Contemporary Engineering Sciences, Vol. 10, 2017, no. 23, 1113 - 1122
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/ces.2017.79121

A Matlab Program to Develop the Mass and Energy Analysis of Control Volumes

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Abstract

This paper presents the methodology and results of a parametric study to determine the influence of changing input variables on the behavior of a compressor and a turbine using a GUI registered in Matlab® called VolControl, and validated by the undergraduate students in mechanical engineering of the Universidad del Atlantico, which allows to perform the energy analysis of different stationary flow devices in a practical, interactive and user friendly way. The fundamental thermodynamic equations used for the development of the algorithm and the maximum error percentages obtained during the validation are presented. With the help of the software it was possible to determine the working fluid which cause the compressor to have a more optimum performance, as well as the quality level at the output of the turbine generating a high power output.

Keywords: Matlab, Computational Tool, Thermodynamic, Mass and Energy Analysis, Control Volumes

1. Introduction

The use of laboratories has a fundamental role in the development of any course in engineering, providing real manipulation of instruments and devices, allowing students to bond and compare what they have learned in the theoretical classes with what happens in reality, but there are disadvantages such as the cost of creating a laboratory and its maintenance [1]. The use of computer tools for the simulation of engineering processes is presented as a more than interesting alternative to complement the theoretical foundations given in the classroom. It has been verified that the implementation of the simulation with didactic objects increase the interest of the students and their motivation [2].The teaching of thermodynamics approach has progressed from the traditional theoretical method with the use of computer technology allowing the student to have a greater participation in the development of classes [3], [4]. Ahmet Gurses [5], through the implementation of a t test found that the students instructed through interactive teaching performed significantly better than the traditional teaching method.

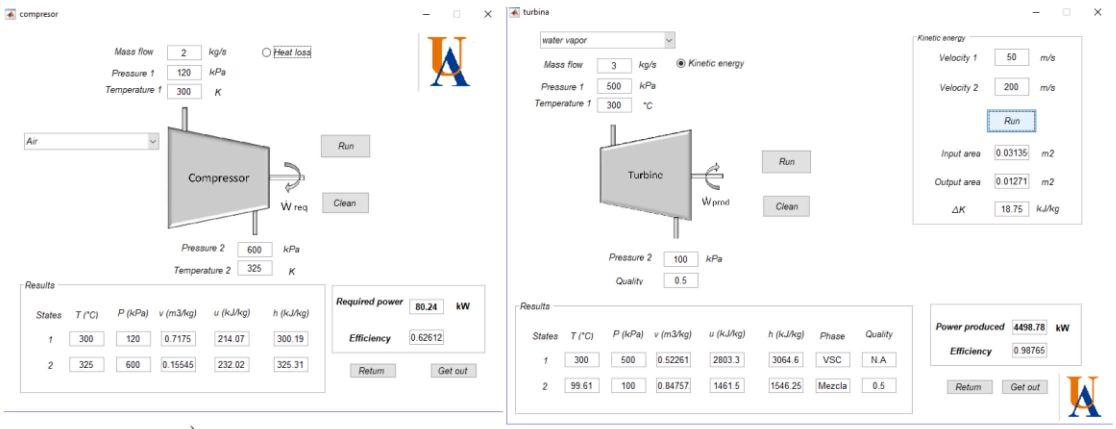
There are currently a variety of commercial software capable of simulating processes and equipment in order to achieve greater efficiency such as Aspen, ChemCAD, CCTherm, Pro / II, Simsci,etc. [6]–[10], however these have been developed for industrial purposes and cover so many topics that due to their robustness, lack of tutorials that facilitate the student learning. For this reason some software have been developed for educational purposes such as COMSOL Multiphysics, ANSYS Fluent, OpenCalphad, etc., having a great positive impact with their implementation in the teaching of thermodynamics [11]–[13], however these software have a high level of complexity, directing their use mainly on postgraduate students.
Because of the lack of simple, practical and interactive software focused on the learning of undergraduate students, it was developed a novel interactive software named Vol Control, that focus on facilitating the understanding of mass and energy analysis of open systems, giving the student the possibility to understand and explain the phenomena that occur in a device of steady flow selected before the variation of one or more settings.

2. Methodology

2.1 Presentation of the software

VolControl is a software set in Matlab®, which allows the energy analysis in different engineering devices, which operate under a steady flow regime, in which no intensive or extensive property changes over time within the control volume. VolControl is designed with the aim of becoming a support tool for students and professors of mechanical engineering at the University of the Atlantic in the study of open systems in the field of Thermodynamics I in a practical and interactive way that allows students to facilitate the understanding of the effect of the different variables in the development of the system, through a parametric variation, changing one or more initial conditions

The software has a main interface as shown on Figure 1, in which the user can select the type of stationary flow device to be analyzed, in the options found nozzle, diffuser, compressor, turbine, throttling valve, mixing chamber and heat exchanger.



a) b)

Figure 1. Volcontrol software interface, a) Compressor case study, b) Turbine case study.

The software was designed with a level of difficulty that let undergraduate students an easy, dynamic and interactive management through the different interfaces, helping them to understand the level of influence of a particular variable on the whole process analyzed. Also, the evaluation in the educational field can be done at any time and placed by the teacher. The software was not designed for industrial purposes, its usefulness is mainly pedagogical, focused on teaching and facilitating the assimilation of the processes that occur in stationary flow devices.

The software provides the teacher with a new method of teaching and evaluation that help the change of methodology of the thermodynamics classes in a theoretical-practical way by implementing the simulation, stimulating the interest of students in energy analysis of open systems to facilitate their understanding with the help of the graphical user interface (GUI) of VolControl

2.2 Fundamental Equations

All the equations used in software development will be presented in detail below, which are extensively studied in different academic texts [14]–[16] .

For analysis of stationary flow devices, it is necessary to perform mass and energy balance. Because this type of device complies with the principle of mass talk, mass balance is shown in eq. (1).

$$\sum \dot{m}_1 = \sum \dot{m}_2 \rightarrow \ \rho_1 V_1 A_1 = \rho_2 V_2 A_2 \ . \tag{1}$$

These types of devices are in steady state so the energy balance can be expressed as shown in eq. (*2*).

$$\dot{Q}_{entrada} + \dot{W}_{entrada} + \sum_{entrada} \dot{m}\theta = \dot{Q}_{salida} + \dot{W}_{salida} + \sum_{salida} \dot{m}\theta \tag{2}$$

where

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

Because in the stationary flow devices the potential energy change is very small compared to changes in kinetic energy, labor or heat, in the software development was considered negligible, therefore, eq. (2) is summarized as shown in eq. (4).

$$\dot{Q}_{entrada} + \dot{W}_{entrada} + \dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{Q}_{salida} + \dot{W}_{salida} + \dot{m}\left(h_2 + \frac{V_2^2}{2}\right). \tag{4}$$

Each stationary flow device has its own operating conditions, which is why eq. (4) may vary depending on the device studied.

For the study of the compressors, which are devices that are used to increase the pressure of the fluid, thanks to an external work supply, in these devices the potential energy changes are insignificant and the handled speeds are too low, therefore the kinetic energy changes are negligible. Generally, the compressors are well insulated and do not present significant losses of heat, however, VolControl allows the user to add losses of heat if it is needed as shown on Figure 2.

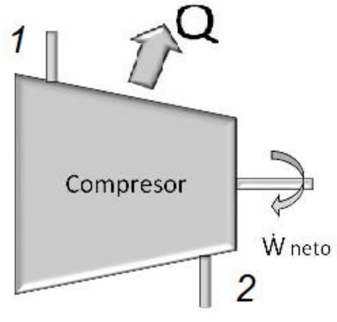


Figure 2 Diagram of a Compressor.

The output variables of the Compressor interface are the required power and efficiency. Taking into account the conditions explained above in eq. (4), the power is obtained as follow:

$$\dot{W}_{entrada} = \dot{Q}_{salida} + \dot{m}(h_2 - h_1). \tag{5}$$

The efficiency is given by

$$\eta = \frac{\dot{m}(h_2 - h_1)}{\dot{W}_{entrada}}. \tag{6}$$

In the case of turbines as shown on Figure 3, which are devices that produce power, heat transfer is generally not considered because they are very well isolated devices, potential energy changes are negligible. The working fluid in the turbines undergoes high velocities, however, changes in kinetic energy do not generate a great impact compared to the enthalpy change, although VolControl allows the user the option of adding kinetic energy changes if desired.

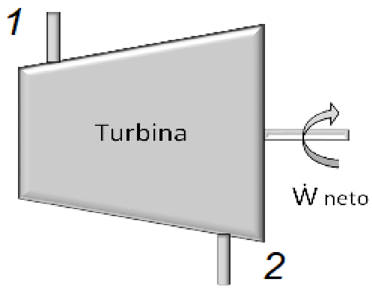


Figure 3 Turbine diagram.

The energy balance for a turbine is shown in (6).

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{W}_{salida} + \dot{m}\left(h_2 + \frac{V_2^2}{2}\right). \tag{6}$$

The output variables of the Turbine interface are the power produced and the efficiency, then, rearranging eq. (7) gives the value of the power produced as follows:

$$\dot{W}_{salida} = \dot{m}(\Delta h - \Delta V). \tag{7}$$

The efficiency is calculated as

$$\eta = \frac{\dot{m}(h_2 - h_1)}{\dot{W}_{salida}} \tag{8}$$

3. Results and Discussion

In this item the validation of the VolControl software is presented, making a comparative study between the results obtained by the undergraduate students in Mechanical Engineering and the calculations of manual way using the texts of literature in classic Thermodynamics. Next, the parametric results are presented, with their respective analysis only for the turbine and compressor study cases.

3.1 Validation of VolControl software

In order to validate the computer application developed, a comparative analysis was performed between the average results obtained by a group of 33 students when the case studies were solved manually and with the application, obtaining a maximum absolute error of 0.091% for the case of calculation of compressor and turbine efficiencies as shown on Table 1.

Table 1. Validated result for the VolControl software.

Case study	Parameter	GUI	Manual	Error (%)
Compressor	η (%)	62.61	62.60	0.019
Compressor	$\dot{W}$(kW)	80.24	80.24	0.000
Turbine	η (%)	95.19	95.10	0.091
Turbine	$\dot{W}$(kW)	1112.55	1112.55	0.000

3.2 Compressor case study

Figure 4 shows the behavior of a compressor under the influence of the temperature change (T2-T1) on the required power ($\dot{W}$in) and its efficiency (η) using different working fluids (air, nitrogen, carbon dioxide) with operating conditions shown in Table 2. The temperature in the compressor output was changed every 25K in the range 325K to 550K.

Table 2. Compressor Operating Conditions.

P_1 (kPa)	T_1 (K)	P_2(kPa)	$\dot{m}$(kg/s)	q (kJ/kg)
120	300	600	2	15

In figure 4, it can be seen that the required power is directly proportional to the temperature change, in a linear way; On the other hand, the efficiency for the different working fluids, increases exponentially as the temperature change increases.

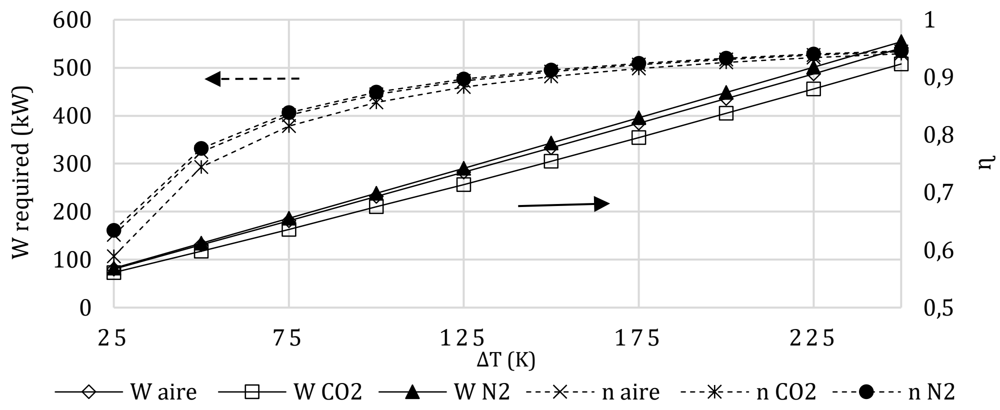


Figure 4. Compressor analysis results.

It is also possible to compare the behavior of the three working fluids used during the study, it can be observed that nitrogen produces a higher power consumption than air and carbon dioxide operating under the same conditions, in the same way, this is the substance that presents a better performance in the compressor in terms of efficiency, being notoriously higher when compared with the efficiency obtained with the carbon dioxide, however, it is very close to the efficiency obtained by the air. These differences in efficiencies become insignificant when the temperature change is increased, therefore, it is concluded that using carbon dioxide the compressor exhibits a more optimal behavior because it requires less power compared with the other fluids and their efficiencies are quite close.

3.3 Turbine Case Study

In an adiabatic steam turbine, the behavior of the work and efficiency was analyzed under the influence of the ΔP / P1 ratio on the power produced and the quality of the substance at the turbine outlet, with the operating conditions shown in Table 3. The pressure at the outlet was varied every 50kPa in the range of 100kPa to 450kPa leaving the inlet pressure constant and the quality varying 0.5 units between (0-1).

Table 3. Turbine operating conditions with steam

P_1 (kPa)	T_1 (°C)	$\dot{m}$(kg/s)	V_1(m/s)	V_2 (m/s)
500	300	3	50	200

Figure 5 shows the results of the analysis performed on the turbine, it can be observed that the power produced by the turbine increases slightly when the ΔP / P1 ratio increases, the efficiency also presents a very similar behavior.

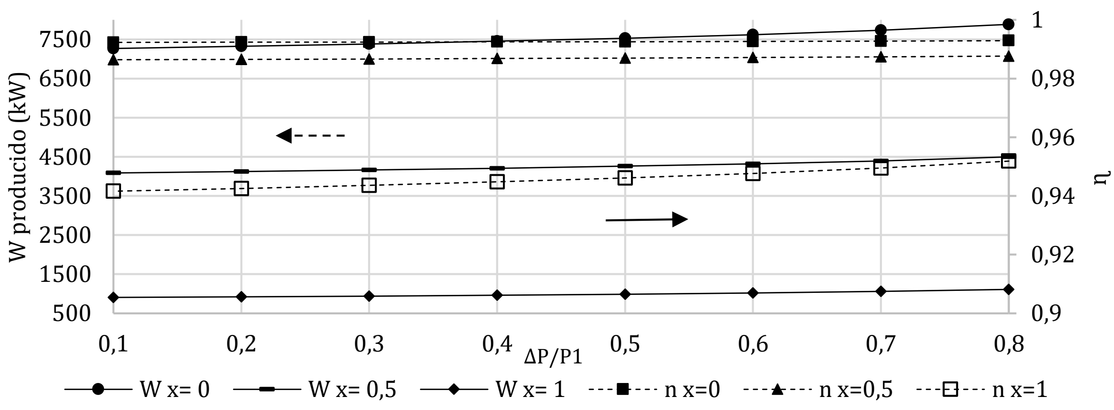


Figure 5. Results of Steam Turbine Analysis

In addition, it is possible to contemplate a great increase in the power produced by the turbine by varying the quality of the fluid, producing a higher power as the quality tends to 0, that is to say when the fluid is as close as possible to the saturated liquid state, where higher efficiency is also obtained.

4. Conclusions

A mathematical tool for mechanical engineers was presented "VolControl v1.0", focused on the mass and energy analysis of different flow devices with the application of two case studies for two different devices, which were compressor and turbine. The program uses fundamental equations of thermodynamics such as mass and energy balances, for which it requires the entry of the minimum input variables for the correct development of the process through the device studied, in order to determine the required power and efficiency, as well as the thermodynamic states of the fluid both at the inlet and at the outlet of the selected device.

It was determined that the carbon dioxide was the working fluid that gives to the compressor the best performance, compared with air and nitrogen. Taking into account that the carbon dioxide was the fluid with the lower power requirement and efficiency, increasing the change of temperature, the efficiencies of the three fluids were very close to each other. In the turbine, it was evident that the variation of the ΔP / P1 ratio caused a slight increase in power output and efficiency, but the most significant change was obtained when varying the quality of the substance at the output of the turbine, where the best performance was obtained when the fluid tended to be a saturated liquid. Finally, the use of Graphical User Interface (GUI) can increase the efficiency of a class of thermodynamics, because it helps the students to have a better understanding of what happens through the stationary flow devices.

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Received: October 12, 2017; Published: November 16, 2017