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ClosedSystem: A New Educational Software to Study the First Law of Thermodynamics in Closed Systems Using Matlab

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Abstract

This paper presents the development of a new educational software to study the first law of thermodynamics in some case studies of closed systems using Matlab. The fundamental equation used in the software is presented, and the results obtained by the ClosedSystem software for a case study of a cylinder-piston device with springs and a cylinder-piston device are analyzed in detail. In addition, the accuracy of the data was demonstrated by comparing the program outputs with the manual calculations of 34 undergraduates mechanical engineering students from Universidad del Atlántico, obtaining the higher absolute error of 0.065% and 1.12% for the two educative problems presented above respectively. Finally, in order to analyze the main parameters involving in the Energy's balance of these processes a complete parametric study was developed for each case with the assistance of the new software.

Keywords: educational software, energy balance, first law of thermodynamics, closed systems

1. Introduction

Nowadays, the evaluation of the energy consumption trough the first law of thermodynamics is recognized as a strategic component in sustainable development and challenges relating to climate change, energy security and economic development at the lowest cost to society, which over time researcher and engineers have studied hard in order to explain the essence of them [1]. Today it has been revealed that the main factor that produces these manifestations is the energy transformations in the systems, which has a relative meaning and an approach that depends on the specific system. In classical thermodynamics the energy transformed into work or heat, can be estimated by means of the first law of thermodynamic [1]. In addition, the energy can be stored within the devices in various forms [2], one of these ways is known as internal energy, which is an indicator of the molecular activity of a substance, and its continuous change is generated by heat or work as demonstrated by J. P. Joule [3].

The mentioned forms of energies in some fluids had been studied in common quasi-static or quasi-equilibrium systems, focusing on the rate of energy transferred in these processes by work and heat [4], also in closed systems when the mass remains constant in all the thermodynamics states under the expansion or compression of the boundary [5]. These processes even when they are an idealization of the irreversible systems, can have a close behavior to real ones, for example, in an engine where the thermal energy is converted to mechanics energy, cannot be applied a quasi-static analysis due to the high speeds produced by the gas combustion, however, making a succession of states of quasi-equilibrium to a single real reaction within the unitary displacement of the engine can be a good approximation [6-9].

For the above, the main contribution of this paper is to present a new educational software to study the first law of thermodynamics in closed systems using Matlab, in order to facilitate the mathematical study of these phenomena, under a quasi-equilibrium point of view, improving the numerical process using some conditionals and arrays for all the cases involved in the software, in addition the program presents the operational characteristics of usability and learnability due to the undergraduate students required a less amount of efforts to learn how to use the software in a thermodynamic course.

2. Methodology

2.1 Presentation of software

ClosedSystem is a software created in Matlab that let users to make analysis of the energy balance in the most common closed systems, which are handled in processes of quasi-equilibrium and there is not mass flow crossing their boundary [10], [11]. Many software has been developed to show the significative learning of the undergraduate engineering student [12-17]. ClosedSystem has been designed to be a support tool in virtual labs from the program of Mechanical engineering at Universidad del Atlántico, in the thermodynamic analysis of closed systems, facilitating the comprehension of the process in students making the learning an active and constructive process; in other words the fundamental activities in the thermodynamic knowledge construction process is oriented to the self-learning, changing the input variables in the systems to obtain the output variable, required to elaborate the tables and graphics shown on Figure 1.

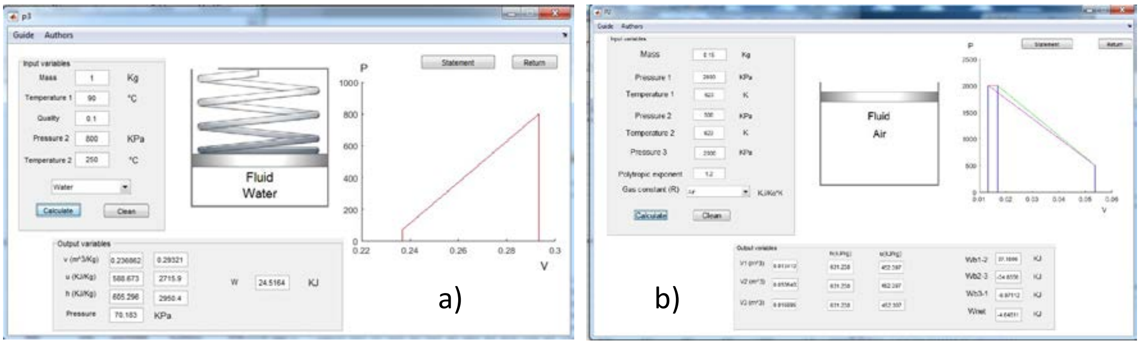

Figure 1. Software interface ClosedSystem, a) case study cylinder-piston spring, b) case study device cylinder-piston.

2.2 Fundamental Equations

To solve the case studies of energy balance application in closed systems, the software contains a fluid properties database, and equations to calculate energy transfer available in classical thermodynamic books [1-3]. The boundary work has place in the cylinder-piston device, and to determine this form of energy the differential work is calculated as follow:

$$\boldsymbol{\delta W = FdS = PdV} \quad (1)$$

where *F* is the force, *dS* is the differential distance, *P* is the pressure and *dV* a differential volume. Then, by integrating equation $\boldsymbol{\delta W} = \text{FdS} = \text{PdV}$
(1) it is obtained

$$\boldsymbol{W = \int_1^2 PdV} \quad (2)$$

where *P* is the pressure in the internal face of the piston and the work also can be expressed as the area under the curve in a *P*-*V* diagram, resulting the following equation

$$\boldsymbol{A = \int_1^2 dA = \int_1^2 PdV} \quad (3)$$

where the differential area is equal to *PdV*.
On the other hand, the polytrophic process is one in which the pressure-volume equation is given as

$$Pv^n = C \tag{4}$$

where *n* y *c* are constants determined by the phenomenon of expansion or compression of gases, resulting

$$W = \int_1^2 PdV = \int_1^2 C/_{V^n}\, dV = \frac{P_2V_2 - P_1V_1}{1-n} \tag{5}$$

For an ideal gas the previous equation can be written in the following way

$$W = \frac{mR(T_2 - T_1)}{1-n} \tag{6}$$

where *R* is the ideal gas constant. For the case of n=1 it leads to indetermination, so the work should be calculated as follow:

$$W = \int_1^2 CV^{-1}dV = PVln\left(\frac{V_2}{V_1}\right) \tag{7}$$

Equation applied to the cylinder-piston spring device
To calculate the energy transfer by work in the cylinder-piston spring device the equation (3) was used, leading to

$$W = P_1 * m(V_2 - V_1) + \left(\frac{P_2 - P_1}{2}\right) * m(V_2 - V_1) \tag{8}$$

which can be simplified as

$$W = \left(\frac{P_1 + P_2}{2}\right) * m(V_2 - V_1). \tag{9}$$

Equation applied to the cylinder-piston device
The ideal gas equation of state was used in this device solution,

$$PV = mRT \tag{10}$$

Under an isothermal process from state 1 to 2 it is obtained that

$$P_1V_1 = P_2V_2 \tag{11}$$

resulting the equation $W = \int_1^2 CV^{-1}dV = PVln\left(\frac{V_2}{V_1}\right)$ (7) as

$$W_{1-2} = P_1V_1 \ln\left(\frac{v_2}{v_1}\right) \tag{12}$$

To find the work from state 2 to 3, the equation (4) for the polytrophic process is used

$$W_{2-3} = \frac{P_3 V_3 - P_2 V_2}{1-n} \quad (13)$$

Then, to find the work from state 3 to 1, is applied the equation $\boldsymbol{W} = \int_1^2 \text{PdV}$ (2), resulting

$$\boldsymbol{W_{3-1} = P_3(V_1 - V_3)} \quad (14)$$

Finally, to determinate the net work the following equation can be use

$$\boldsymbol{W_{net} = W_{1-2} + W_{2-3} + W_{3-1}} \quad (15)$$

where the sign of each work is (-) for compression or (+) for expansion of the fluid.

3. Results and discussion

In this section it is presented the validation of the ClosedSystem software, making a comparative study between the results obtained by the undergraduate students of mechanical engineering and the manual calculations based on classical thermodynamics books. In addiction, the parametric results and discussion only for two case studies are presented.

3.1 Validation of the software ClosedSystem

In order to validate the software, a comparative analysis was carried out between the average results obtained by a group of 34 students, when the case studies were solved manually and with the use of the software, obtaining a maximum absolute error of 1.12 % in the case of the calculation of the work required in the closed systems as shown on Table 1.

Table 1.Validation Results of Closed System Software.

Case study	Parameter	GUI	Manual	Absolute error (%)
Case 1	W(kJ)	106.24	106.31	0.065 %
Case 2	W(kJ)	-10.56	-10.68	1.12 %

Note. Case 1: Cylinder-piston with springs device, Case 2: Cylinder-piston device

In order to help undergraduate students to learn the thermodynamics fundamental related to closed systems, four learning factors were promoted with an educational guide, allowing to measuring on the students the level profundization of the topic through the *analysis* item, the quality grade of the chart developed in the *graph* factor, the result robustness by mean of the *table/graph*, and finally the ability to obtain, organized and present efficiency the information in the factor called *document.* Table 2 shows the student performance result for each factor, the total mean obtained whit the standard deviation and the minimum and maximum grade achieved.

Table 2.Validation Results of Closed System Software.

Case	*Analysis*	*Graph*	*Table/Graph*	*Document*	Mean		Min.	Max.
Case 1	3,43	3,75	3,87	3,75	3,7	0,79	1,95	4,8
Case 2	3,55	3,85	4,14	3,72	3,82	0,61	2,12	4,75

From avobe table it can be noticed that the higher standard deviation is realated to the exercise with the greater complexity, in this case the cylinder-piston with spring device case study has presented the largest standard deviation in comparison with the other case, which allows to infer that a group of students presented difficulties solving or understanding othe phenomenon. On the other hand, the problem with the lowest standard deviation has a similar dispersion measure to the above mentioned one, therefore we can determine that although there is less complexity, it is possible that the same group had problems when doing the work, this helps the teacher to determine the aspect to be improved and then correct them.

3.2 Case study 1: cylinder-piston with springs device

The study was focused on determining the effect of the change of (ΔT) at different quality on the relationship (v_2/v_1) and W (kJ), considering the initial conditions shown in Table 3.

Table 3. Initial Conditions.

m(kg)	T_1(°C)	P_2(kPa)	T_2(°C)	Quality
1	90	800	250	0.1

The inlet flow temperature (T_1) was varied every 10°C in a large range from 70°C to 160°C, while the quality was evaluated to 0.1, 0.2, 0.3 and 0.4, as shown on Figure 2.

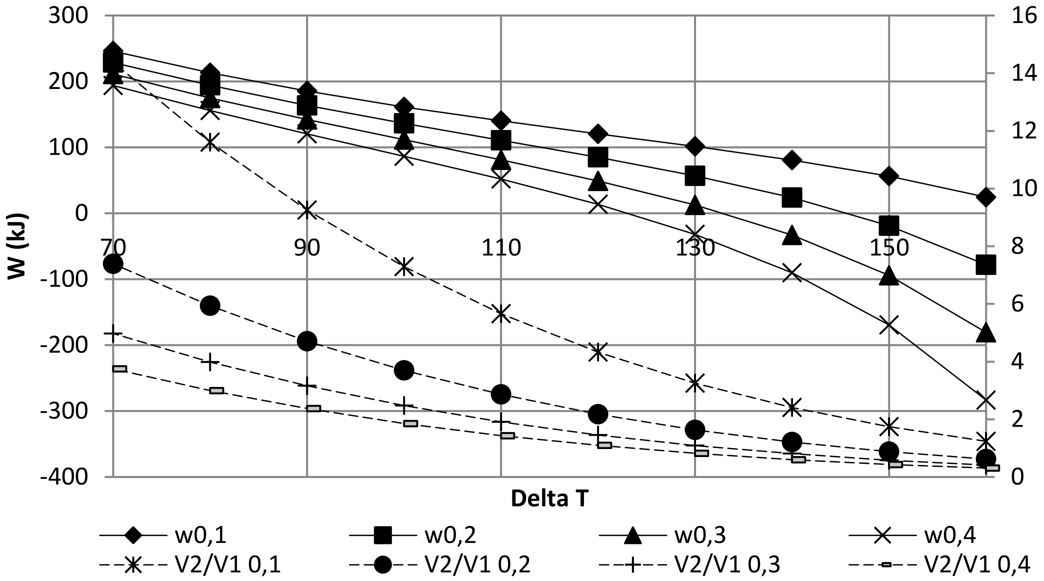

Figure 2. Results for the case study cylinder-piston spring device.

From the result obtained for this case, it can be deduced that as T_1 and water quality increase, the work tends to shift from expansion to compression more quickly, and the ratio v_2 / v_1 becomes similar after a ΔT greater than 160, behavior that can be explained due to the fact that the quality of the fluid is maintained, since under normal conditions as the temperature increases the quality of the fluid must change and the volume must increase, however in this case the volume decreases, and according to the Charles law to have this increase the process must be isobaric, property that in this process does not remain constant.

3.3 Case study 2: cylinder-piston device

In the case study where the device cylinder-piston was considerate, the study was oriented to determinate the influence of the change ($\Delta P/P_1$) to the relationship (v_2/v_1) and W (kJ) at different polytropic exponents, according to the initial conditions listed in Table 4.

Table 4. Initial conditions.

m(kg)	P_1(kPa)	T_1(K)	P_2(kPa)	T_2(K)	n	P_3(kPa)
0.15	2000	623	500	623	1.2	2000

The outlet flow pressure (P_2) was varied every 20 kPa in a large range from 500 kPa to 680 kPa, while the polytropic exponents was evaluated to 1.2, 1.4, 1.6 and 1.8, as shown on Figure 3.

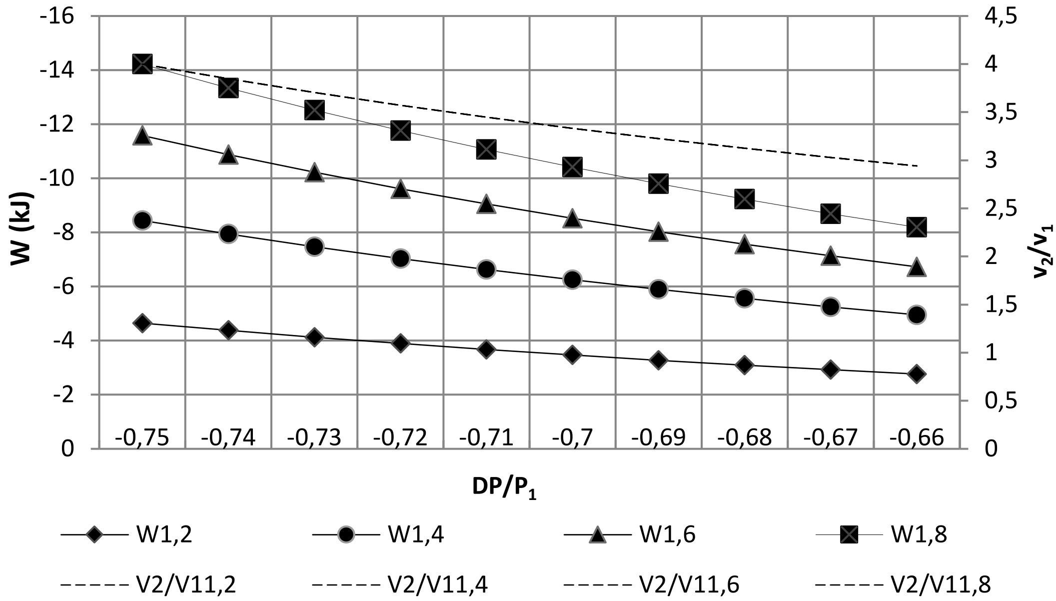

Figure 3 . Results for the case study device cylinder-piston.

From the above result, it can be concluded that, the work is directly proportional to the ratio v_2/v_1, however the slopes are not equal or similar, since the net work is influenced by a third volume (v_3) which is altered by the polytropic exponent, also it can be seen that in this example the ratio v_2/ v_1 is not affected, therefore the curve to different exponents is the same, unlike W that presents several curves, as well as through the graphical result can be deduced that under a greater relationship of $\Delta P/P_1$, the W of the different functions were more closer, which can reach a point where the differences between their magnitudes are negligible.

4. Conclusions

The results were successful, since the error found between the manuals and software solutions had been low, in addition ClosedSystem had a good reception by the students, so was possible to demonstrate through the applied tests that the interface is a tool easy to use since it does not require advanced knowledge in computer science, also from the educational point of view the software helps to study the energy balance in some common closed systems easier to understand for the users with little knowledge on the subject. The software developed is a simple interface and allow to the user evaluate a wide range of conditional to identify some characteristics of the phenomena occurring in these processes.

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