PRELIMINARY CLOSED Brayton CYCLE STUDY 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 develop a demonstrative simulator of CBCL in nominal operation conditions. The ENU/IEAv 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. At this moment the simulator is running with Helium as the working fluid. Simplified models of heat and mass transfer are being developed to simulate thermal components. Future efforts will focus on keeping track of the modifications being implemented at the NOELLE 60290 turbo machine in order to build the CBCL.

1. INTRODUCTION

The thermoelectric generators based on a Closed Brayton Cycle Loop (CBCL) concept have shown to have great adaptation capabilities [1, 2, 3, 4]. It may be combined with several types of heat source (for example, nuclear reactor, natural gas, sugar cane waste, etc). Analysis of CBCL include: performance of heatsource, dynamic performance of power design, gas hermetic systems, compatibility of integrated systems, and reliability of the power conversion system. The main aspects that affect the performance of CBCL power conversion system are: turbo machine efficiency, heat exchange efficiency, composition of the working fluid, and cycle temperature and pressure.

In general, the subsystems of the CBCL are: interface with a hot source, a unity of power conversion (turbo machine), a heat rejection system, a distribution and management of electricity. The thermodynamic cycle include: gas compression, heat addition, gas expansion...
and heat rejection. The working fluid normally is a mix of inert gases [2, 3, 4] that gives the best combination of heat transfer performance.

A simple recuperated CBCL developed by M. J. Barrett [5, 6], for example, is a power conversion system of easy comprehension and define the main concepts: simple design, easy system for servicing, few components, easy testing on earth, qualified for surface missions, and conversion between 20 kWe and 300 kWe. The Sandia National Laboratories (SNL) [2], for example, built a CBCL to validate its operational procedure for latter coupling with nuclear reactor core. The plant has a market turbo machinery with a gas bearings alternator of 30 kWe output, rotating at 96000 rpm and a electrical heater limited to 80 kWth at 1000 K output.

At the Nuclear Energy Division of the Institute for Advanced Studies (ENU/IEAv) a re-design work is being performed at NOELLE 60290 [7] turbo machine in order to adapt it to a CBCL. Natural gas burning will be used as a hot source, and a water tank will be used as a cold source. The SNL CBCL design [2] may be taken as example for components connection and sensors installation. This paper presents a steady state mathematical initial modeling for the CBCL being developed at ENU/IEAv. The main objectives of this work are: to help CBCL component specification initial definitions, development of simple computational models to simulate the desired CBCL and development of a demonstrative simulator with a user-friendly graphic interface for visualization of the physical phenomena involved at the CBCL.

2. NOELLE 60290 TURBO MACHINE

The microturbo NOELLE 60290 turbo machine is used at Mirage III and Estandard IV aircraft starting. It is composed of two stages, in which only the first stage allows the desired adaptation to a CBCL. The main components of first stage are: electrical motor, compressor, combustion chamber, and turbine. The electrical motor is used to spin the compressor before the microturbo starts. The compressor is of a centrifuge type, and the turbine is of an axial type. All components are connected to one shaft. The Fig. 1a shows the front side of the NOELLE 60290, detailing the air intake. Fig. 1b shows back side of the NOELLE 60290 turbo machine, detailing the hot gas exit.

![Figure 1. NOELLE 60290 Turbo Machine.](image-url)
A new proposed design is necessary for operation of the NOELLE 60290 turbo machine as a CBCL. Fig. 2 illustrates the first possibility for the NOELLE 60290 new design. Fig. 2a shows the working fluid flow path. Fig. 2b shows the microturbo with the detail of the recuperator inclusion. Fig. 2c shows the detail of the recuperator tubes. Fig. 3a shows the second possible solution for the redesign of the NOELLE 60290. In this case the recuperator is located a little more to back of the whole structure. Fig. 3b presents a frontal view of the recuperator. Both Fig. 2 and 3 present possibilities that are being evaluated at the writing of this contribution.
3. **CBCL MODELING**

The developed CBCL static simulator consists of simplified mathematical models, based on mass and heat transfer. The modeled components are: a compressor, a single stage turbine, a recuperator, a heat exchanger with hot source (heater), a heat exchanger with cold source (cooler), and ducts.

The model used for compressor and turbine was obtained considering thermodynamic balance with simple relations using the pressure ratio (for the compressor) and the pressure loss ratio (for the turbine) [8, pp. 83].

For the recuperator, in this first stage it was assumed an arrangement of the staggered bank of pipes in perpendicular position to the flow of hot gases. It was considered that the hot gas passes through the bank of pipes, and the cold gas runs inside the pipes.

A conventional heat source based on natural gas burning type is been considered. This choice was due cost constrains. The decision of using a natural gas heating might be revised in latter development stages. The heater specifications are limited to nominal conditions of the NOELLE 60290 turbo machine. For now, the model consists in a tube directly in contact with a flame of constant temperature.

For the cold source a simple helicoidal tube immersed in a large water tank was considered, in this first model approach. The idea is to use the high thermal capacity of the water tank. In this way a natural convection heat transfer coefficient was used and the Morgan correlation [9, pp. 502] was chosen. As the work progresses that is going to be substituted by an assembly of heat pipes exposed to the atmosphere.

For the duct models, it was considered a perfect thermal insulation, in a way that pressure loss is a consequence of only friction, determined by the Moody friction factor [9, pp. 424] and temperature loss is determined considering the perfect gases correlation.
4. CBCL INTEGRATION AND SIMULATION

The NOELLE turbo machine and CBCL components integration will be done with pipe connections. Fig. 4a illustrates the thermodynamic cycle used by the CBCL in development. Fig. 4b shows the graphic interface that will be used by the simulator.

In the present phase of the development of this CBCL, the recuperator has been integrated into the body of the NOELLE 60290, eliminating 2 pipes to avoid unnecessary losses. However, in Fig. 4b the recuperator remains physically separated from the NOELLE, aiming a better comprehension of the position of this part in the cycle. Numerical values for the thermodynamic cycle are currently being produced and analysed.

![Figure 4. (a) CBCL thermodynamic cycle configuration. (b) CBCL graphic interface with all components explicitly displayed.](image)

5. CONCLUSIONS

The aim of this work was to develop a first step steady state model of a recuperated CBCL. The model is not ready yet, and because of that only theoretical assumptions were presented. This should be understood as a work in progress. And the most recent results will be presented at the conference. In spite the model simplicity it is already been used as a design tool for the CBCL. So far the model was used to establish the temperature-pressure profile around the CBCL, using helium as working fluid. Future work will address the case for other gases, such as CO$_2$, air, Xe, Ar, N$_2$, and the combinations of some of them. It will be included the electricity generation modules and a better loss model. Also, changes will focus on removing some simplified assumptions and reproducing more closely the CBCL being designed. As the work progress and the actual system is built, feedback from the experiment will correct or eliminate any misguided assumption.

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