursues the stimulation of learning strategies by the student; constructivism takes the learning as an active process of the students; socio-constructivism focuses on the integral development of the student.

With the progress of the educational theories, the students have taken a more critical role in their education [31], where they are responsible for their learning process. Therefore, the main contribution of this paper is to present the development of a new educational package focused on the teaching of thermodynamics where the students can improve their theoretical-practical skills, without limiting their learning to the institution's facilities, as is the case with classical engineering laboratories. The software package uses the applications of information and communications technologies (ICT). It contains three software that can be downloaded from the SICVI platform of the University, allowing students to use it from anywhere and at any time. In this way, the student can be motivated to do research, allowing them to analyze thermodynamic processes [32, 33], applied energy, and entropy balances [34, 35] making parametric variations that are usually tedious when doing them manually. The aim is to encourage the development of lifelong learning

[36, 37], increase the ability of students to analyze the phenomena that happen in these processes, and train engineering students to meet the competencies of the ABET accreditation model [33, 34, 35, 36].

The literature review of the educational theories used to develop this new educational software is included in section 2. Section 3 presents the motivating example, where the benefits of this new software on the student learning process are shown. Then, in section 4 (Proposed design), the structure and organization of the new educational package in the area of thermodynamics are developed and supported in a flowchart of the algorithm. Section 5 (methodology) presents the technical specification of the graphical user interface, a description of the cognitive skills developed with the educational package, the method used to score the test results, and the fundamental equations involved in the informatics application. The results and discussions are presented in section 6. This section contains a sensitivity analysis, the case studies used, and a usability test analysis done to the computational package. Finally, the conclusion is presented in section 7.

2. Literature review

Different research results in recent years have recognized the importance of e-learning-based education for the development of the cognitive skills of undergraduate students [42]. Virtual environments can be integrated into almost all thematic content developed in any university curricula allowing the transmission of knowledge more effectively to build in the student a critical and analytical perspective [43].

For students, it is particularly essential the use of e-learning, since in some cases, there is an inability to develop a learning process without Virtual environments. Also, the connectivity offered by these tools is an essential element for the development of the teaching-learning process outside the classroom. It allows access to information from anywhere [44].

Despite this reality, few policies and initiatives have been developed to support the use of e-learning and educational software for engineering education [45]. It may be happening due to the thought that e-learning and educational software replace the process of understanding of this generation through a traditional classroom [46]. However, some companies, educational centers, and university professor research groups emphasize the importance of creating classes of high-quality content based on e-learning for engineering education [47]. Also, they focus on the creation of significant learning spaces [1], based on both Constructivism [1] and Cognitivism educational theory [1].

For engineering students, significant learning based on practical experiences in e-learning [48] and educational courses [48] has been fundamental in the learning processes since they have allowed complementing the theoretical concepts developed in an academic thermodynamics class [49]. E-learning lets the development of critical thinking and self-learning with the help of the Information and Communication Technologies ICT integrated by the developed software [50].

On the other hand, the constructivism theory was developed by important authors such as Jean Piaget, and Lev Vygotsky [51]. It is based on the development of very relevant authentic educational activities in the area of specific knowledge for the construction of new knowledge [52]. Thus, for the development of the activities with the assistance of e-learning, students acquire new knowledge taking as a basis the previous teachings acquired in the fundamental concepts and definitions [53].

The other relevant educational theory in the development of learning strategies for e-learning is cognitivism [54], where students organize their mental schemes to achieve the desired knowledge in the best way with interaction with the developed tools. Thus, the use of educational software improves the development of cognitive abilities in students [55].

Some commercial software solutions and tools allow the development of specialized studies, such as ANSYS, ChemCAD, Hysys, among others [56] However, due to the extensive technical requirements, these tools have not been widely used in the learning process of engineering

students. Thus, computer solutions based on educational software have been proposed with a low degree of complexity, to achieve a better conceptual adoption of the topics involved [57]. Therefore, educational modules have been developed in e-learning platforms to promote the use of programs in the area of thermodynamics. It was created for thermodynamic analysis of open systems [58], and the calculation of entropy and exergy in closed systems [59], to determine the positive impact that it generates in students.

3. Motivating example

The new generation of engineering students belongs to the Z generation that was born in the mid-1990s, and the early 2010s as ending birth years. This generation uses digital technology (Computers, tablets, cellular, video games handheld Consoles, etc.) from an early age, and they do it in a relaxed and effortless way. They use the internet and social media daily.

These skills, acquired by the technological advance of the time they were born, allow this generation to study in a more relaxed, faster, and more motivating way with the use of computers. For this reason, when teachers leave the use of the traditional method of the classroom board and the use of video beam to give more participation to the student in their preparation using computers, their motivation increases, making their teaching process more effective.

It has been evidenced when in classes, they use specialized software such as Aspen HYSYS to simulate different chemical and physical processes obtaining excellent results. Traditional teaching methods are not as effective in this generation. Mechanical, Chemical, and Process engineering classes have many important laboratories in their curriculum to complement the theoretical part. However, the theoretical part is so extensive due to the many processes and variables involved, that it is challenging to cover all topics with laboratories.

On the other hand, there are many classes related to industrial processes such as thermodynamics [60], heat [61], and mass transfer [62], etc. It is beneficial to develop software for each type of unit operation that helps complement laboratories. With the creation of the software, three things are fundamentally helped:

a) Classes do not have to be entirely face-to-face.

The software helps to simulate the different unit operations as if it were a real laboratory. In fact, it can be studied more process variables and analyze the multiple behaviors that cannot be seen in a real laboratory. It helps to understand many phenomena that cannot be explained in standard classroom classes.

b) Motivation increases.

Students who use digital technology from an early age are highly motivated to use computers in almost all of their classes. It helps them to be more involved in their classes and their learning.

c) Laboratory expenses decrease.

The creation of software decreases the number of laboratories that have to be done for a regular class, and the use of many chemical reagents and essential elements such as water would be avoided. Also, it helps to reduce environmental pollution because the waste caused by laboratories is diminished.

The software is easy to use and can be easily installed on educational platforms that make students have direct contact with them immediately. Evaluations can be done quickly as soon as each experience ends. The only complicated part of this methodology is to create a student-friendly software for each subject considering each specific process. It is hard work for the teacher, but at the end, when the software is produced, the

work becomes very easy because only simple modifications to the user interfaces would be needed over time.

4. Proposed design

The proposed design is an informatics tool named TermolabUA, which is an educational package composed of three software of mechanical/chemical/process engineering focused on particular areas of thermodynamics. The first software, named VOLCONTROL, is a software focused on mass and energy balances for steady-state flow devices such as nozzle, diffuser, compressor, turbine, throttle valve, mixing chamber, and heat exchanger. In the case that the user select diffuser a new window will appear with a drawing of the system with the corresponding input variables, such as inlet area, temperature, pressure, velocity, and heat transferred to the surroundings, and the output variables such as outlet area, mass flow, and velocity. However, the software was designed to change the output variables depending on the needs of the user. Also, the user can select a different process from the software such as the compressor and follow the same sequence used for the diffuser. It means that the algorithm can analyze any variable wanted by the user.

The second software, CarnotCycle, is focused on the study of the principles of the entropy balance and lets the analysis of reversible and irreversible processes in a heat engine, heat pump, refrigeration cycle, and power cycle. In the case of choosing the refrigeration cycle, the input variables are the kind of refrigerant, heat obtained by the environment, inlet pressure of the compressor, volumetric flow rate, and output pressure. If a heat engine is chosen, the same sequence is used.

The third software, CombustionUA, let the students analyze complete and incomplete combustion processes, facilitating the study of essential aspects such as the dew temperature of the products or the adiabatic flame temperature for fifteen different fuels. The effect of the humidity of the air is considered as an input to analyze the effect of the water vapor in the efficiency of the combustion process.

The software VOLCONTROL, CarnotCycle, and CombustionUA were registered in the government entity named National Copyright Office (DNDA-Dirección Nacional de Derechos de Autor, <http://derecho.deautor.gov.co/>) with registration numbers 13-64-123, 13-66-21, and 13-66-22, respectively.

It is necessary to have the corresponding Matlab Compiler Runtime installed to execute the programs. The educational package works on any computer that operates with Microsoft Windows 64 bit and free space of 71.2 Mb. Figure 1 shows a schematic of the flow chart of the TermolabUA package.

5. Methodology

5.1. Presentation of the graphical user interface

The educational package was designed with a comfortable level of difficulty that allows undergraduate students to interact through the different graphical user interfaces, helping them to understand the level of influence of a specific variable selected over the entire process analyzed. Figure 2 shows a preview of some of the graphic user interfaces of the TermolabUA package.

TermolabUA was designed primarily for pedagogy, focused on teaching the thermodynamics class, giving the teacher a new method of teaching and evaluation. This computational tool allows complementing the theoretical-practical courses of thermodynamics with the use of computer simulation, stimulating the interest of the students in the analysis of different thermodynamic processes and ensuring that students comply with the ABET accreditation model competencies as it is summarized in Figure 3.

The proposed educational package allows measuring the degree of compliance of the Thermodynamics subject at Universidad del Atlántico with learning outcomes by Engineering undergraduate students.

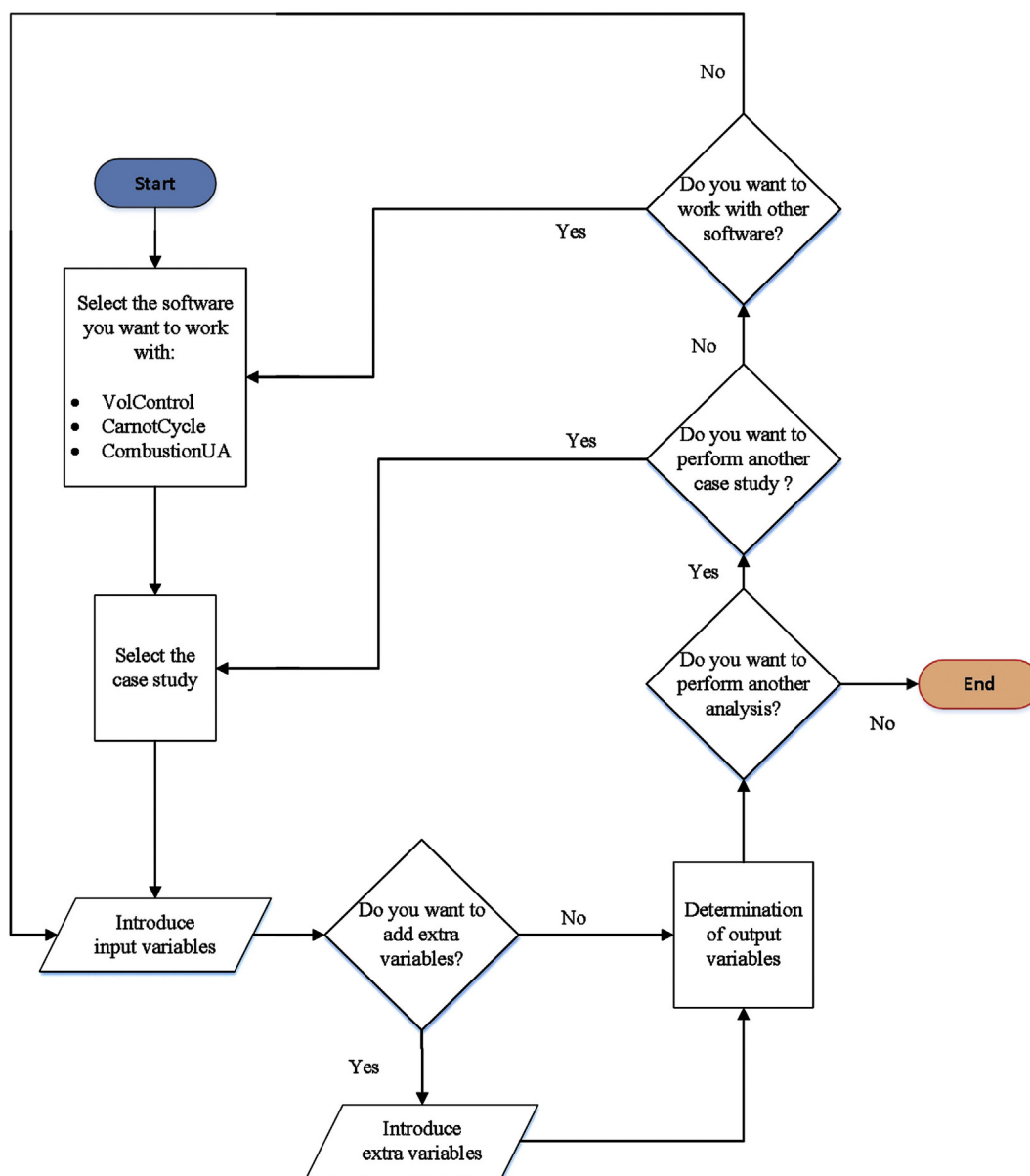


Figure 1. TermolabUA Flow chart.

According to the ABET standards, the educational objective of the program are considered as “Basic knowledge” in the simulation and modeling of chemical processes, while the Learning Outcomes are (a) Ability to apply knowledge of mathematics, science and engineering, (b) Ability to design and conduct experiments, as well as analyze and interpret data, (d) Ability to work in multidisciplinary teams, and (e) Ability to identify, formulate and solve engineering problems, [41].

From the selected Program Educational Objectives, and some learning outcomes suggested by ABET for the Mechanical Engineering and Chemical Engineering program, the necessary evidence was collected to measure the degree of student learning when performing this activity through e-learning.

5.2. TermolabUA

The authors developed some statistical tests to measure student performance by solving case studies with software assistance and manually. The case studies are included in a workshop, as shown in Figure 4.

However, the educational skills considered in this study were not only those of producing graphs clearly, but also in evaluating four essential

cognitive skills (argumentative claim, modeling, interpreting data/information, and organization) [63]. They were considered when solving each case study based on the significant learning theory [64], as follows:

The cognitive skill named argumentative claim (Cognitive Skill – 1, CS1) was obtained when students defend conclusions from data, developing a strong opinion/argument through explicit, well-sequenced claims, and interpreting the scope of the case study. In this sense, the student could demonstrate his idea and opinion with reasons that justify the analysis supported in the fundamental thermodynamic laws in the result and discussion section of the Workshop. This skill is referenced to the NGSS Science Practice 7 standard [65].

Also, the cognitive skill named modeling (Cognitive Skill – 2, CS2) based on the standards NGSS Science Practices 2 [65] and CCSS.MATH.PRACTICE.MP2 [66], was reached when the student generates a visual representation of the data, using appropriate tools to understand and analyze the real situations in the case study.

Also, it was expected that the student achieves the cognitive skill named interpreting data/information (Cognitive Skill – 3, CS3) from sources and draw, which was obtained when the student read the problem statement, understands the phenomena involved in the case study,

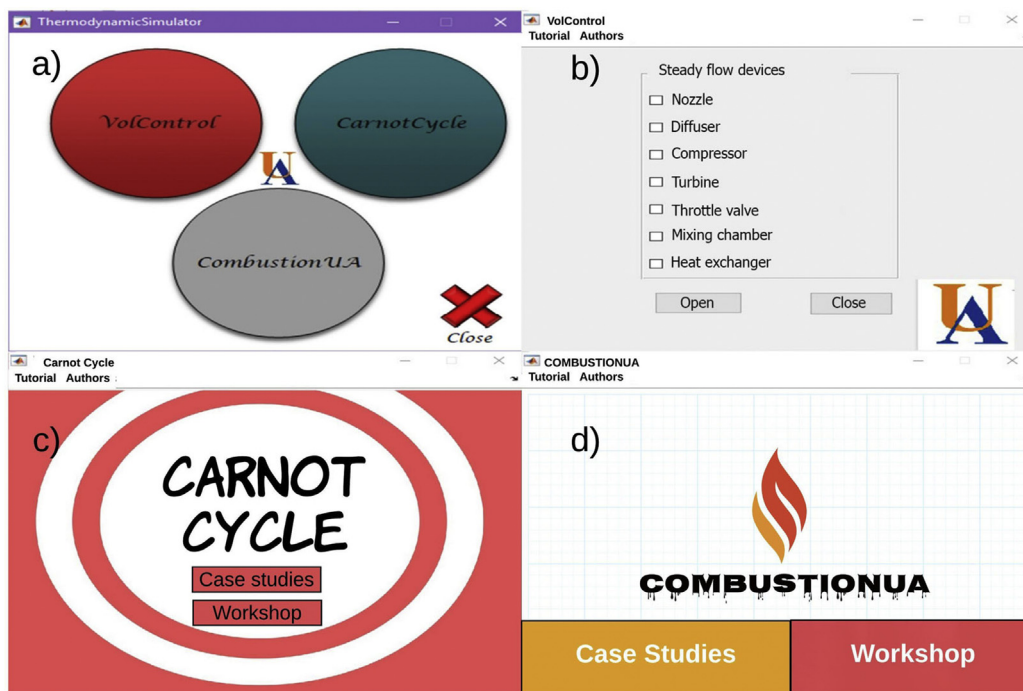


Figure 2. TermolabUA user interface, a) Main window, b) VOLCONTROL interface, c) CarnotCycle interface, and d) CombustionUA interface.

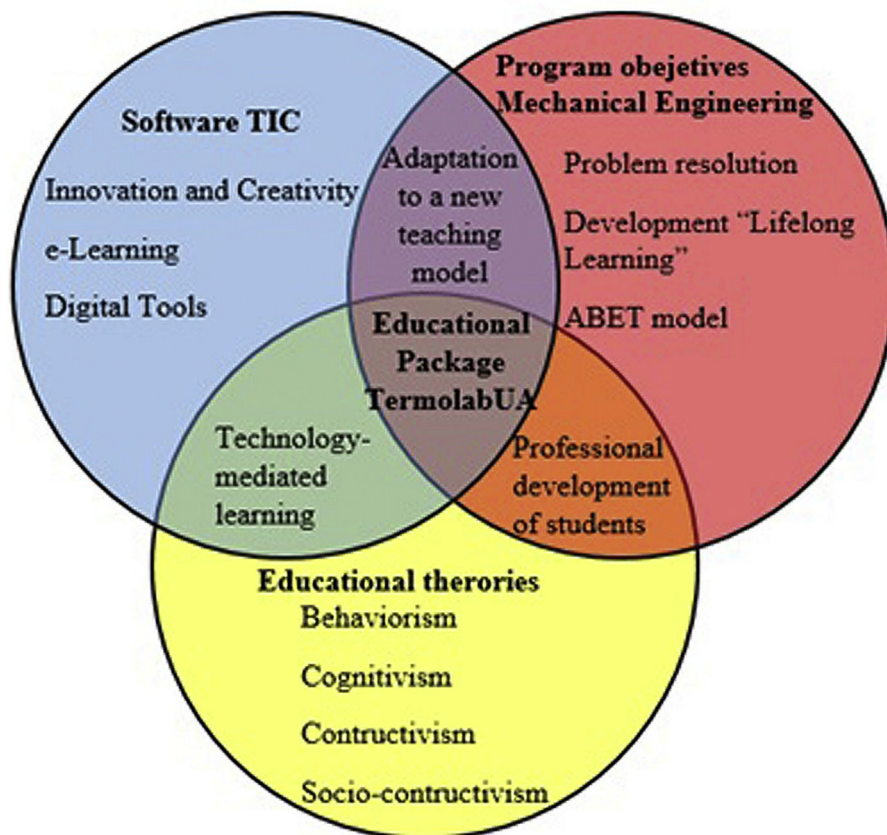


Figure 3. Venn diagram of TemolabUA.

Energy balance in Open Systems
Software VolControl v 1.0

Thermodynamics Workshop
UNIVERSIDAD DEL ATLÁNTICO

Name: Paudy Elena Caballero Castillo Date: 03/09/2018

1. In a nozzle device as shown in Figure 1, it is desired to study the influence of the temperature change on the ratio of areas (A_2/A_1) and the ratio of velocities (V_2/V_1) at different ΔP (kPa), using the VolControl v1.0 software. The operating conditions are shown in Table 1. The temperature change must be varied every 2°C in the range (6°C-18°C), for four output pressure values between (100kPa - 250kPa). Write the result values in Table 2 and plot the result values in Figure 2; also perform the analysis and discussion from the results.

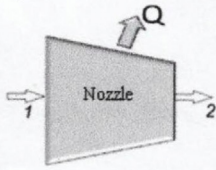
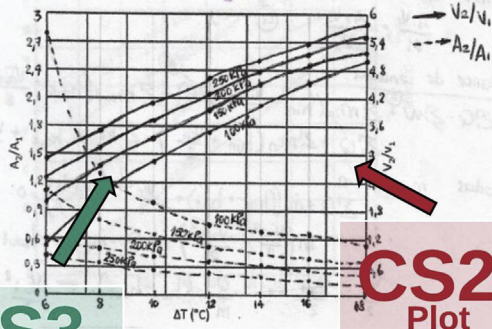


Figure 1. Nozzle diagram

P_1 (kPa)	T_1 (°C)	V_1 (m/s)	A_1 (cm ²)	(kW)
300	200	45	110	1.5

Table 1. Operating conditions of de Nozzle

AT (°C)	$P_1=100\text{ kPa}$		$P_2=150\text{ kPa}$		$P_3=200\text{ kPa}$		$P_4=250\text{ kPa}$	
	A_2/A_1	V_2/V_1	A_2/A_1	V_2/V_1	A_2/A_1	V_2/V_1	A_2/A_1	V_2/V_1
6	2.8590	1.0468	1.1765	1.9043	0.9497	2.4812	0.4192	2.9514
8	1.3321	2.2367	0.8078	2.7514	0.4645	3.1891	0.3414	3.5727
10	0.9738	2.9850	0.6531	3.3981	0.3915	3.7662	0.2985	4.1062
12	0.8249	3.5501	0.5673	3.9380	0.3441	4.2669	0.2666	4.5750
14	0.7189	4.0816	0.4987	4.4125	0.3111	4.7350	0.2428	5.0011
16	0.6444	4.5122	0.4526	4.8403	0.2810	5.1211	0.2311	5.3931
18	0.5882	4.9531	0.4167	5.2335	0.2632	5.4990	0.2209	5.7586



CS4

CS3

CS2

Table - Plot

Analysis and discussion.

It was observed a proportional relation between the output area and the fluid temperature change also by reducing the temperature values every 2°C at constant pressure there was an increase in the output velocity and a decrease in output area of the nozzle. However a change in the pressure values at constant temperature the outlet area is smaller as the pressure increases so they are inversely proportional. In addition, at constant temperature both the velocity ratio and pressure increased which is a consequence of the conservation of mass-energy where kinetic energy is more important there are smaller areas. Thus to reach the desired discharge velocity the area must be reduced to the desired value but at high values the output area is independent of the output temperature.

CS4

CS3

CS2

CS1

Analysis and discussion

Figure 4. Example of a workshop made by a student with VOLCONTROL software.

and carry out activities to complete the table and plot of the Workshop correctly. This cognitive skill is defined according to the standard NGSS Science Practice 4 [65], and CCSS.MATH.PRACTICE.MP3 [66].

Finally, the last cognitive skill evaluated was the organization (Cognitive Skill - 4, CS4), according to the CCSS.ELA-LITERACY.CCRA.W.4 standard [66], which measures the use of text structure and documentation to communicate with clarity and coherence the technical ideas.

5.3. Participants of the study and scoring criteria

For the validation of the educational package, three evaluative workshops on Steady-state flow devices, CarnotCycle, and Combustion processes were developed. These workshops were done by 120 Senior Mechanical Engineering students of the Thermodynamic class at Universidad del Atlántico. The students solved some specific case studies

where they had to perform a parametric variation. The workshops were solved with the help of the software, and without the help of the software to compare both results. A teaching assistant (T.A.) with high knowledge in the subject of thermodynamics was the person who graded the different workshops mentioned above with the aim of evaluating the educational competences acquired by the students, thus avoiding a possible bias of the thermodynamic professors, or designers of the educational software. After grading the workshops, the T.A. organized all the student grades in tables of a worksheet in Excel to be analyzed eventually with the help of statistical software.

Regarding the research design, it was used Simple Comparative Experiments to know whether two different groups give different or similar results. Then, a Student's t-test was used to compare the advantage of using the software quantitatively. It was used the computers of the University so that the students could do the Workshop in Matlab.

Table 1. Scoring rubric.

Cognitive skills [37, 38, 39, 40]/Test section	Excellent (4.6–5.0)	Satisfactory (4.0–4.5)	Need improvement (3.0–3.9)	Unsatisfactory (1.0–2.9)
CS1/Analysis and discussion	It develops the opinion/argument of the problem with a clear claim.	It describes the opinion/argument of the problem with some critical details.	Ambiguous description of the opinion/argument with some details that do not clarify the analysis of the problem	Confusing opinion/argument of the problem with few details
CS2/Plot	Presents a very well-organized visual representation highly explained	Present a clear and organized scheme easy to understand.	Visual representation with enough data but disorganized	It presents an unclear visual representation, without coherence among the parts that compose it.
CS3/Table -Plot	It presents an outstanding data and information interpretation that meets the established criteria without errors.	Data and information interpretation meet the established criteria, with up to two errors	Data and information interpretation with simple structure but well organized with at least three failures.	There is an interpretation of the information with not enough data. It does not meet the established criteria with more than three errors.
CS4/Document	Excellent text structure and documentation of the results, with clarity and coherence	It presents good text structure and documentation, but some details are missing.	Acceptable text structure and documentation; it does not meet the requirements of a coherence text.	Incorrect text structure and incomplete documentation.

Different criteria and standards were used to cover all the necessary skills to assess the different levels of performance of the students, as shown in Table 1.

5.4. Fundamentals equations

The relevant equations to solve the case studies of each software are taken from popular thermodynamics books. The general equations used are presented below.

5.4.1. General equations used in VOLCONTROL software

For the analysis of steady flow devices, it is necessary to perform the mass balance, resulting in Eq. (1).

$$\sum \dot{m}_i = \rho_1 v_1 A_1 = \rho_2 v_2 A_2 \tag{1}$$

and the energy balance [67], see Eq. (2).

$$\dot{Q}_{in} + \dot{w}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} + \dot{w}_{out} + \sum_{out} \dot{m}\theta \tag{2}$$

where the energy of a flow is calculated by the mean of Eq. (3).

$$\theta = h + \frac{V^2}{2} + gz \tag{3}$$

5.4.2. General equations used in CarnotCycle software

Carnot Cycle simulates a refrigeration cycle, which uses different refrigerants; in this case, 134a refrigerant was used as a working fluid. The software calculates the most important properties in each of the states, such as the specific volume, enthalpy, and internal energy, given operating conditions. With the volumetric flow as an input, the program calculates the mass flow \dot{m} , and then the power required by the compressor as follows in Eq. (4).

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) \tag{4}$$

where h_1 y h_2 are the enthalpies located at the compressor inlet and outlet, respectively.

The thermal efficiency of the cycle is determined through the coefficient of performance (COP) as a function of the removed heat of the refrigerated space (\dot{Q}_L), and the power energy consumption (\dot{Q}_L), as follow in Eq. (5).

$$COP = \frac{\dot{Q}_L}{\dot{W}_{in}} \tag{5}$$

The heat rejected during the condensation process in the refrigeration cycle is calculated using Eq. (6), which is the energy balance for a closed-loop system.

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} \tag{6}$$

Considering a reversible process (Carnot refrigeration cycle), the COP_{Rev} is a function only of the temperature of the thermal energy reservoir, T_H (heat source) and T_L (heat sink), as follows in Eq. (7).

$$COP_{Rev} = \frac{1}{\frac{T_H}{T_L} - 1} \tag{7}$$

Now, it is proceeded to calculate the power required by the compressor operating in a reversible process the calculated using the COP_{Rev} and the removed heat of the refrigerated space (\dot{Q}_L), as shown in Eq. (8).

$$\dot{W}_{Rev} = \frac{\dot{Q}_L}{COP_{Rev}} \tag{8}$$

Next, it is determined the heat rejected in a reversible process () with Eq. (9), as follows:

$$\dot{Q}_{H rev} = \dot{Q}_L + \dot{W}_{Rev} \tag{9}$$

5.4.3. General equations used in CombustionUA software

The algorithm allows choosing the desired fuel to work and the type of combustion happening in the system. When incomplete combustion is selected, the amount of CO₂ produced is calculated using Eq. (10).

$$CO_2 = 1 - \left(\frac{CO}{100} \right) \tag{10}$$

where CO is the input that denoted the percentage of carbon monoxide.

To consider the humidity of the air, it is necessary to determine the vapor pressure of the water in the air, which is calculated using the relative humidity (ϕ_{air}) and the saturated vapor pressure $P_{sat@T_{air}}$, as shown in Eq. (11).

$$P_{v, air} = \phi_{air} P_{sat@T_{air}} \tag{11}$$

The number of moles of water in the air is determined by Eq. (12).

$$N_{v, air} = \left(\frac{P_{v, air}}{P_{total}} \right) N_{total} \tag{12}$$

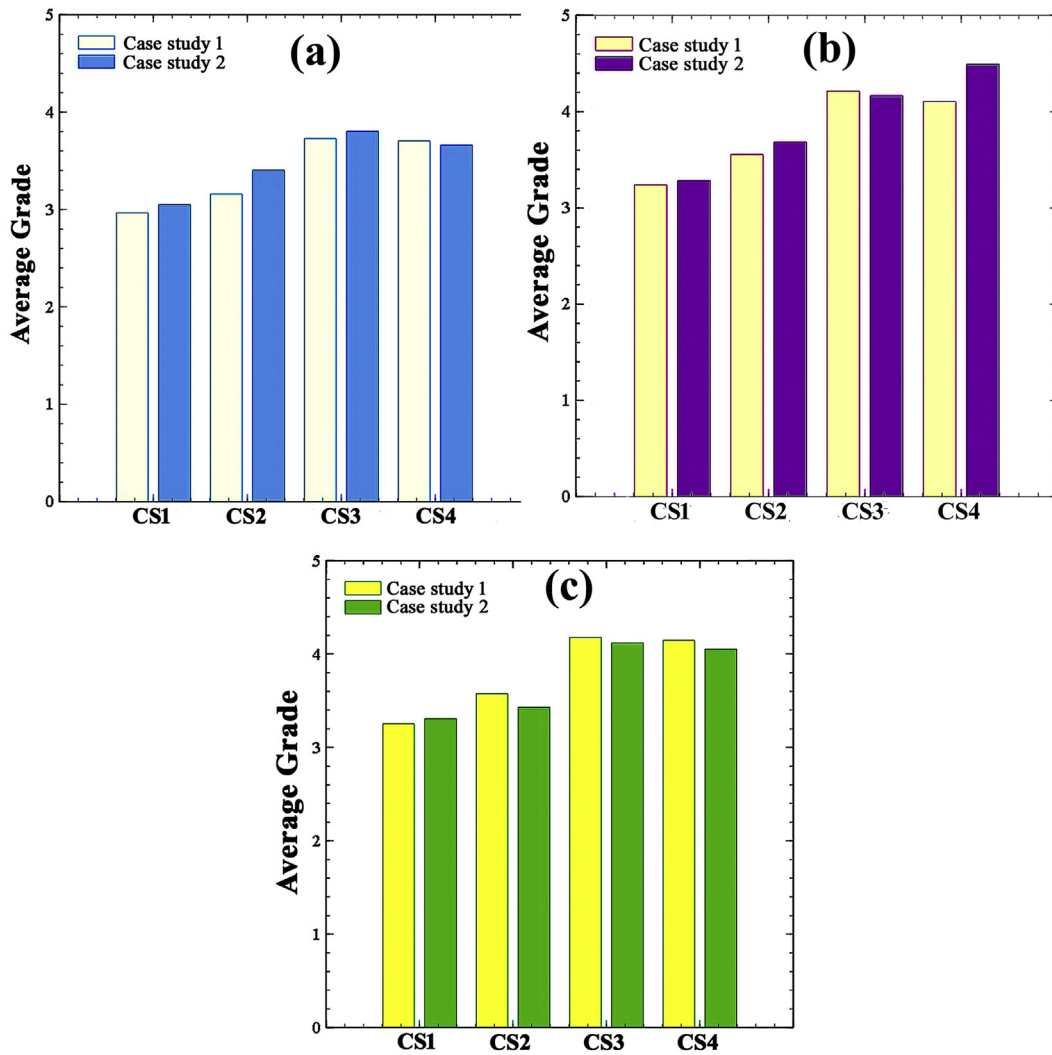


Figure 5. Overall student grades of all the cognitive skills for the workshops made with all the software a) VOLCONTROL, b) CarnotCycle, and c) CombustionUA.

where P_{total} is the total pressure of the system, and N_{total} is the total number of moles.

The air-to-fuel ratio (AF), which is the mass ratio of air to fuel present in an internal combustion engine, is calculated using Eq. (13).

$$AF = \frac{m_{air}}{m_{fuel}} \quad (13)$$

To determine the dew point temperature of the products, first, it is necessary to calculate the partial pressure of the water vapor ($P_{v, prod}$) using Eq. (14).

$$P_{v, prod} = \left(\frac{N_{v, prod}}{N_{prod}} \right) P_{total} \quad (14)$$

The saturation temperature of the partial pressure of the water vapor is the same dew point temperature of the products, and it is calculated using the Equation of Antoine. To apply the first law of thermodynamics to combustion processes, a stationary flow in a combustion chamber is considered. It is a function of the enthalpy of each component of the reaction, which is calculated using Eq. (15).

$$Enthalpy = \bar{h}^{\circ}_f + (\bar{h} - \bar{h}^{\circ}) \quad (15)$$

where \bar{h}°_f is the standard enthalpy of formation in the Standard state (25 °C and 1 atm), \bar{h} is the sensible enthalpy in the specified state, and \bar{h}° is

the sensible enthalpy in the Standard state. When the kinetic and potential energies are insignificant, the energy balance for a chemical reactive stationary system to calculate the interchange of heat (Q_{out}) is determined with Eq. (16) as follows:

$$Q_{out} = \sum N_r (\bar{h}^{\circ}_f + \bar{h} - \bar{h}^{\circ})_r - \sum N_p (\bar{h}^{\circ}_f + \bar{h} - \bar{h}^{\circ})_p \quad (16)$$

where N_r is the number of moles of reactive, and N_p is the number of moles of products.

6. Results and discussions

6.1. Sensitivity analysis

A descriptive analysis was done to show the results of all the workshops. Figure 5 shows the assessment of the students in each cognitive skill for the workshops made with the help of the software VOLCONTROL (Figure 5a), CarnotCycle (Figure 5b), and CombustionUA (Figure 5c).

The same pattern was presented for all the software, and the cognitive skills with the lowest grade were CS1 (3.0–3.3) and CS2 (3.2–3.7) corresponding to argumentative claim, and modeling. It means that even when the students understand all the phenomena happening in thermodynamic processes using the help of the software, the students still have weaknesses in the ability to analyze and discuss these phenomena to

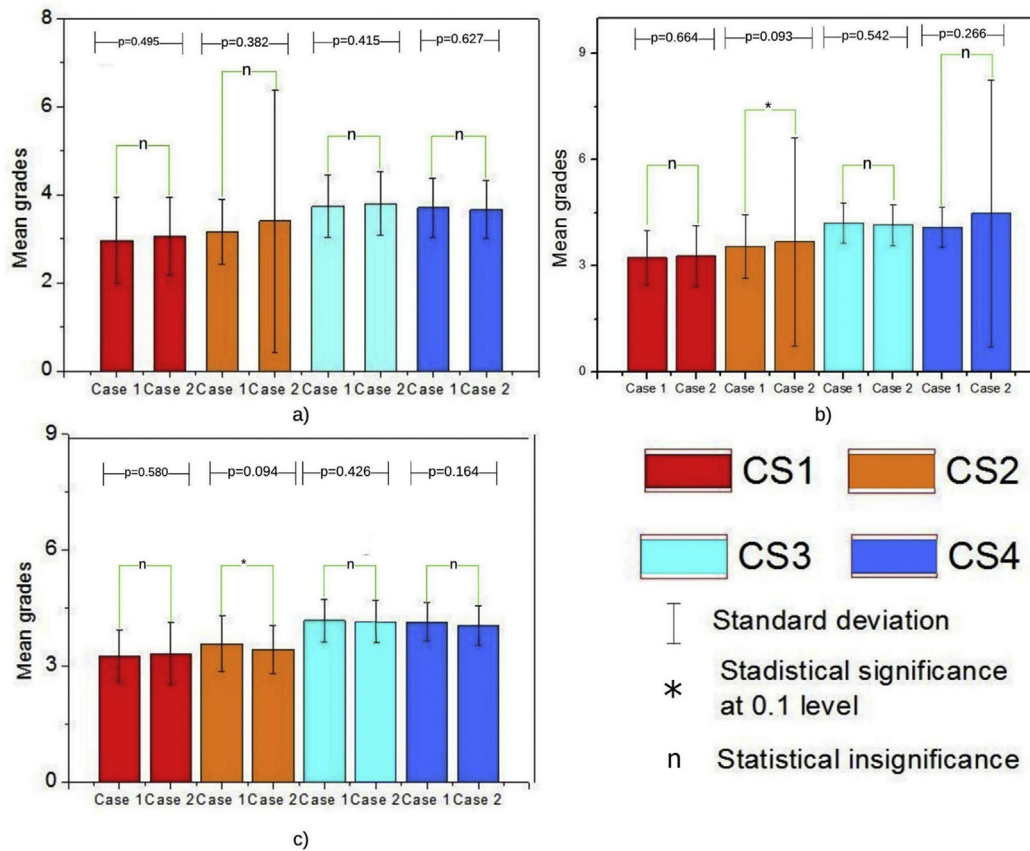


Figure 6. T-Test result by cognitive skills for the software, a) VOLCONTROL, b) CarnotCycle, and c) CombustionUA.

Table 2. Tukey test to compare the results of the cognitive skills.

Tukey test, workshop-VOLCONTROL

	Mean Diff	P	Sig	LCL	UCL
CS2/CS1	0.273	0.1686	0	-0.069	0.615
CS3/CS1	0.758	9.8E-8	1	0.416	1.100
CS3/CS2	0.485	0.0020	1	0.144	0.827
CS4/CS1	0.675	3.1E-6	1	0.333	1.017
CS4/CS2	0.402	0.0136	0	0.060	0.744
CS4/CS3	-0.083	0.9229	0	-0.425	0.259

Tukey test, workshop-CarnotCycle

CS2/CS1	0.360	0.1439	0	-0.075	0.796
CS3/CS1	0.931	3.3E-7	1	0.496	1.367
CS3/CS2	0.571	0.0044	1	0.135	1.006
CS4/CS1	1.040	0.0000	1	0.604	1.475
CS4/CS2	0.679	3.9E-4	1	0.244	1.115
CS4/CS3	0.108	0.9185	0	-0.327	0.544

Tukey test, workshop-CombustionUA

CS2/CS1	0.221	0.0104	0	0.038	0.403
CS3/CS1	0.869	0.0000	1	0.686	1.051
CS3/CS2	0.648	0.0000	1	0.465	0.830
CS4/CS1	0.802	0.0000	1	0.619	0.985
CS4/CS2	0.581	0.0000	1	0.399	0.764
CS4/CS3	-0.067	0.7825	0	-0.249	0.114

Note: argumentative claim (Cognitive Skill – 1, CS1), modeling (Cognitive Skill – 2, CS2), interpreting data/information (Cognitive Skill – 3, CS3), organization (Cognitive Skill – 4, CS4).

Table 3. T-Test for the student grades to evaluate the effect of the software.

a					b				
	N	Mean	StDev	SE Mean		N	Mean	StDev	SE Mean
T-Test for the student grades for Case 1 and Case 2, workshop-VOLCONTROL									
Case 1	120	3.39	0.61	0.056	Case 2	120	3.48	0.94	0.085
Case 1-before	120	2.83	0.89	0.044	Case 2-before	120	2.84	0.55	0.050
Difference = μ (Case 1) - μ (Case 1 before)					Difference = μ (Case 2) - μ (Case 2 before)				
Estimate for difference: 0.56					Estimate for difference: 0.631				
T-Test of difference = 0(vs >):					T-Test of difference = 0(vs >):				
T-Value = 7.71 P-Value = 3.31E-13					T-Value = 6.34 P-Value = 1.29E-9				
T-Test for the student grades for problems P1 and P2, workshop-CarnotCycle									
Case 1	120	3.77	0.45	0.041	Case 2	120	3.91	1.22	0.111
Case 1-before	120	3.11	0.35	0.033	Case 2-before	120	3.11	0.59	0.055
Difference = μ (Case 1) - μ (Case 1 before)					Difference = μ (Case 2) - μ (Case 2 before)				
Estimate for difference: 0.661					Estimate for difference: 0.79				
T-Test of difference = 0(vs >):					T-Test of difference = 0(vs >):				
T-Value = 12.5 P-Value = 4.94E-28					T-Value = 6.41 P-Value = 7.49E-10				
T-Test for the student grades for problems P1 and P2, Workshop- CombustionUA									
Case 1	120	3.78	0.44	0.040	Case 2	120	3.73	0.43	0.039
Case 1-before	120	3.28	0.39	0.036	Case 2-before	120	3.26	0.37	0.034
Difference = μ (Case 1) - μ (Case 1 before)					Difference = μ (Case 2) - μ (Case 2 before)				
Estimate for difference: 0.505					Estimate for difference: 0.46				
T-Test of difference = 0(vs >):					T-Test of difference = 0(vs >):				
T-Value = 9.34 P-Value = 6.91E-18					T-Value = 8.73 P-Value = 4.45E-16				

Table 4. Operating conditions of the nozzle.

P ₁ (MPa)	T ₁ (°C)	V ₁ (m/s)	A ₁ (cm ²)	Q̇ (kW)
0.3	200	45	110	1.5

finally make an excellent conclusion defended with strong arguments. Students generally have lots of knowledge, but their ideas are not well-organized, hindering the interpretation of the incumbency of the case studies. The weak arguments cause the readers not to be interested in the theme, or even worst, they can be confused.

The students also have difficulties in cognitive skill modeling (CS2); however, their average grades were slightly higher than those obtained in CS1. They show their lack of preparation when making a complete plot with all the necessary information for the readers. It is difficult for the reader to understand visually the different trends of the dependent variables obtained in a specific case study.

On the other hand, it can be seen that students present well to excellent average grades (3.8–4.6) in the cognitive skill CS3 and CS4, which are interpreting data/information and organization, respectively. It means that students can get data from tables and make plots from them so easily, giving a reasonable interpretation of the trends obtained with the multiple dependent variables. Besides, students get all the information and prepare documents in a well-organized way.

The increment of the average grade obtained in CS3 and CS4 was about 1.0 points, which correspond to the 33% regarding the average grade earned in CS1 and CS2. It indicates that engineering students are receiving excellent technical preparation in thermodynamic classes; however, their training on communicating the information they collect is inadequate.

6.1.1. Student's t-test

In addition to the descriptive statistical study, the data were subjected to t-Student tests, where the means of each category for the two proposed case studies Case 1 and Case 2 of all the workshops were compared to determine the statistical difference for all the cognitive considered. A similar analysis was done to compare the averages of the workshops done

with and without the help of the software, thus quantify the impact of the software.

Figure 6a shows the results of the T-test for the CS1, CS2, CS3, and CS4 applied to the Workshop of the first law of thermodynamic using the software VOLCONTROL. There is no significant difference between the problems proposed in any of the categories evaluated because none of the T-tests performed showed a P-value lower than 0.005. It means that both problems have a similar level of complexity, and the students have the same management in the topics covered by the two case studies proposed.

It can be seen that the means of the student grades of the proposed case studies of the software CarnotCycle presented in Figure 6b, did not show a significant difference in any of the cognitive skills evaluated, excluding the CS2 where there is a statistically significant difference at the P-value = 0.093.

In this software result, lower P-values were found compared to the first Workshop of the VOLCONTROL software. It means that the case studies present a similar level of difficulty, and the students have the same level of handling in the topics covered by both case studies.

Besides, Figure 6c shows the results of the t-tests performed on the mean grades of the students obtained from the combustion process workshop. The result shows that there was no statistically significant difference in the student mean grades of Case 1 and Case 2 proposed for the CS1, CS3, and CS4.

Subsequently, the Tukey HSD (honestly significant difference) test was performed, which allows comparing the means of all categories. Table 2 shows the results of the Tukey HSD tests applied.

The precision of the results obtained in Table 2 can be compared visually with Figure 5. It can be seen that with the use of all the software, practically, the same pattern of the results was obtained in all of them. There is no significant difference between argumentative claim (CS1)

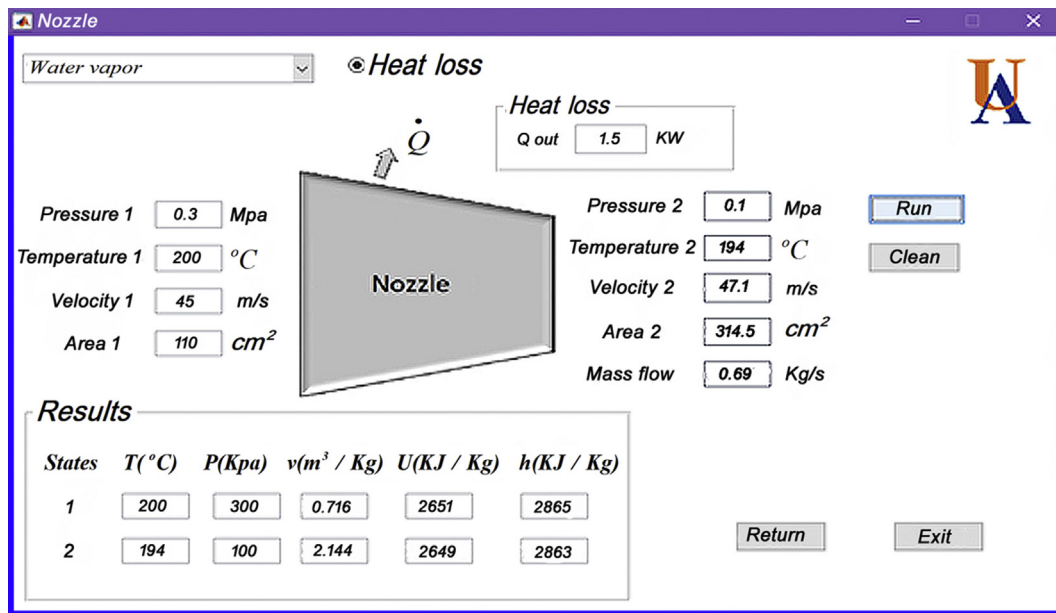


Figure 7. Screenshot of a GUI of VOLCONTROL software.

and modeling (CS2), and between interpreting data/information (CS3) and organization (CS4). Any other combination has significant differences, and for all the cases, according to Figure 5, the average grades were higher for CS3 and CS4 than for CS1 and CS2.

It indicates that students need more training when trying to explain results with strong arguments (CS1) and more preparation when

making plots (CS2) that contain complete information easier to understand to the readers. However, the student can get the data for multiple variables in a table and then prepare plots (CS3) to analyze the trends of the different output parameters. Also, according to the results, the students can present the final document with an excellent organization (CS4).

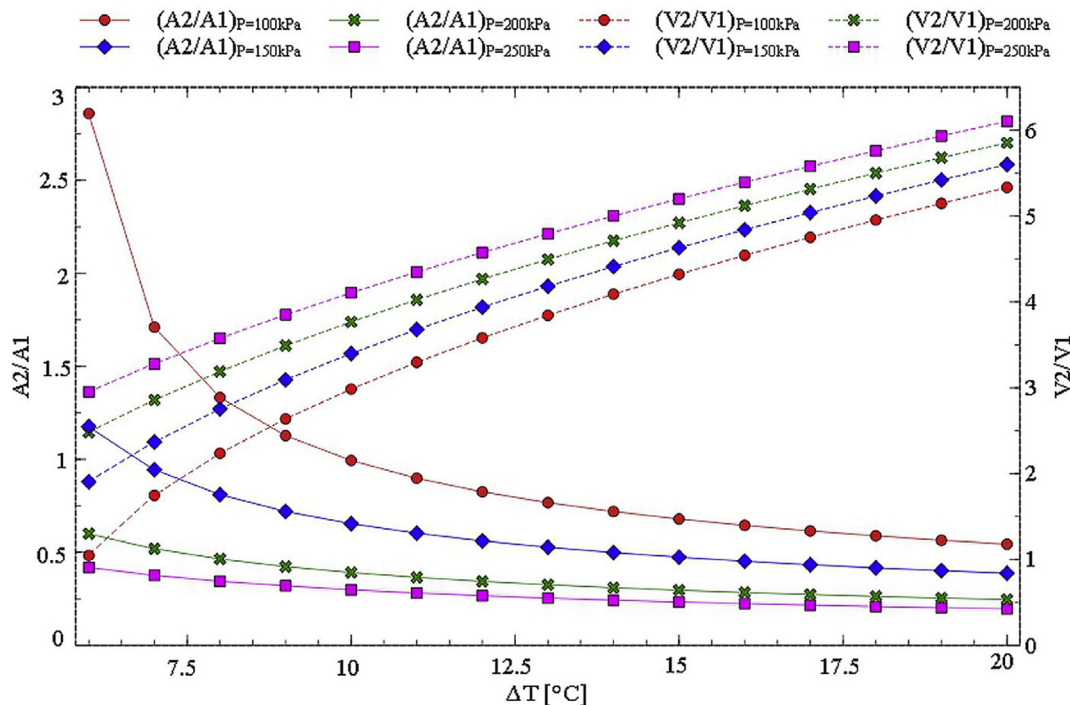


Figure 8. Velocity and area ratios as a function of the difference in temperature for multiple pressure values at the output.

Table 5. Operating conditions of the refrigeration cycle.

Fluid	\dot{V} (L/min)	Quality	P ₂ (kPa)	T ₂ (°C)	T _H (°C)	\dot{Q}_L (kW)
R-134A	50	1	1200	85	45	7.5

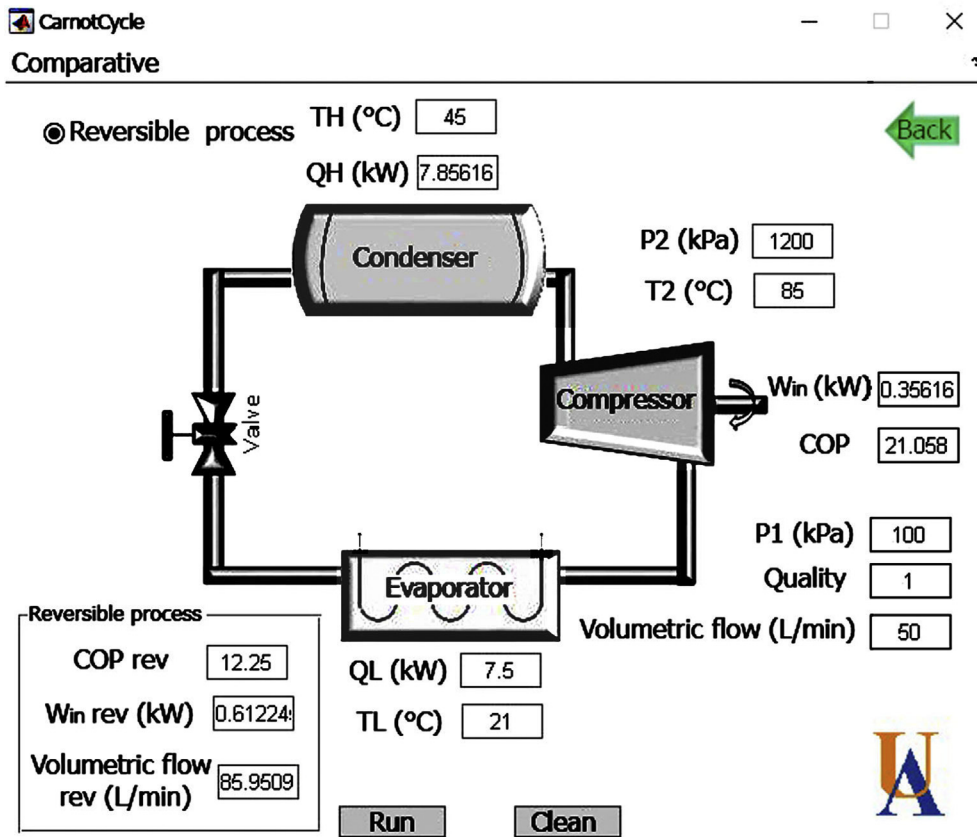


Figure 9. Screenshot of a GUI of CarnotCycle software.

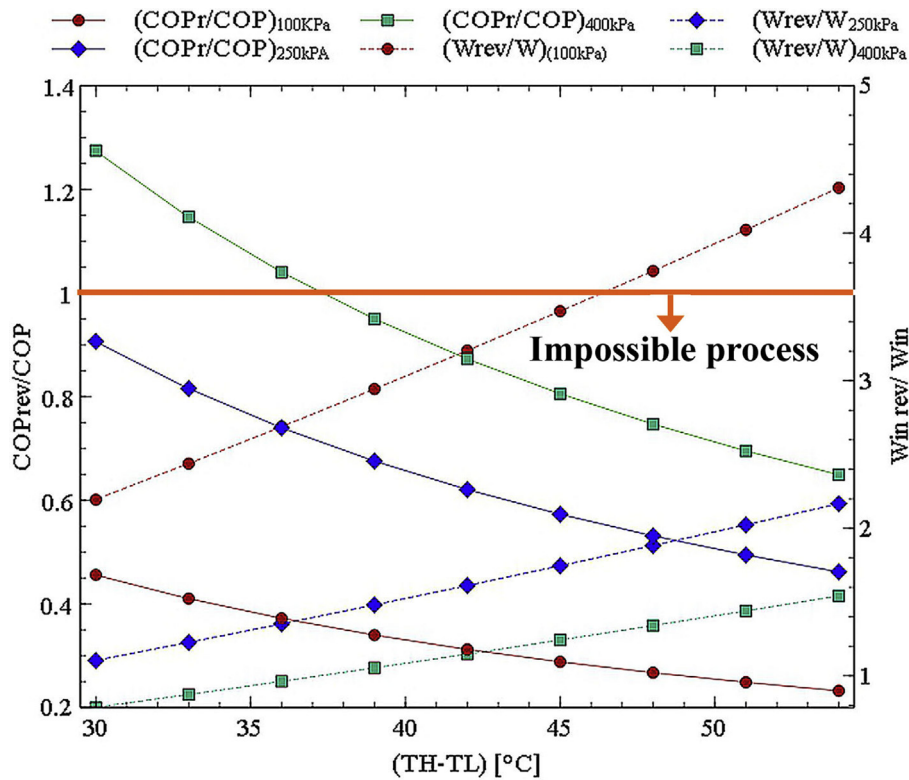


Figure 10. Behavior of the air conditioner performance using CarnotCycle software.

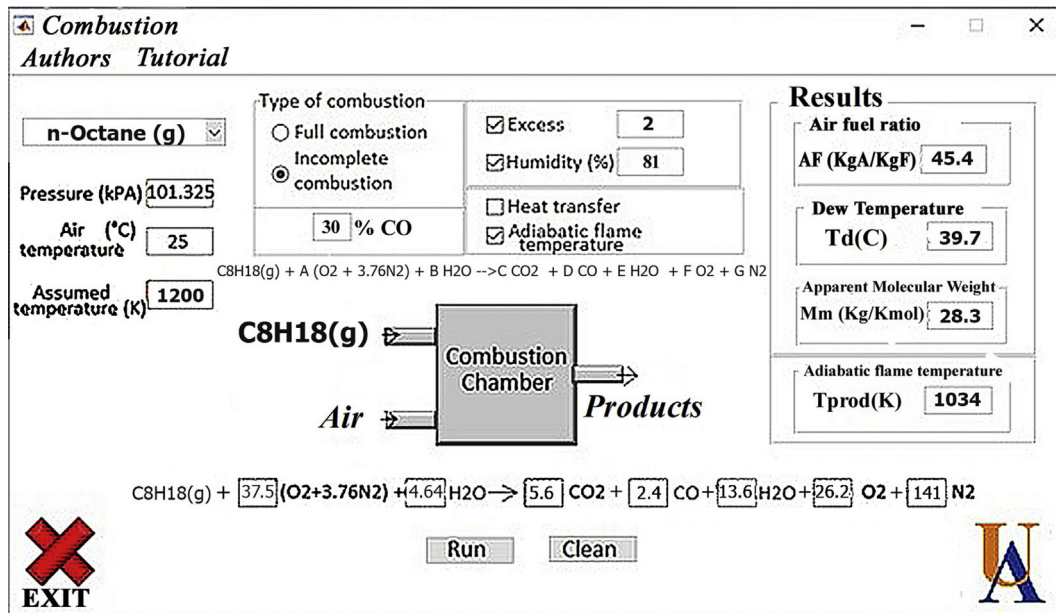


Figure 11. Screenshot of a GUI of CombustionUA software.

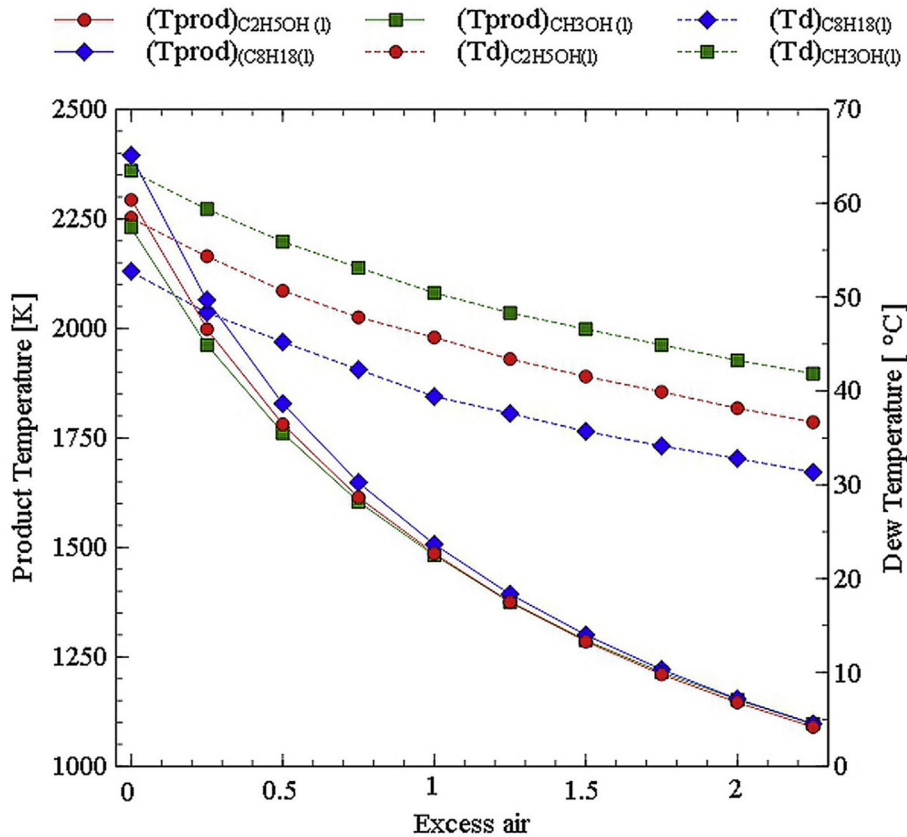


Figure 12. Effect of the excess air in the product temperature and dew point temperature in a complete combustion system.

As mentioned at the beginning of this section, t-Student tests were also performed where the means of each of the problems presented in the workshops solved with and without the software were compared to determine whether the use of the software causes a significant improvement in student performance or not. The means presented in Table 3 correspond to the mean of all the cognitive skills evaluated in each case study, Case 1 and Case 2. These results show the t-tests done on

the student average grades of the case studies of the VOLCONTROL workshop. Case 1 refers to the case one solved with the help of the software. Case 1-before refers to case one solved without the help of the software. The same terminology was applied to the results obtained with the software CarnotCycle and CombustionUA.

The T-tests performed for the proposed case studies of the first Thermodynamics Law workshop show that the average grades of the case

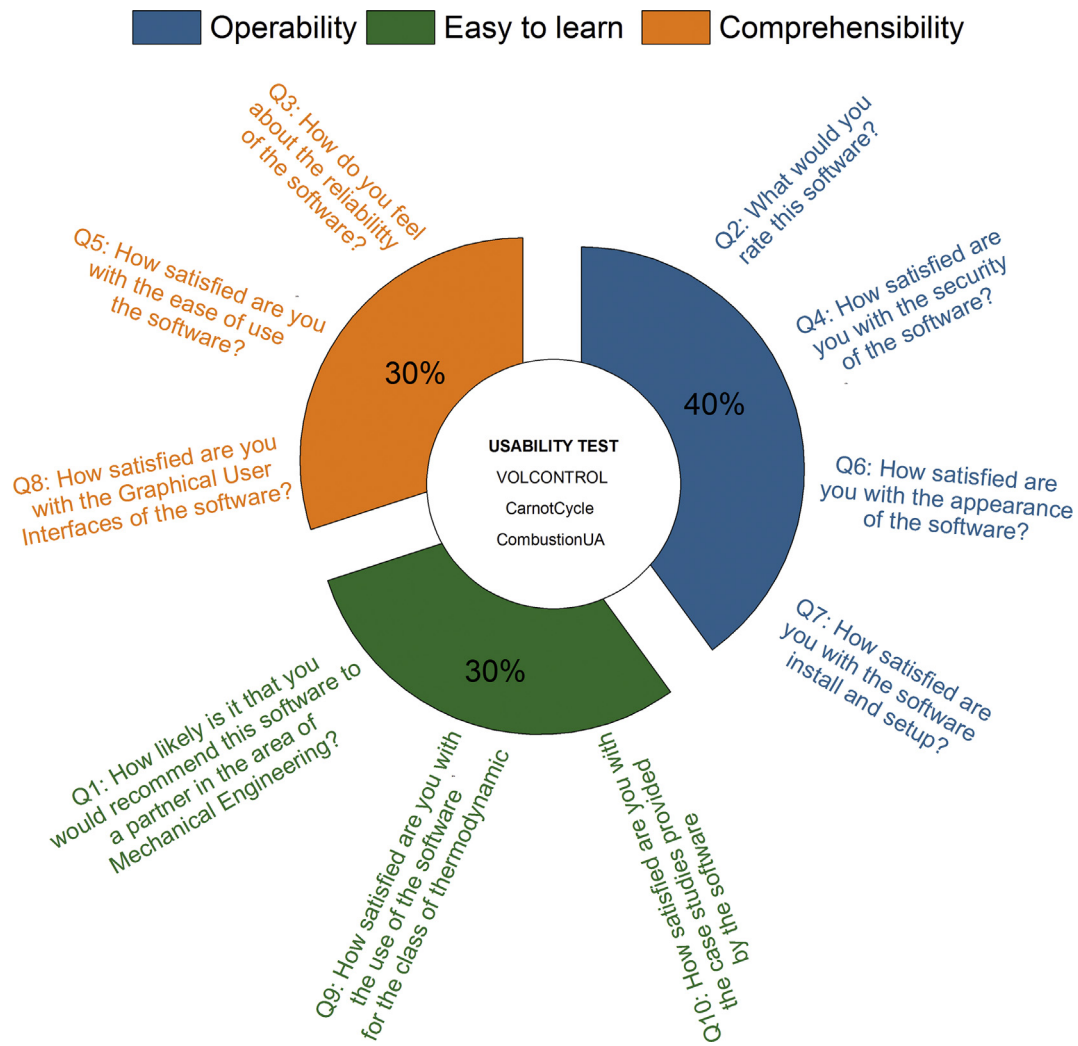


Figure 13. Student satisfaction survey questions to measure the usability of the educational package.

made with the help of the software are higher than the average of the case studies of the Workshop done without using the software. Also, the t-test yielded a P-value lower than 0.005, which means that there is a significant difference between the averages of the workshops solved with and without software. This result helps to demonstrate that the use of VOLCONTROL software had a positive impact on student performance in the two case studies presented in the Workshop.

Also, T-tests of the CarnotCycle workshop showed P-values lower than 0.05 in the case 1 and case 2 proposed, presenting a higher average on the case studies of the Workshop solved with the help of the software. It means that the use of CarnotCycle had a significant positive impact on student performance, as well.

The results obtained with the combustion process workshop had the same pattern of those obtained in the workshops of the first and second law of thermodynamics. In the three workshops, the use of the software causes an improvement in the grades of the students.

6.1.2. Case studies

6.1.2.1. Analysis of a nozzle using VOLCONTROL. The behavior of a water vapor nozzle was analyzed considering the effect of the temperature change (T_1-T_2) in the ratio of the areas (A_2/A_1) and the ratio of the inlet and outlet steam velocities (V_2/V_1) at multiple differences in pressure ΔP (kPa), with the operating conditions shown in Table 4. The outlet temperature was varied every 1 °C, and the inlet temperature

stayed constant. The outlet pressure was changed every 50 kPa in the interval between 100 kPa to 250 kPa.

Figure 7 shows a screenshot of a GUI of VOLCONTROL at the time of solving the case study presented above for one of the given operating conditions.

Figure 8 shows that the difference in pressure has an effect on the velocity of the fluid at the outlet of the nozzle. It happens because the enthalpy of water vapor not only depends on the temperature but also on the pressure. Besides, it can be seen that for the same difference in temperature, the outlet velocities decreases as the difference in pressure increases. However, this effect is reduced considerably when the difference in temperature is increased.

Regardless of the working fluid, unusual behavior is observed when working with low pressure at the outlet of the nozzle and with a small change in temperature. Under these conditions, the nozzle operates as a diffuser because the A_2/A_1 ratio is higher than 1. The nozzle returns to its normal behavior when the difference in temperature increases. It means that there must be a restriction on the operating conditions of the nozzle at high ΔP and low ΔT that let the theoretical thermodynamic results match the real behavior of the nozzle.

6.1.2.2. Compressor analysis of a refrigeration cycle using CarnotCycle. The behavior of an air conditioner compressor was analyzed, collecting the data of the high temperature (TH), low temperature (TL) reversible COP, real COP, required power in the reversible cycle (W_{in}

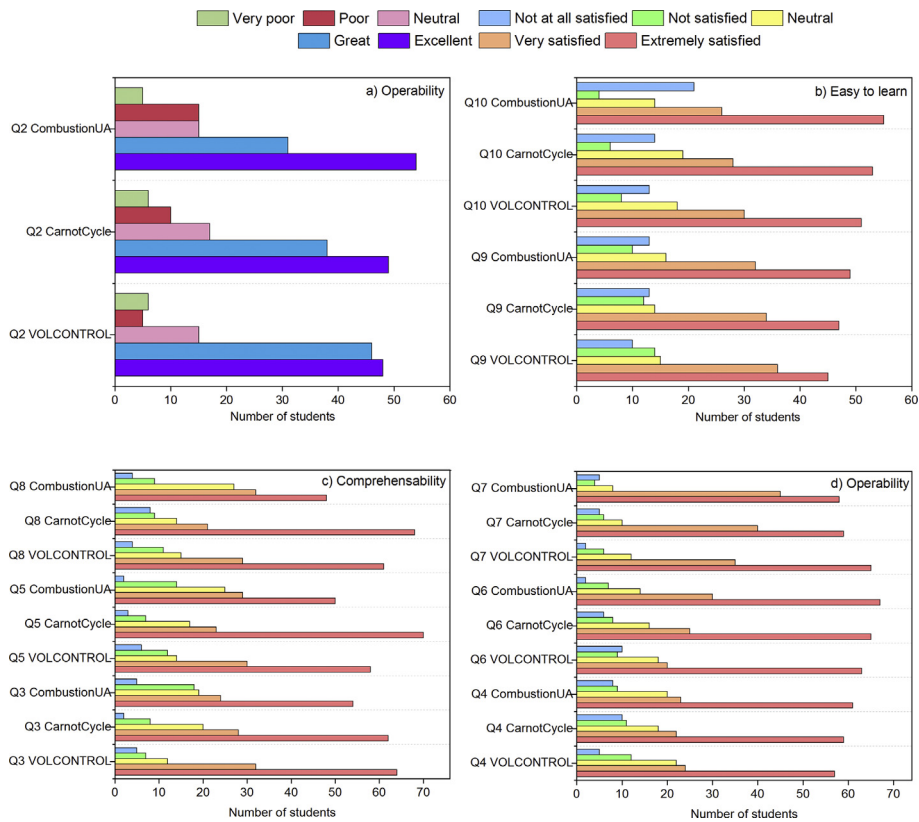


Figure 14. Results of the survey applied to the students.

Rev), and the required power in the real cycle (\dot{W}_{in}). Then, it was plotted the ratio between the reversible COP and the real COP (COP_{rev}/COP), and the ratio between the required power in the reversible cycle and the power needed in the real cycle ($\dot{W}_{in rev}/\dot{W}_{in}$) as a function of the difference between the high and low temperatures ($TH-TL$ on), for multiple pressure values, operating under the conditions shown in Table 5. The low temperature was changed every 3 °C from -9 °C to -15 °C, for three pressure values from 100 kPa to 500 kPa.

Figure 9 shows a screenshot of the CarnotCycle interface at the time of solving the case study presented above for one of the given operating conditions.

Figure 10 shows the results of the analysis performed on the compressor of an air conditioner system. It can be seen that as the difference in temperature increases ($TH-TL$), the ratio COP_{rev}/COP decreases, and the ratio $\dot{W}_{in rev}/\dot{W}_{in}$ increases linearly. When the inlet pressure of the compressor increases, the COP_{rev}/COP ratio increases. However, this effect is reduced at high differences in temperature ($TH-TL$). On the other hand, when the inlet pressure rises, the $\dot{W}_{in rev}/\dot{W}_{in}$ ratio decreases. This effect is reduced at low differences in temperature ($TH-TL$).

It is essential to highlight that the results obtained when the COP_{rev}/COP ratio is lower than one indicates that the condition is impossible to get. In cases where the COP_{rev}/COP ratio is 1, it means that the maximum theoretical coefficient of performance was achieved. In this case study, it is expected that the student would be able to identify the effect of the source and sink temperatures on the reversibility of the thermal machine. It makes that many students acquire the cognitive skill argumentative claim by observing and interpreting an impossible process with COP_{rev}/COP values lower than 1. The students explain with good arguments the reason for these impossible results presented, concluding that for these cases, the second law of thermodynamics is violated through the Clausius statement for the operation of thermal refrigeration

machines and heat pumps. The cognitive skill interpreting data/information (Cognitive Skill – 3, CS3) is achieved with this case study as well. Finally, some students propose new operating conditions where this ratio is higher than one to obtain an irreversible or real process.

6.1.2.3. Analysis of excess air in a complete combustion process using CombustionUA. The behavior of a complete combustion process was analyzed to view the effect of the excess air on the adiabatic flame temperature and the spray temperature of the products, for different fuels, operating under inlet conditions of 25 °C and 101.325 kPa. It was varied the excess air in the range from 0 to 2.25, for three different fuels in liquid phase: ethyl alcohol, methyl alcohol, and n-octane. Figure 11 shows a screenshot of the CombustionUA software at the time of solving the case study mentioned above for one of the given operating conditions.

Figure 12 shows the results of a complete combustion process when excess air was varied. The temperature of the products refers to the adiabatic flame temperature because there is no loss of energy from the combustion chamber to the surroundings. It can be seen that the adiabatic flame temperature decreases drastically with a parabolic trend when the excess air increases.

The dew point temperature exhibits a behavior similar to the adiabatic flame temperature since it also has a parabolic trend and decreases as the excess air increases. However, the decrease in the dew point temperature is not as extreme as the obtained with the adiabatic flame temperature.

Figure 12 also shows that there is no significant difference among the adiabatic flame temperatures of the studied fuels, which becomes practically negligible as the excess air is increased. However, the type of fuel has a high effect on the dew point temperature, where the methyl alcohol had the highest dew point temperature, and the n-octane had the lowest dew point temperature.

From the results obtained, it was possible to determine a set of advantages of the learning methodology proposed in this work, compared to other alternative methods such as blended learning.

By using e-learning, the student in his training process requires more effort, since he does not have the continuous guidance in a classroom. Therefore, the student learns to take responsibility for his training on his initiative. Moreover, the integration of the new educational package to the different virtual platforms allows the student to contact the teacher to clarify the concerns of the case studies, at the same time, he can participate in complementary activities such as participation in discussion forums, activity on the platform, and evaluations.

On the other hand, the main advantage identified in this methodology is the flexibility of schedules, where the student decides when to study, and when to download the application. The student only needs to have an internet connection to be able to access the course content, contact the tutors or take the exams. At the same time, in the blended mode, this is partially restricted, which compromises the flexibility with geographical barriers and required displacements.

6.2. Usability test analysis

It was necessary to analyze the usability of all the computational package to be sure that it makes all the duties safely, effectively, and efficiently when used by the students. Also, all the software should have a friendly environment where the students enjoy doing their assignments [68]. For that reason, it was developed a satisfaction survey consisting of 10 questions, see Figure 13. The survey was filled by the 120 Senior Mechanical Engineering students of the Thermodynamic class of Universidad del Atlántico. The results allowed measuring the internal and external attributes of the new educational tool.

The questions used in the satisfaction survey for all the software integrated into the educational package were created according to the IEEE Standard for a Software Quality Metrics Methodology [69]. It proposes the characteristics of Easy to learn (Q1, Q9, and Q10), Operability (Q2, Q4, Q6, and Q7), and Comprehensibility (Q3, Q5, and Q8). The study population was only limited to students who worked with the tool because the usability depends not only on the software but also on the degree of training of the users. Figure 14 shows the results of the software usability, which were obtained through the survey done at the end of the software training.

These results show the impact of the software on the cognitive growth of the students, and in their experience of handling the technological tools. In the three categories, the survey shows an average of 57 students that are very satisfied with the characteristics of the educational package presents compared with the average of 7 students that are not completely satisfied.

Figure 14a was separated from the others because the results of question 2 have a different evaluation system. It can be seen that the average of students with a positive notion of the VOLCONTROL software is 94. In the case of the Carnotcycle software, it was 87, and in the case of CombustionUA, the average was 85 software. It allows affirming that the operability of the software is one of the main characteristics of the development of technological tools because they offer a practical environment for the development of research experiences in the classrooms. Figure 14b presents the results of the study of the set of easy to learn questions. Although the three software obtains a high percentage of positive answers, the tool that presented the best study cases is the software CombustionUA with 55 students, followed by Carnotcycle with 53 and finally VOLCONTROL with 51.

It can be highlighted that the content of the mentioned computational tools satisfies the objectives of the course of thermodynamics, as shown in the results of question 9. The software that has extreme satisfaction for the development of investigations in the course is CombustionUA with 49 students. Figure 14c presents the results obtained from the set of questions focused on the comprehensibility of the applications, where question 5 stands out. It analyzes the impact that has a graphical tool on the

analysis of results that each one of the software presents. CarnotCycle presents the best satisfaction of this tool with 70 students, followed by VOLCONTROL with 58 students and Carnotcycle with 50. The installation method, design, and security of the software are assessed in the operability category, as shown in Figure 14d. It can be seen that the best results of the applications are obtained in the installation category, evaluated in question 7. It happened because the number of satisfied and extremely satisfied students is 302 students compared to question 4 (246 students) and question 6 (270 students).

7. Conclusions

In this work, it was evaluated the level of statistical significance of the effect of the new educational package TermolabUA on the learning process of undergraduate students in thermodynamics. The educational package is constituted by three interactive software that studies the combustion processes, the second law of thermodynamics, and the energy balance applied to open systems.

Based on the results of the grades obtained by the students when developing the thermodynamics workshops with the help of the new educational software and in a manual way, the performance of the students was compared in three topics according to four cognitive skills (argumentative claim, modeling, interpreting data/information, and organization), which follow some standards of international learning.

Considering a significance level of 95%, for all the workshops made with the three software, the P-values were lower than 0.05. Also, the average student grades in the three cases were higher when using the software than without using them. It indicates that the three software significantly improved the cognitive skills of the students.

There was a deficit in the cognitive skill - argumentative claim - because the case studies presented in the academic books of thermodynamics are usually nondidactic. It is challenging for students to make parametric variations in some input variables to see their effect in other output variables. The use of interactive software reduced the deficit in the cognitive skill 3 category, where the student presents an outstanding data and key information interpretation that support the ideas and conclusions.

With the case study "Analysis of a nozzle using VOLCONTROL," it was found that when the differences between the inlet and outlet temperatures of a nozzle were small, and the working pressure was low, the nozzle exhibits an irregular behavior working like a diffuser. So, this case study helps to develop the cognitive skill 4 in the student, where the student presents an excellent text structure and documentation of the results obtained with clarity and coherence, which is an evidence of the pertinence and benefit of the new educational package.

It was observed that in a refrigeration cycle, when the quality of the refrigerant approaches zero in the condenser inlet, more reversibility tends to occur, exceeding the maximum possible performance coefficient for significant differences between high and low temperatures. With the quick help of the software, the students analyzed this behavior and improved their cognitive skill argumentative claim by observing and interpreting an impossible process where $COP_{Prev} = COP$. The students used good arguments to explain the reasons for this impossible result. This learning methodology promoted the participation of the student in the classes, motivating a self-taught training.

Declarations

Author contribution statement

G. Valencia, L. Obregón: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

J. Garcia: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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