

Making Use of Graphical Interface Tools to Simulate Thermodynamically Brayton Cycles using Air or Carbon Dioxide as Work Fluids

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Abstract — Power cycles are constituted by a series of thermodynamic processes that aid transform the thermal energy of a fluid in mechanical work, which, after, can be used to many purposes mainly to get through generators, electrical energy. There are many types of power cycles in the world, using various work fluids. The Brayton Cycle is a gas power cycle that uses mostly air and combustion reactions to move turbines and produce mechanical work. Due to its low cost and environment issues, this power cycle is being improved by new technologies, such as more efficient turbine that use supercritical carbon dioxide as work fluid. This work aims the development of a computer program, in MatLab software, with an graphical interface (GUI, graphical Unit Interface) to simulate, thermodynamically, many configurations of Brayton cycles using air or carbon dioxide as work fluid, providing to the user the values of the main parameters of these processes, that is: required heat in the combustion chamber; generated work in turbine(s); required work in compressor(s) and the thermal efficiency of the power cycle. This computer program provides good results at real conditions by using the thermodynamic properties of the gases, showing that it can be used, safely, to design equipment for these thermodynamic cycles and as support for teaching disciplines of Applied Thermodynamic. Visual presentation is made, friendly, through of Graphical Unit Interfaces (GUI).

Keywords—*Brayton Cycle; Air; Carbon Dioxide; Simulation; GUI-MatLab*

I. INTRODUCTION

The human consume of energy is increasing year by year. However, cheaper and more efficient methods to produce this energy are increasingly sought, at the same time that environmental issues will become more relevant, such as pollution and nature preservation. Thus, many studies are aimed for improving and implementing new technologies for this purpose.

The most part of the energy, generated in the world today, comes from thermoelectric power plants, which use a fuel (coal, gas, radioactive materials, etc.) to heat a fluid and move turbines. After, this mechanical work is converted, mainly, into electricity.

To transform efficiently the heat of a fluid in mechanical work, these power plants work by using thermodynamic cycles, which are constituted by many equipment type, such as compressors, turbines, heaters, coolers, etc. There are other ways to produce energy, such as solar panels, wind farms, etc. However, power cycles keep being the most used method to produce energy [1-4].

Between these power cycles, there are the steam power cycles, which use thermodynamic state changes of the work fluid, water, to produce energy, and the gas power cycles, which keep the work fluid in the same thermodynamic state in entire process (gas). Examples of gas power cycles are the Otto and Diesel cycles, which are used in cars' engines, and the Brayton cycle, which is used in some power plants to produce electrical energy.

The Brayton cycle use a heated and pressurized gas to move turbines and produce energy. Usually, this cycle uses air as work fluid, although others may be used. Ideally, this cycle is constituted by four stages, which are:

- Isentropic compression in the compressor(s);
- Isobaric heating in the combustion chamber;
- Isentropic expansion in the turbine(s);
- Isobaric cooling in the cooler.

In these stages, the values of the thermodynamic properties of the gas, such as the entropy and enthalpy, change at the same time with the conditions of temperature and pressure. In the compressors, energy is used to increase the gas pressure and, in the combustion chamber, combustion reactions occur, which release a great quantity of thermal energy and increases the gas temperature. In the turbines, the

energy of these thermodynamic changes is converted in mechanical work.

With the current technology and the development of new materials, the air temperature inside the cycle can reach more than 1400,0°C. For becoming the Brayton cycle more efficient, many improvements can be used, modifying the basic structure of the cycle to reduce the required heat or to produce more mechanical work. For reducing the required heat, it is used regenerators, which use the air that leaves the turbine to preheat the fluid at the beginning of the cycle.

For producing more mechanical work, it is also used an intermediate cooling between the compressors and a reheating between the turbines, by assuming that both compressors wasting the same energy and that the turbines producing the same quantify of mechanical work. These improvements can be used depending of the capacity and the financial resources of the power plants [1-4].

Nowadays, besides of air, researches are made to implement others equipment and fluids, such as a gas turbine that uses supercritical carbon dioxide as work fluid with great efficiency and low cost. This gas, produced after a combustion reaction, has a series of singular properties that helps to increase the efficiency of the power cycle, such as higher values of thermodynamic properties, mainly enthalpies, capacity to flow better than the air in the thermodynamic cycle and to dissolve substances such as grease and other lubricants, besides the less noxious the environment [5,6].

For designing properly the equipment of any configuration of Brayton cycle, four parameters should be analyzed. They are:

- Required heat in the combustion chamber;
- Work generated in turbine(s);
- Required work for compressor(s);
- Thermal efficiency of the cycle.

These parameters can be determinate in a thermodynamic simulation of the process. To do this, nowadays; many computer programs are available working with different ranges and providing to the user many configurations of Brayton cycle, but none of them offer the possibility to perform the thermodynamic simulation at real conditions. Besides, the computer program developed in this work can also be used for teaching disciplines of Applied Thermodynamics in undergraduate and graduate courses.

II. METHODOLOGY

There are many methods to calculate the thermodynamic properties of a fluid. This determination may be made by equations of state or thermodynamic tables of a pure substance [7].

However, in both cases, it is necessary, at least, the knowledge of two thermodynamic properties of the system to determinate other properties. In previous work, it was used a "spline" method to correlate and predict thermodynamic properties from two known thermodynamic properties [8]. This method was implemented into our computer program to simulate thermodynamically the performance of Brayton cycles.

For obtaining the main parameters of a Brayton cycle, it is necessary calculate, through mass, energy and entropy balance equations, thermodynamic properties of gases such as enthalpy and entropy. They are determinate when beginning the simulation. Based on this, the computer program, developed in this work, requests to the user the values of temperature and pressure in each stage of the thermodynamic cycle.

In the first place, the program asks to the user the work fluid used in the cycle, which may be air or carbon dioxide. After that, the thermodynamic conditions of the system will be requested. The temperature should be provide in °C and the temperature range, for a Brayton cycle that uses air, is between 0,0 and 1400,0 °C and, for a Brayton cycle that uses carbon dioxide, is between 0,0 and 800 °C. Pressure at the beginning of the process should be provide in bar and its range is between 1,0 and 10,0 bar. As an additional parameter, the pressure ratio should be provided. In Brayton cycles, the pressure ratio represents the relation between the final and initial pressure in the process compression and should be between 5 and 20. These values are used to find the thermodynamic properties of air or carbon dioxide inside the "spline" method implemented in the computer program. Besides, the computer program also requests the configuration of Brayton cycle that user wants, among the three available ones, that are:

- Basic Brayton Cycle;
- Regenerative Brayton Cycle;
- Brayton Cycle with intermediate cooling, reheating and regeneration.

After these specifications, the computer program runs a thermodynamic simulation of a Brayton cycle and provides to the user the values of the main parameters, as is shown in the following energy balance equations for a basic configuration cycle:

$$W_T = H_{out} - H_{in} \quad (1)$$

$$W_C = H_{out} - H_{in} \quad (2)$$

$$Q_B = H_{in} - H_{out} \quad (3)$$

$$\eta = \frac{W_T - W_C}{Q_B} \times 100\% \quad (4)$$

All these equations are mass and energy balances assuming isentropic condition in turbines and

compressors, steady state and disregarding the kinetic and potential energies in the thermodynamic cycle.

In the interface developed with GUI-MatLab, there is an image that represents all the configurations of Brayton cycles available in the computer program, numbered according to the order cited above. This image helps for understanding the user about the thermodynamic simulation of Brayton cycles. This image is shown in Fig. 1. Users can also decide the irreversibility of the power cycle. Sources of irreversibility in real conditions of a thermodynamic cycle may be friction, pressure drops, etc. For simulating thermodynamically Brayton cycles, user

can choose between an ideal condition (with an isentropic efficiency of the equipment as 100%) or a real condition (with an isentropic efficiency of the equipment being assumed by the user).

In real conditions, the values of mechanical work in compressors and turbines are corrected according to the following equations:

$$W_{T,real} = W_T \times E_{fT} \quad (5)$$

$$W_{C,real} = \frac{W_C}{E_{fC}} \quad (6)$$

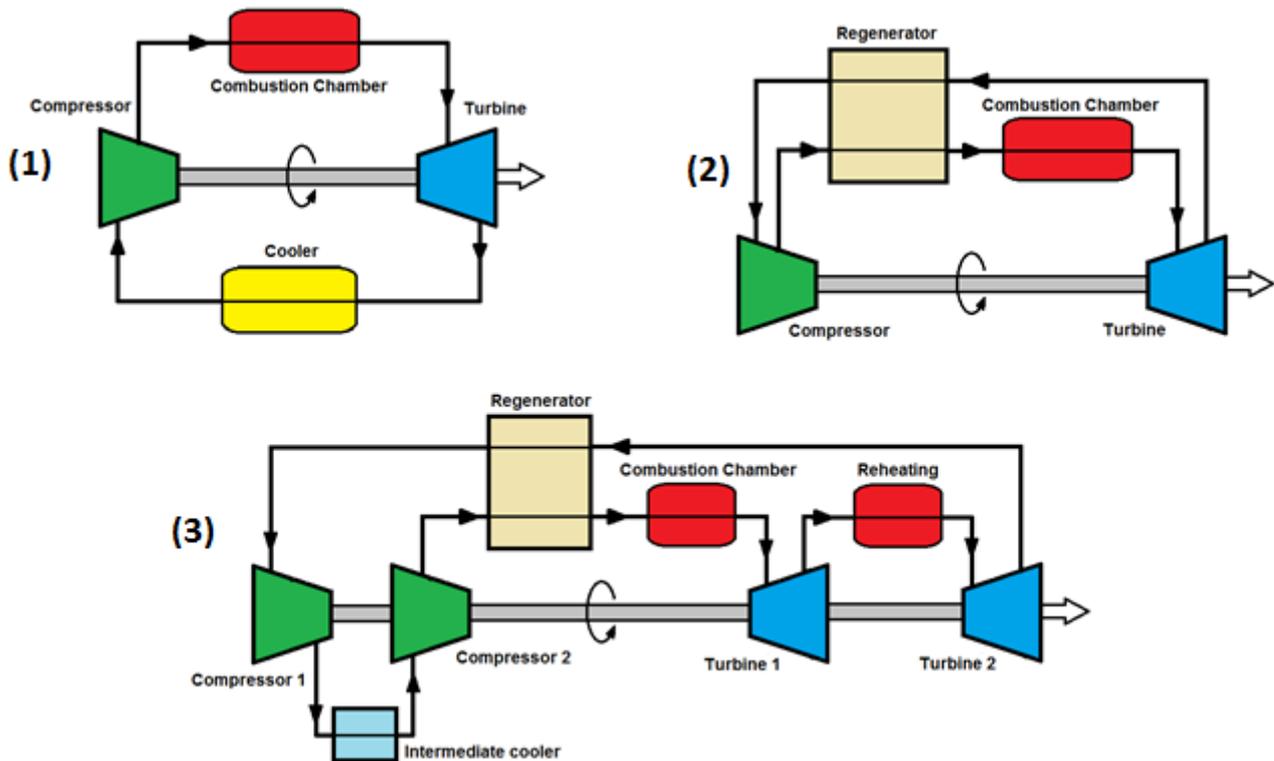


Fig. 1. Image containing all the configurations of Brayton cycle available in the computer program

With all these options, it was designed an interface in GUI-MatLab to make easy interaction with the user. This interface is shown in Fig. 2. It is worth noting that the computer program developed in this work uses the real thermodynamic properties of gases, compared to others that use the ideal properties [9]. The use of ideal properties, used by a great number of Thermodynamics books and computer programs, becomes the calculation of the cycle parameters more simple, but it may lead to considerable errors in final results.

III. RESULTS AND DISCUSSIONS

Results obtained with the computer program, developed in this work, were compared with the others ones obtained in simulations made by hand

with mass, energy and entropy balance equations and thermodynamic tables and examples of Brayton cycles taken from books of Thermodynamics [1, 10, 11].

Tables 1 to 6 show the results obtained for all the configurations of Brayton cycle available in the computer program developed in this work, with R_p representing the pressure ratio, T_c representing the temperature in the compressor ($^{\circ}C$), T_t representing the pressure in the turbine (bar), P_i representing the pressure at the beginning of the process (bar), ϵ representing effectiveness of the regenerator (%) and η representing the thermal efficiency of the cycle (%). Although all examples provide all the four main parameters of a power cycle, only the efficiency was used for comparison between the sources, with a relative error calculated through of the equation:

$$E = \frac{|\eta_{work} - \eta_{example}|}{\eta_{work}} \times 100\% \quad (7)$$

Table 1 presents the results obtained for ideal condition (reversible process) and basic Brayton cycles using air as a work fluid. Table 2 shows the results obtained for real conditions (irreversible process) and basic Brayton cycles using air as work fluid. Meanwhile, Table 3 presents the results obtained for ideal (reversible process) and basic Brayton cycles using carbon dioxide as a work fluid. On the other hand, Table 4 shows the results obtained for ideal conditions (reversible process) and

regenerative Brayton cycle that using air as work fluid. Table 5 also presents the results for ideal condition (reversible process) and regenerative Brayton cycles for carbon dioxide as a work fluid. Finally, Table 6 presents the results for ideal conditions (reversible process) of Brayton cycles with intermediate cooling, reheating and regeneration using air as a work fluid. In the cases that the Brayton cycles use supercritical carbon dioxide, because it is a recent technology still in development, the tables don't have examples from books, only having examples calculated by hand for comparison.

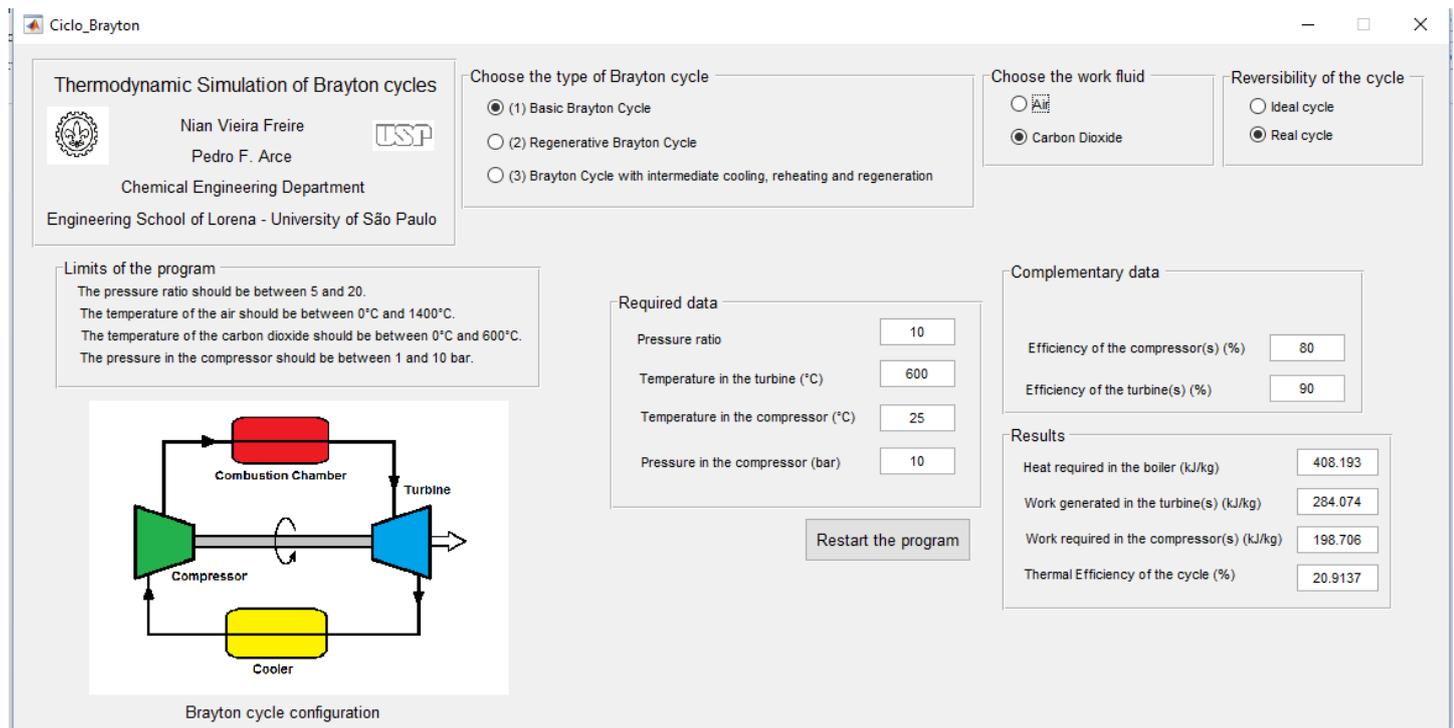


Fig. 2. GUI-MatLab interface after a simulation

Table 1. Results for ideal and basic Brayton Cycle using air

Ideal and Basic Brayton Cycle (Air)						
Source	Tt	Tc	Rp	Pi	η	E
Book [1]	1026,85	26,85	8,0	1,0	42,60	11,64
Program					38,16	---
By hand					38,00	0,42
Book [9]	850,00	25,00	5,0	1,0	36,90	11,97
Program					32,95	---
By hand					32,28	2,03

Table 2. Results for real and basic Brayton cycle using air

Real and Basic Brayton Cycle (Air)								
Source	Tt	Tc	Rp	Pi	Eft	Efc	η	E
Book [1]	1026,85	26,85	8,0	1,0	85	80	26,60	17,71
Program							22,60	---
By hand							22,37	1,03
Book [9]	850,00	25,00	5,0	1,0	80	80	18,70	5,49
Program							17,73	---
By hand							16,69	5,85

Table 3. Results for ideal and basic Brayton cycle using carbon dioxide

Ideal and Basic Brayton Cycle (Carbon Dioxide)							
Source	Tt	Tc	Rp	Pi	η	E	
Program	550,00	25,00	5,0	1,0	25,43	---	
By hand					25,41	0,08	
Program	450,00	15,00	10,0	1,0	35,97	---	
By hand					35,75	0,61	

Table 4. Results for ideal and regenerative Brayton cycle using air

Ideal and Regenerative Brayton Cycle (Air)							
Source	Tt	Tc	Rp	Pi	ϵ	η	E
Book [9]	1100,00	15,00	10,0	1,0	100,0	59,50	0,46
Program						59,23	---
By hand						57,66	2,65
Book [10]	726,85	26,85	6,0	1,0	80,0	47,59	0,40
Program						47,78	---
By hand						47,09	1,44

Table 5. Results for ideal and regenerative Brayton cycle using carbon dioxide

Ideal and Regenerative Brayton Cycle (Carbon Dioxide)							
Source	Tt	Tc	Rp	Pi	ϵ	η	E
Program	550,00	25,00	5,0	1,0	80	42,36	---
By hand						42,35	0,02
Program	450,00	15,00	10,0	1,0	100	38,24	---
By hand						38,08	0,42

Table 6. Results for ideal Brayton cycle with intermediate cooling, reheating and regeneration using air

Ideal Brayton Cycle with Intermediate Cooling, Reheating and Regeneration (Air)							
Source	Tt	Tc	Rp	Pi	ϵ	η	E
Book [1]	1026,85	26,85	8,0	1,0	100,0	69,90	2,40
Program						71,62	---
By hand						71,96	0,48
Book [9]	850,00	25,00	5,0	1,0	100,0	66,60	5,90
Program						62,89	---
By hand						64,26	2,18

Based on the previous tables, it is possible to observe that the results, obtained by the computer program, have a good accuracy in relation with the examples made by hand with relative errors smaller than 3,0% in most of the cases to both of the work fluids, although the errors for Brayton cycles working with carbon dioxide are smaller. Errors, higher than 3,0%, occurred due to the small values of thermal efficiency, that cause a small value in the denominator of the equation (7) and, thus, a high value to the relative error.

Compared with the examples of books, the relative errors are very high. This fact happens because, generally, thermodynamics books use ideal properties of the gases in their tables. These ideal values of entropy and enthalpy become easier the calculation of the main parameters of the processes, but it may lead considerable errors in certain cases. Results obtained in examples made by hand are calculated using, as well as the computer program, real thermodynamic properties of the air. Therefore, the results are more accurate and reliable in these cases.

Although the computer program, developed in this work, and the examples made by hand use the same reference states to determinate the thermodynamic properties of the fluids, the correlation and interpolation tools of MatLab generate small errors in the values of the thermodynamic properties such as enthalpy and entropy due to the method used by this software to perform the interpolations. These values with errors continue happening in the progress of the simulation and, at the end, may result in a final value next to the expected or with a little difference, corresponding to relative errors of 3,0%. This problem doesn't happen so much with the carbon dioxide because its temperature range in the computer program is low, compared with the one of air, which just causing little errors. Despite this, the computer program provides accurate values to the main parameters of Brayton cycles.

The program of this work can be downloaded from the following links:

- For MatLab users:

https://www.dropbox.com/s/rbgana1m383ltvt/Brayton_cycle_web.exe?dl=0

- For MatLab non-users:

https://www.dropbox.com/s/p09z3zhuc39jmxq/Brayton_cycle_mcr.exe?dl=0

IV. CONCLUSIONS

Based on the results obtained with the computer program developed in this work, it is possible to affirm that they were obtained results with a good accuracy to simulate thermodynamically Brayton cycles with

different configurations, using the real thermodynamic properties of gases in the simulation provided reliable values of the main parameters of these thermodynamic cycles. Besides, the computer program, with a friendly interface made in GUI-MatLab, was implemented with the main configurations of Brayton cycles and with the options of choice between ideal and real conditions, this is for reversible or irreversible processes, respectively, for Brayton cycles and for two work fluids: air and carbon dioxide. With this versatility the computer program becomes very useful and a good tool to design equipment in industry and for teaching disciplines of Applied Thermodynamics in undergraduate and graduate courses.

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LIST OF SYMBOLS

B: Combustion chamber;
C: Compressor;
E: Relative error (%);
 E_{fC} : Isentropic efficiency of the compressor (%);
 E_{fT} : Isentropic efficiency of the turbine (%);
GUI: Graphic User Interface;
 H_{in} : Enthalpy in the entrance of the equipment (kJ/kg);
 H_{out} : Enthalpy in the exit of the equipment (kJ/kg);
MatLab : Matrix Laboratory;
 P_i : Pressure in the beginning of the cycle (bar);
 Q_B : Heat in the combustion chamber (kJ/kg);
 R_p : Pressure ratio;
T: Turbine;
 T_C : Temperature in entrance of the compressor ($^{\circ}C$);
 T_T : Temperature in entrance of the turbine ($^{\circ}C$);
 W_C : Work required in the compressor (kJ/kg);
 W_T : Work generated in the turbine (kJ/kg);
 ϵ : Effectiveness of the regenerator (%);
 η : Thermal efficiency of the cycle (%).

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