Application of the First Law of
Thermodynamics for Closed Systems Using
a Graphical User Interface

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Abstract

In this article, it is presented the study of energy transfer and work done in closed systems using an educational graphical user interface (GUI) developed in Matlab as a pedagogical strategy to promote the significant learning in engineering. The program uses several experimental correlations reported in the literature for solving the problems. The systems studied were a Cylinder-piston device, and a Container with separation, both cases with water and R-134a refrigerant as working materials. The study was made of two cases, superheated steam, and vapor-liquid equilibrium analyzing the behavior of heat and work as a function of pressure and volume changes. For water, it was found that the work was directly proportional to the relation final volume to initial volume. They decrease at different scales when the absolute value of $|\Delta P/P_1|$, and temperature decreases. The same pattern was obtained for R-134a refrigerant. In the case of the container with division (system superheated steam – saturated vapor), an increase in the relation final pressure to
pressure of container A causes a decrease in the total heat needed to maintain the mixture in equilibrium L-V.

**Keywords:** education, software engineering, energy balance, energy by work, heat transfer, closed systems

### 1. Introduction

Nowadays, the use of software for learning has become fundamental in high-performance institutions, since the software composed by conditional and numerical calculations improve the student learning process [1]. It has been confirmed that using a GUI as an educational tool promotes the interest in engineering courses on the students, which makes the use of some educational software as a complementary option to the traditional approach [2-4].

Also, some researchers have also demonstrated that students supported with virtual laboratories get better performance than those who have received regular classes, based on a systematic process stimulating and empowering each student individually to acquire the fundamental knowledge [5]. A compulsory topic studied in mechanical and chemical engineering undergraduates is the first law of thermodynamics, which is the classical expression to evaluate the conservation of energy principle in the closed and open systems. The energy can cross the boundaries of a closed system only by heat or work [6], so it is necessary to work on an educative program that helps students to understand the different energy transformations according to classical thermodynamics [7, 8] including all the fundamental equations involved in the thermodynamic process [9]. Particular educative applications have been made to help the user to quantify the internal energy change to estimate the heat and work transferred in closed systems, at the same time allowing to student clarify the mathematical expression used in thermodynamics to calculate the expansion or compression work in closed systems [10].

Considering the great importance of closed systems in engineers, this study aimed at using a graphical user interface made in Matlab called ClosedSystem to simulate the thermodynamic process of some important case studies in closed systems. The systems studied were a Cylinder-piston device, and a Container with separation, both cases with water and R-134a refrigerant as working materials. The study was made of two cases, superheated steam, and vapor-liquid equilibrium analyzing the behavior of heat and work as a function of pressure and volume changes.

### 2. Methodology

#### 2.1 Presentation of the software

It was used the software ClosedSystem to elaborate the energy analysis in quasi-equilibrium processes in traditional closed systems. With the help of the software,
it was run two different processes (see Figure 1 and Figure 2) at different operating conditions to analyze the different trends obtained that help to understand the phenomenon inside the systems.

![Figure 1. Diagram of Cylinder-piston device.](image1)

![Figure 2. Diagram of the container with the division.](image2)

### 2.2 Fundamental Equations

In closed systems, the energy balance is taken into account for the calculation of work and heat. Therefore the equation to do this procedure is

\[ E_{input} - E_{output} = \Delta E_{system} \tag{1} \]

where \((E_{input} - E_{output})\) is the net transfer of energy by heat, work and mass, and \(\Delta E_{system}\) represents the change of internal energy, kinetic, potential, among others.
In classic thermodynamics, $\Delta E_{\text{system}}$ leads to the following equation,

\[ Q_{\text{input}} - W_{\text{output}} = \Delta E_{\text{system}} \]  \hspace{1cm} (2)

To calculate the energy transferred by work in the cylinder-piston device using superheated steam as worked fluid, the relation used as function of the fluid properties in state 1 and 2 are

\[ W_{\text{out}} = \frac{p_1 + p_2}{2} \cdot (v_2 - v_1) \]  \hspace{1cm} (3)

\[ W_{\text{in}} = \frac{p_1 + p_2}{2} \cdot (v_1 - v_2) \]  \hspace{1cm} (4)

The energy balance to find the heat with an output work is,

\[ Q_{\text{in}} = m(u_2 - u_1) + W_{\text{out}} \]  \hspace{1cm} (5)

where $u_2 - u_1$ represents the change of internal energy between state 1 and 2 of the working fluid in $kJ/kg$, and $m$ the mass of the fluid in $kg$. In the case study of container with division to calculate the heat transfer to the surrounding, the work is neglected since the container is considered a rigid body obtaining,

\[ Q_{\text{out}} = m_A(u_{AB} - u_A) + m_B(u_{AB} - u_B) \]  \hspace{1cm} (4)

where $u_A$ and $u_B$ are the initial internal energies of containers A and B, and $u_{AB}$ is the internal energy when the division is removed.

3. Results and discussion

This section presents the studies carried out on the traditional closed systems proposed by the software ClosedSystem, as well as the validation of the user interface through the analysis applied to the results of 34 undergraduate students in Mechanical Engineering at the Universidad del Atlántico. The parametric results and analysis of variance are also presented for three case studies presented as follow.

3.1 Validation of the software

A comparative analysis was made to validate the application developed, with the results obtained by 34 undergraduate mechanical engineering students using the software and the traditional method of solution. It was obtained an absolute maximum error of 0.86% and 0.01% when estimating the work $W$ and total heat $Q$ respectively, in the case study Cylinder-piston device, and container with a division. (see Table 1).
Table 1. Results of software validation

<table>
<thead>
<tr>
<th>Case study</th>
<th>Parameter</th>
<th>GUI</th>
<th>Manual</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder-piston device (superheated steam)</td>
<td>W(kJ)</td>
<td>80.28</td>
<td>80.98</td>
<td>0.86 %</td>
</tr>
<tr>
<td>Container with division</td>
<td>Q(kJ)</td>
<td>2199.07</td>
<td>2199.45</td>
<td>0.01 %</td>
</tr>
</tbody>
</table>

3.2 Case study 1: Cylinder-piston device. (superheated steam) - water

In a cylinder-piston device, it was studied the work and the ratio \( V_2/V_1 \) as a function of \( \Delta P/P_1 \) at different Temperatures, according to the initial conditions of superheated steam shown in Table 2.

Table 1. Initial Condition

<table>
<thead>
<tr>
<th>m(kg)</th>
<th>( P_1 )(kPa)</th>
<th>( T_1 )(°C)</th>
<th>( P_2 )(kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1000</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

A parametric study was developed, when \( P_2 \) changed each 10 kPa in the range of [500 kPa to 590 kPa], under a change of temperature \( \Delta T \) of [0 °C, 100°C, 200°C, 300°C], resulting in the behavior shown in Figure 3.

Figure 3. Pressure-volume work in a cylinder-piston device.

Analyzing the phenomena with water as working fluid, it can be seen that the work is directly proportional to the relation \( V_2/V_1 \), which is mathematically correct due to they have the same pattern of decrease at different scales when the absolute value of \( |\Delta P/P_1| \), and the temperature decreases. Only for the temperature of 500°C, which is the initial temperature of the system, the work done tends to zero when \( |\Delta P/P_1| \) is
close to zero and it is obvious because at that temperature $P_2 = P_1$ and $V_2 = V_1$. For the other lines, the work done is different than zero because $V_2$ is higher than $V_1$.

### 3.3 Case study 2: Container with the division. (superheated steam) - water

It was studied the process of a mixture of superheated steam with liquid and vapor in equilibrium in a container with a separation wall. It was analyzed the variation of $(V_F/V_A)$ and the total heat needed to maintain the mixture in equilibrium $L-V$, as a function of changes in $(P_F/P_A)$ and the vapor quality $(x)$, based on the initial conditions shown in Table 3.

<table>
<thead>
<tr>
<th>$m_A$ (kg)</th>
<th>$P_A$ (kPa)</th>
<th>$T_A$ (°C)</th>
<th>$m_B$ (kg)</th>
<th>Quality $(X_B)$</th>
<th>$T_B$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>200</td>
<td>1</td>
<td>0.1</td>
<td>100</td>
</tr>
</tbody>
</table>

The final $P_A$ was changed each 20 kPa in the interval of [500 kPa – 680 kPa], to different vapor quality in the division B [0.1, 0.3, 0.5, 0.7], as shown in Figure 4.

![Figure 4. Total Heat as a function of pressure at different vapor qualities in container B.](image)

As shown in Figure 4, there is a dependence between the relation $V_F/V_A$ and the total heat, $Q$. It is appreciated that an increase in $P_F/P_A$ causes a decrease in the total heat needed to maintain the mixture in equilibrium $L-V$. However, the variation is slow as seen in the slope of the plots of $Q$. Regarding the relation $V_F/V_A$, it can be seen a decrease as well, when $P_F/P_A$ decreases. It can be seen that the vapor quality of container B has a higher effect than the effect given by the final pressure, which is close in meaning to the distinguish Boyle's law that estimates a considerable quantity of gas must be present in the container without division.
3.4 Case study 3: Case study of the cylinder-piston device (superheated steam) -134a refrigerant

In a cylinder-piston device, it was studied the work and the ratio \( \frac{V_2}{V_1} \) as a function of \( \frac{\Delta P}{P_1} \) at different Temperatures, according to the initial conditions of superheated steam - 134a refrigerant as shown in Table 4.

<table>
<thead>
<tr>
<th>m(kg)</th>
<th>( P_1 ) (kPa)</th>
<th>( T_1 ) (°C)</th>
<th>( P_2 ) (kPa)</th>
<th>( T_2 ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1000</td>
<td>60</td>
<td>500</td>
<td>60</td>
</tr>
</tbody>
</table>

The pressure \( P_2 \) was changed every 10 kPa in the range of [500 kPa to 590 kPa] to different \( \Delta T \) [0 °C, 20°C, 40°C, 60°C], obtaining the results shown in Figure 5.

Figure 5. Case study piston-cylinder device

Comparing figure 5 with the plot of the water (figure 3), it can be seen that it follows the same trend. However, the scale of the work differs strongly because the refrigerant has a high vapor pressure that makes it evaporate faster than the water at low temperatures as seen in figure 5 causing a small work done in the system. Analyzing the phenomena with 134a refrigerant as working fluid, it can be seen that the work is directly proportional to the relation \( \frac{V_2}{V_1} \), which is mathematically correct due to they have the same pattern of decrease when the absolute value of \( |\Delta P/P_1| \), and the temperature decrease. Only for the temperature of 60°C, which is the initial temperature of the system, the work done tends to zero when \( |\Delta P/P_1| \) is close to zero and it is obvious because at that temperature \( P_2=P_1 \) and \( V_2=V_1 \). For the other lines, the work done is different than zero because \( V_2 \) is higher than \( V_1 \).
4. Conclusions

It was made a study of energy transfer and work done in closed systems using an educational graphical user interface developed in Matlab. The systems used were a Cylinder-piston device, and a Container with separation, both cases with water and R-134a refrigerant as working materials. Superheated steam and vapor-liquid at equilibrium were analyzed in the Container with separation observing the behavior of heat and work as a function of pressure and volume changes. It was found that there is a dependence between the relation V_F/V_A and the total heat, Q. It was also seen that an increase in P_F/P_A causes a decrease in the total heat needed to maintain the mixture in equilibrium L-V. It was found a decrease in the relation V_F/V_A when P_F/P_A decreases. It can be seen that the vapor quality of container B has a higher effect than the effect given by the final pressure. For water used as working fluid in the Cylinder-piston device, it was found that the work was directly proportional to the relation final volume to initial volume. Both, the work done and the relation V_2/V_1 decrease when the absolute value of |ΔP/P_1|, and temperature decreases. The same pattern was obtained for R-134a refrigerant. Only for the temperature of 60°C, which is the initial temperature of the system, the work done tends to zero when |ΔP/P_1| is close to zero and it is obvious because at that temperature P_2=P_1 and V_2=V_1. For the other lines, the work done is different than zero because V_2 is higher than V_1.

References


Application of the first law of thermodynamics


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