A PRELIMINARY DESIGN FOR A SIMPLIFIED CLOSED BRAYTON CYCLE MODELING FOR A SPACE REACTOR APPLICATION

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Abstract. *The Nuclear Energy Division (ENU) of the Institute for Advanced Studies (IEAv) has started a preliminary design study for a Closed Brayton Cycle Loop (CBCL) aimed at a space reactor application. The main objectives of the study are: 1) to establish a starting concept for the CBCL components specifications, and 2) to build a demonstrative simulator of CBCL. This preliminary design study is developing the CBCL around the NOELLE 60290 turbo machine. The actual nuclear reactor study is being conducted independently. Because of that, a conventional heat source is being used for the CBCL, in this preliminary design phase. This paper describes the steady state simulator of the CBCL operating with NOELLE 60290 turbo machine. In principle, several gases are being considered as working fluid, as for instance: air, helium, nitrogen, CO2 and gas mixtures such as helium and xenon. However, for this first application pure helium will be used as working fluid. Simplified models of heat and mass transfer were developed to simulate thermal components. A new graphical interface was developed for the simulator to display the thermal process variables in steady state and to keep track of the modifications being implemented at the NOELLE 60290 turbo machine in order to build the CBCL. A set of new results are being produced. This new results helps to establish the hot and cold source geometry allowing to establish estimating costs for building the actual device. These fresh new results will be presented and discussed.*

Keywords: *Nuclear Energy, Space Application, Closed Brayton Cycle, Space Nuclear Reactor*

1. INTRODUCTION

The Institute for Advanced Studies (IEAv) is currently conducting a program called TERRA (TEcnologia de Reatores Rápidos Avançados), (Guimarães *et al.*, 2008), which is the Portuguese acronyms for Technology for Advanced Fast Reactors. This program aims at the establishment of the basis of the nuclear technology to be use at space applications, either to generate heat or electrical energy. The TERRA program is divided in three main areas of research: thermal cycles (namely Brayton and Stirling), fuel elements and nuclear reactor core computer design, and heat pipes for passive heat rejection. This paper presents some new recent developments on the thermal cycle's research. The thermal cycle to be discussed in this paper is the Brayton Closed Cycle. Some previous results have been published elsewhere (Camillo *et al.*, 2008) and (Guimarães and Camillo, 2008). This new contribution outlines the new developments that have been included in the re-design of the NOELLE 60290 in order for it to operate in a closed cycle and give an overview of the full cycle design in preparation for the cost estimation and initiation of the closed cycle construction. Also, some developments and results of the computer design program (Camillo, 2007) created for this task will be presented.

2. THE TURBO MACHINE REDESIGN

The Closed Brayton Cycle consists basically of a turbine, a compressor, cold and hot sources. For better efficiency results, a recuperator was also included in the project of the cycle. The recuperator is a component used to maintain part of the power produced by the hot source and not converted by the turbine. This fraction of the heat power is kept in the cycle, instead of dissipating it on the cold source. The recuperator allows thermal contact between the hot gas of the turbine outlet and the cold gas of the compressor outlet, such that the fluid to be heated arrives at the hot source already pre-heated and the fluid to be cooled arrives at the cold source already pre-cooled. Figure 1 shows a schematic drawing of the cycle with all the components mentioned.

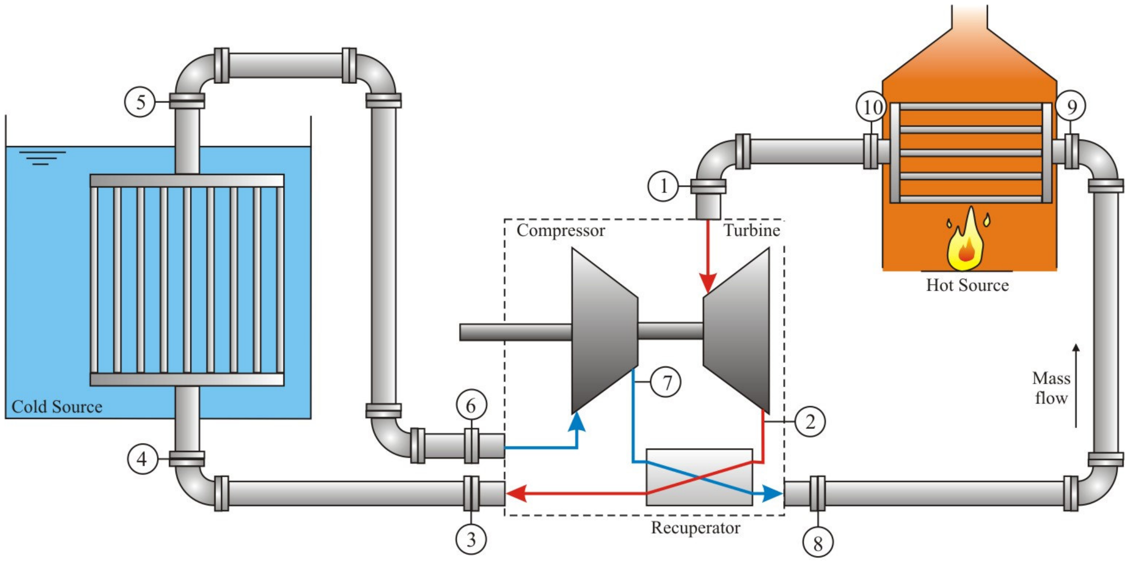

Figure 1. Schematic drawing of the cycle

At this stage of the development, Helium is the work fluid used, and it flows according to the arrows shown on the drawing. The cold source is a tank filled with water, such that the work fluid flows inside a bank of immersed tubes, as shown on the left hand side of Figure 1. The hot source is a natural gas heated oven. The gas flows inside a bank of tubes, the same way as described for the cold source, as shown on the right hand side of Figure 1.

As the TERRA program advances, the tank of the cold source will be replaced for heat pipes, and the oven of the hot source will be replaced for a nuclear reactor. The heat pipes and nuclear reactor design studies are being conducted in parallel lines of research.

At the center of Figure 1 it is shown a schematic drawing for the turbo machine. The dotted box indicates that all three components shown inside it are gathered on the same device. In other words, there are no tubes connecting the compressor or the turbine to the recuperator, avoiding the losses in temperature and pressure that would be observed if tubes were used.

The numbers 1 to 10 across the drawing indicate desirable control points for the cycle operation. At such points, there will be temperature and pressure measurements.

The compressor and turbine used on the turbo machine that is under development were part of a NOELLE 60290 turbo machine. This machine was previously used as Auxiliary Power Unit for a Mirrage aircraft. The NOELLE 60290 used to operate by burning fuel in a combustion chamber and expanding it through the turbine, from where it was expelled to the atmosphere. In other words, it was an open cycle operating machine. The redesign is necessary in order to use it as a closed cycle loop. The redesign was also aimed at the integration of the recuperator to the turbo machine. And the extraction of the combustion chamber, which is no longer necessary. Figure 2 shows the NOELLE 60290 used on the Mirage aircraft as whole and disassembled.

(a) (b)

Figure 2. NOELLE 60290 assembled (a) and disassembled (b)

After several studies and improvements, the current configuration of the turbo machine is as shown in Figure 3. The arrows indicate the way that the turbo machine interacts with the hot and cold sources. The turbine, the compressor, the axis assembly connecting these two components and the shell of the turbine-compressor assembly are the originals from the NOELLE 60290. The radial tubes seen at the back plane of the figure are the recuperator. Inside these tubes flows the work fluid from the compressor outlet. Across and outside them flows the hot work fluid that comes from the turbine outlet. The tubes seen at the higher portion of Figure 3 extract the two flows from the recuperator to each next component, cold or hot sources, as indicated. Another modification can be seen at the first plane of the figure, namely the inlet of the compressor. The axis that connects the compressor to the turbine was prolonged, to allow power extraction from the turbo machine. This way the flow must turn 90 degrees shortly before the compressor inlet. Because of that turn a honeycomb assembly was added to reduce the turbulence at the compressor inlet, minimizing the risk of efficiency loss. Additionally, this prolonged axis is connected to a wheel for power extraction and to an electrical starter for providing the initial torque required to start the turbo machine. This electrical starter was also originally part of the NOELLE 60290.

The final assembly of the turbo machine, cold and hot source, and the tubes connecting each component are shown in Figure 4. This figure is a complete mockup of the room to be constructed and equipped for the turbo machine operation. It also shows an alternator for energy conversion and an assembly of light bulbs to show in a clear and direct manner the power extraction. This mockup shows a room of 4m x 4m, witch gives an idea of the amount of space that will be needed to build the system with these primary components. It is expected that when the proper cold source (heat pipes) and hot source (nuclear reactor) are properly placed these measures will be smaller.

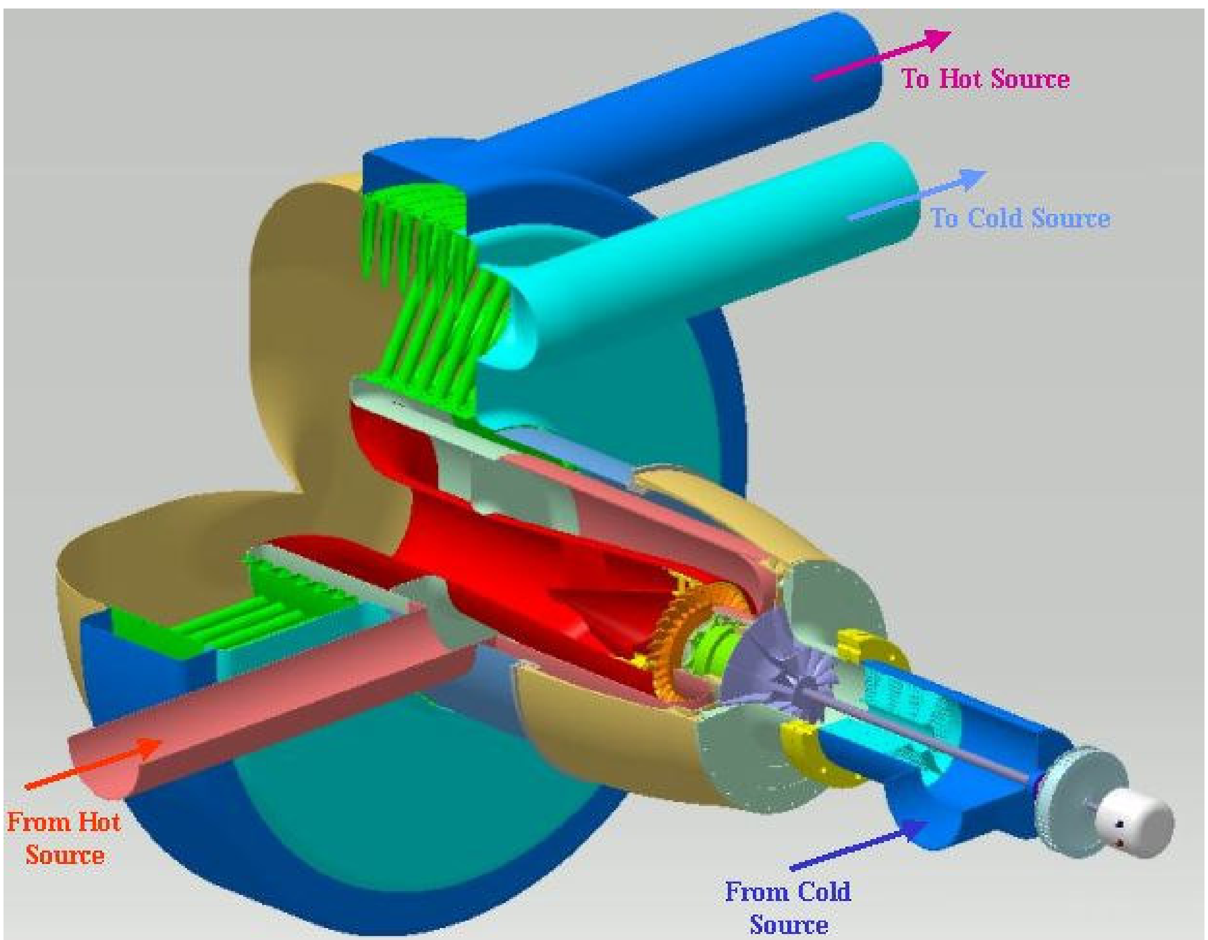

Figure 3. NOELLE 60290 redesign

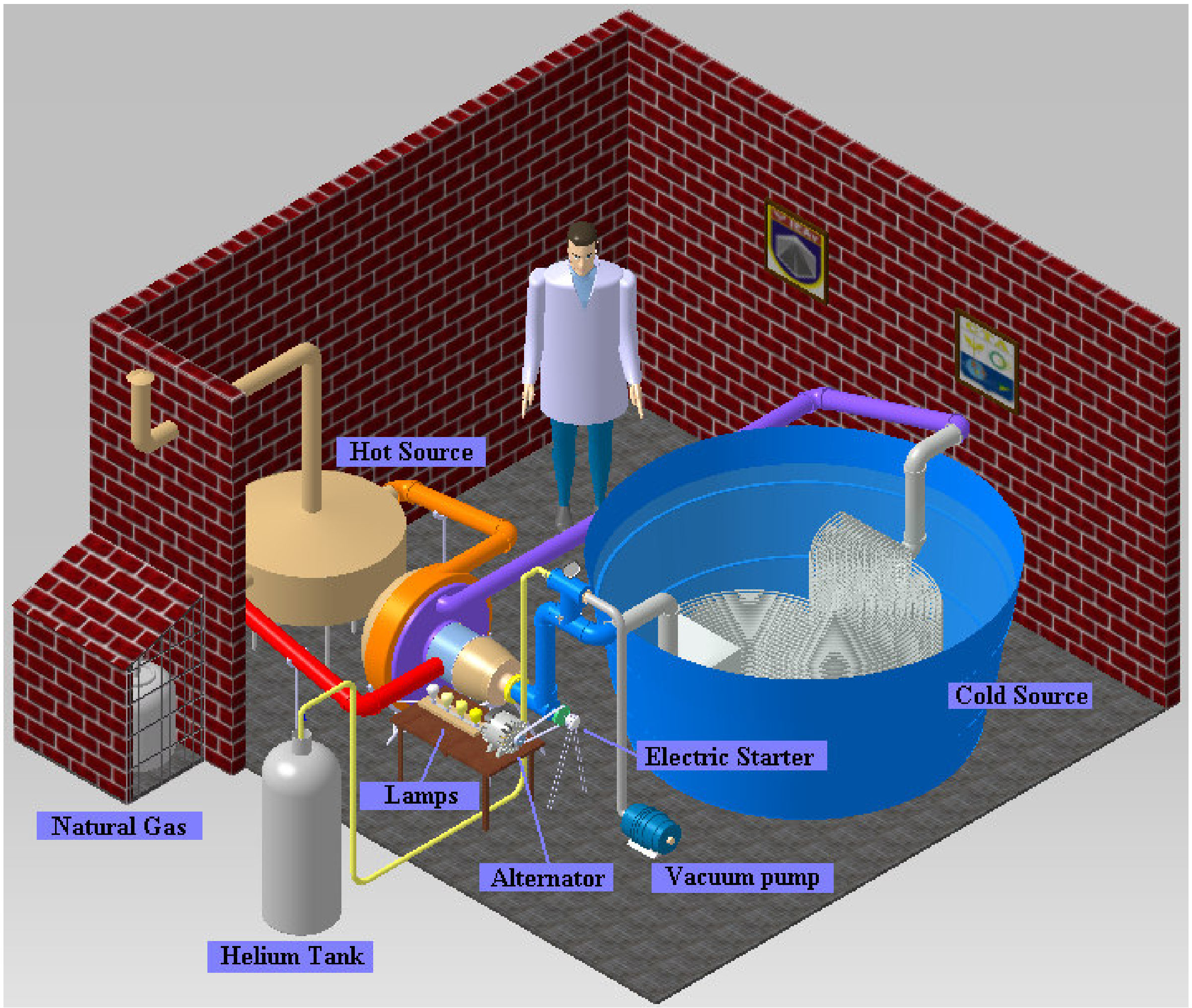

Figure 4. Complete mockup of the Closed Brayton Cycle arrangement

3. MATHEMATICAL MODELING

In addition to the redesign of the NOELLE 60290 it is being conducted a mathematical modeling of each component, aiming at the development of a reliable computer program to calculate the pressure and temperature at several points of control, among other results, for a set of measurements and configuration of each component. This section details the modeling of each component, the assumed suppositions and some of their equations.

3.1. Turbine and compressor

The mathematical modeling for these two components is still at an initial stage. It is used a model presented by Rust (1979). Further studies to improve this modeling are being conducted at this moment (Cohen *et al.*, 2001).

For the turbine:

$$\Delta p = \frac{\beta^{\gamma/\gamma-1}}{r_{comp}}, \tag{1}$$

$$\Delta T = \eta T_i \left(1 - \frac{\beta}{r_{comp}^{\gamma-1/\gamma}} \right). \tag{2}$$

For the compressor:

$$\frac{p_o}{p_i} = r_{comp} \, , \tag{3}$$

$$\Delta T = \frac{T_i}{\eta}\left(r_{comp}^{\gamma-1/\gamma} - 1 \right) . \tag{4}$$

In these equations, β is the pressure loss ratio at the turbine, r_{comp} is the pressure ratio at the compressor, η is the isentropic efficiency at each component, γ is the gas specific heat ratio and the subscripts i and o refer to inlet and outlet, respectively. Also, the mass flow is calculated at the compressor based on the continuity equation.

3.2. Transport Tubes

The transport tubes are used to connect the separated components, namely cold and hot sources, and the turbo machine. The tubes were modeled based on the assumption that there is a total thermal insulation, that the inner tube walls are smooth and that the flow is totally developed.

Based on this set of assumptions, a formulation for pressure loss is obtained (Incropera and DeWitt, 1996), where l is the length of the tube:

$$\Delta p = \frac{f \rho V^2 l}{2D}, \begin{cases} f = 0.316 \,\mathrm{Re}^{-1/4}, \mathrm{Re} \leq 2 \cdot 10^4 \\ f = 0.184 \,\mathrm{Re}^{-1/5}, \mathrm{Re} \geq 2 \cdot 10^4 \end{cases} . \tag{5}$$

The temperature variations due to pressure losses are calculated assuming a perfect gas.

3.2. Cold source

The mathematical modeling of the cold source assumes that there is free convection between the outer tubes wall and water, conduction between outer and inner walls of the tubes, and finally convection between the inner tubes walls and the work fluid. It is neglected any effects the tubes might cause to each other. The pressure loss is modeled the same way as done for the transport tubes.

The free convection modeling is based on equations presented by Incropera and DeWitt (1996), Eq. (6) and Eq.(7), combined with basic convection correlations. The other mechanisms of thermal exchanges were modeled according to basic thermal correlations.

$$\overline{Nu} = \frac{\overline{h}D}{k} \, , \tag{6}$$

$$Nu = \left(0.6 + \frac{0.387 Ra_D^{1/6}}{\left[1 + \left(0.559/\mathrm{Pr} \right)^{9/16} \right]^{8/27}} \right)^2 . \tag{7}$$

3.3. Hot Source

The hot source was modeled assuming that the outer tube walls temperature is constant and equal to the gas flame temperature, namely 923 K. It was used a modeling of internal flux with constant surface temperature given by Incropera and DeWitt (1996). Again, any effects one tube might have over another are neglected and pressure losses are modeled the same way as in the transport tubes. The subscript s indicates conditions at the tubes surface, c_p is the specific heat and $\dot{m}$ is the mass flow rate.

$$\frac{T_s - T_o}{T_s - T_i} = \exp\left(-\frac{A\bar{h}}{c_p \dot{m}}\right). \tag{8}$$

3.4. Recuperator

Finally, the recuperator model was divided in two: inner flow, corresponding to the flow of gas inside the tubes (cold flux); and outer flow, corresponding to the flow across the tubes (hot flux). The pressure loss that occurs in the inner flow is calculated using the model already presented for the transport tubes. The temperature variation for the inner flow is calculated assuming that the heat flux is constant. For the outer flow, pressure loss and temperature changes are obtained using the flow across a bank of tubes, given by Incropera and DeWitt (1996), Eq (9) and Eq. (10). This modeling provides also the heat transfer rate required to calculate the processes for the inner heat flux, Eq. (11). The parameters χ and f are empirical curves that depend on the local Reynolds number and geometrical constraints.

$$\frac{T_s - T_o}{T_s - T_i} = \exp\left(-\frac{\pi D N \bar{h}}{\rho V N_T S_T c_p}\right), \tag{9}$$

$$\Delta p = N_L \chi \left(\frac{\rho V_{\max}^2}{2}\right) f \ , \tag{10}$$

$$q' = N\left(\bar{h}\pi D \Delta T_{lm}\right). \tag{11}$$

4. SIMULATION PROGRAM

Using the equations presented on the previous section, a computer program was built that simulates the thermal exchanges and pressure losses through the cycle. This program was built in MATLAB language, and calculates pressure and temperature at the control points shown in Figure 1. Other results produced by the program are output power and mass flow rate, for a given set of input parameters.

The input parameters for this program are the geometrical characteristics of the cycle, as number of tubes for each arrangement (recuperator, cold and hot sources), their diameter, their length, the transport tubes thickness, among others.

Figure 5 shows the user interface for the simulation program. This figure shows the produced results after the program is executed (by pressing the “Run” button at the graphical interface). Before clicking the “Run” button, the boxes showing temperature and pressure at the schematic drawing of the interface window and the boxes inside the “Results” board are all blank. At the top of the interface window, it can be seen a “Components Configuration” board. All the values inside this board can be changed and are the input variables. The grayed boxes are the predefined parameters; they can also be changed as desired. Once the program is set to run once, it is not necessary to close the interface window to run for another set of values.

The algorithm used by the program is shown by the block diagram of Figure 6. In this figure, each block represents a subroutine in the MATLAB program. As it can be seen, two iterative loops must be used, and there is a convergence process. There is an inner loop, which focus on the convergence of values at the recuperator, and an outer loop, which focus on the convergence of the compressor inlet values.

To help the user follow the processing program, as it starts the run two windows popup are provided. Each one shows a bar that represents the convergence of temperature and pressure at the outer loop, according to its respective title. These windows are presented in Figure 7.

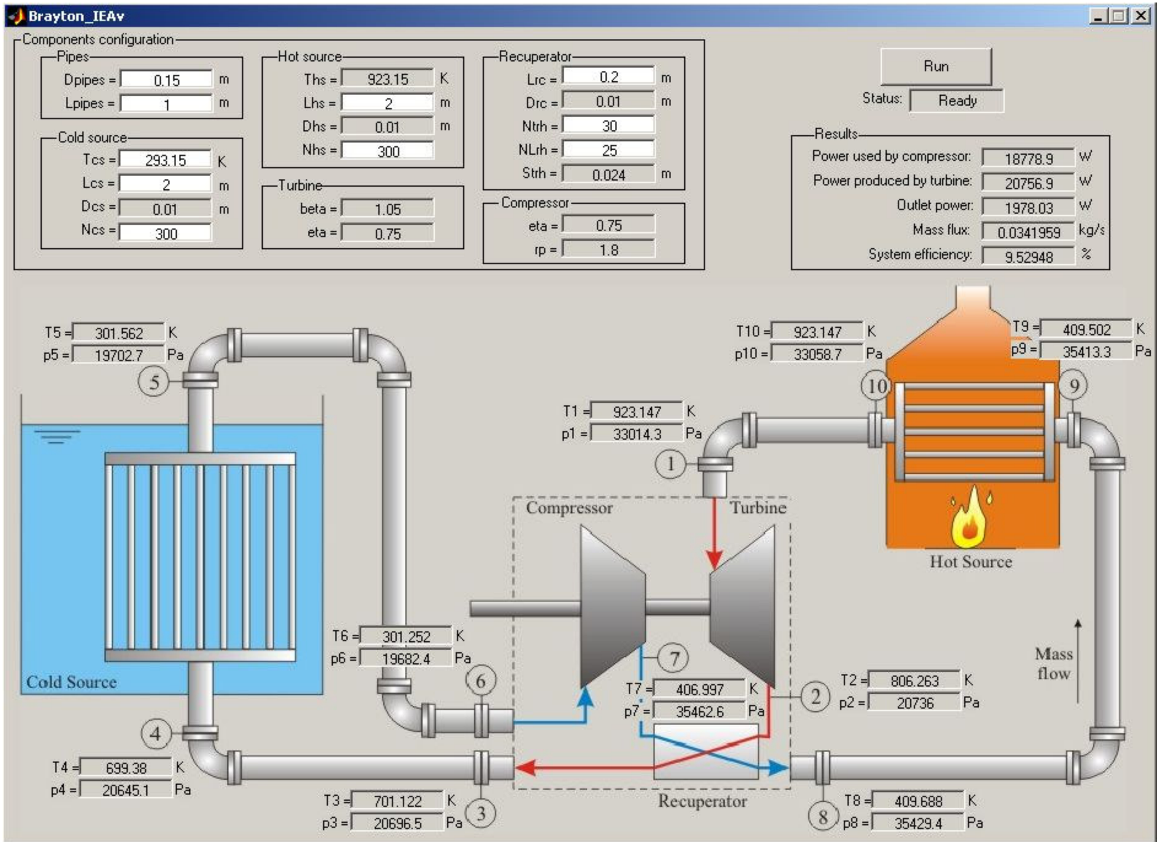

Figure 5. User interface for the simulation program

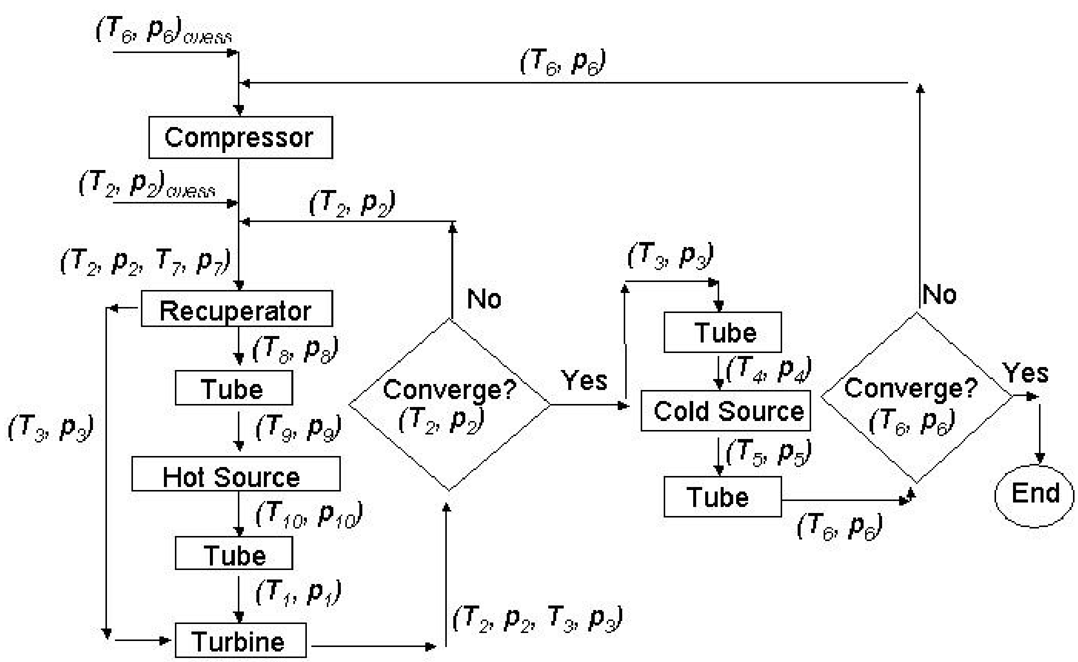

Figure 6. Block diagram used by the simulation program

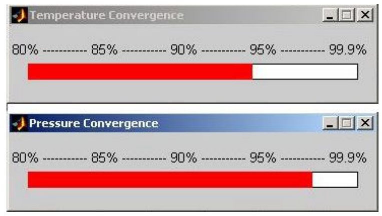

Figure 7. Simulation program popup windows

5. RESULTS AND DISCUSSION

Before any discussions, it is important to emphasize that the results produced by the simulation program are yet not 100% trustable, due to the poor modeling of turbine and compressor. So, the results presented in this section must be seen for their value to the project, not for their reliability.

Table 1 shows some results that can be listed from the parameters calculated by the simulation program. These results are maximums and minimums of temperature, pressure, mass flow, and power data, among others.

Table 1. Useful results given by the simulation program

	Value	Place
Power produced (W)	20756.9	Turbine
Power consumed (W)	18778.9	Compressor
Outlet power (W)	1978	Axis
Mass flux (kg/s)	0.034	-
Efficiency (%)	9.53	-
Maximum temperature (K)	923.14	Hot source outlet
Minimum temperature (K)	301.25	Compressor inlet
Maximum pressure (Pa)	35462.6	Compressor outlet
Minimum pressure (Pa)	19682.4	Compressor inlet
Maximum mass flow (m^3/s)	2.76	Compressor outlet
Minimum mass flow (m^3/s)	0.82	Turbine outlet

Data such as these are very important for the correct materials choice, thermal insulation, thickness and length of each component, for example. Also, these data help to establish the proper instrumentation of the cycle, allowing for the proper choice of thermocouples, Pitot tubes and flow meters. It is being conceived some new forms of measurement devices, such as optical fibers wrapped around pipes. These new measurement devices will be incorporated together with old conventional measurement techniques.

6. REFERENCES

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