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Second Law Analysis of Supercritical CO_2 Partial Cooling Brayton Cycle with Recompression

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Abstract

In the present study, energetic and exergetic analyses and optimization of a supercritical CO_2 ($s - CO_2$) Partial Cooling with recompression (PC) cycle, using reheat and without this, have been performed to study the effect of operating parameters on the optimum pressure ratio, energetic and exergetic efficiencies and component irreversibilities. Optimization is carried out using a Particle Swarm Optimization (PSO) genetic algorithm, and optimum operating conditions based on maximum first law efficiencies are determined. The result shows that the thermal

efficiency of the super critical CO_2 Brayton cycle increases monotonically with the temperature of the cycle.

Keywords: Supercritical Brayton Cycle, Optimization, exergetic analyses

1. Introduction

The development of new energy generation technologies is an issue of great importance worldwide, however, another ideal that is being given a lot of importance and to which many of the recent investigations are being directed, is the improvement of the current systems, in such a way that an optimum level of operation is achieved [1] to complex power generation cycles, which maximize the production of energy without affecting the environment [2]. Rigorous exergetic analyzes of the power cycles have been carried out as part of these studies [3] [4]. These investigations have been favored by the rise of computer systems and the available software packages, which help to achieve better results, such as MATLAB Mathematical Software and its graphical environment used in multiple investigations [5].
Among some of the power cycles exposed to constant improvements, we have the Kalina cycle [6], which is a direct variation of the Rankine cycle in which a solution of two fluids with different boiling points is used as a working fluid. The Goswami cycle [7], which is a new thermodynamic cycle that has the combination of a Rankine cycle and a generation cycle by adsorption. This cycle has been studied through the implementation of various mixtures as working fluid, such as the mixture of water with ammonium [8], which is studied to improve the behavior of the cycle under certain operating conditions.
Numerous studies and investigations have focused on analyzing the behavior of the Brayton s-CO_2 cycle, to find improvements in its operation and with this a wider range of applications, as proposed by Dostal [9] for nuclear applications. On the other hand, Kulhánek and Dostál [10].
In this study, a complete analysis is presented from the first and second law of thermodynamics for a partial cooling Brayton s-CO_2 cycle with recompression, through the use of reheating and without it. The optimal operating conditions of the Brayton s-CO_2 cycle are based on a previous optimization of the operating parameters, such as the pressure ratios and the Split Ratio (SR) until achieving the maximum efficiencies at the established operating conditions.

2. Methodology

2.1. Thermodynamic Cycle

The partial cooling (PC) $s-CO_2$ Brayton cycle is shown in Fig. 1; in this configuration th,ree compressor and two recuperators are used (LTR, Low thermal recuperator and HTR, High thermal recuperator). This layout can reduce the work input during the compression process. Additionally, this configuration can reduce or control the problems of pinch points in the recuperators that do not allow the transfer of heat between the cold and hot water streams [11].

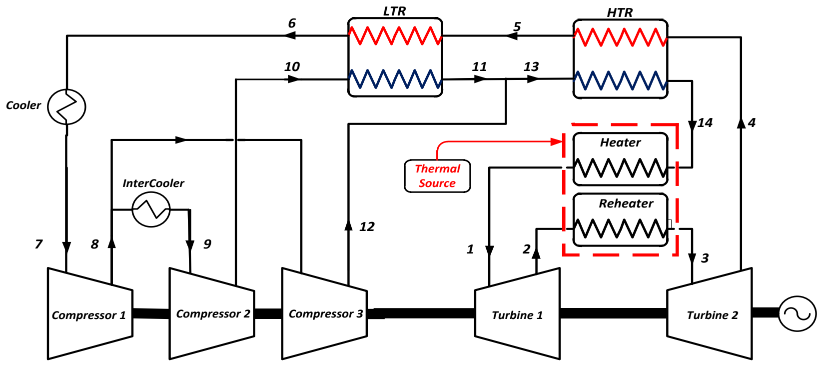

Figure 1. Supercritical $s - CO_2$ PC Brayton Cycle Layout. Adapted from [4]

The stream leaving the LTR (state 6) goes to the Cooler to reduce its temperature and thereby reduce the compression work of the Compressor 1 (C1). Then the stream leaving C1 is split into two streams. The first stream goes to the recompressor (C3), which is operating at exit pressure and temperature of the C1. The second stream goes to Intercooler in which its temperature is reduced before enter to the Compressor2 (C2). The stream leaving the C2 (state 10) passes through the LTR where it receives energy from the hotter stream (state 11), and it is then mixed with the stream (state 12) leaving C3. The mixed stream (state 13) is preheated in the HTR before its final heating in the thermal source. Part of the work produced by the turbines is used to drive the compressors (C1, C2, and C3) [4].

2.2. Fundamental Equations

The fundamental equations used in the study have been widely studied in the literature. For the development of a theoretical model, it's required to make some assumptions [11], like the following:

- Pressure losses in the pipes and heat exchanger are neglected.
- All components of the cycle are well insulated.
- Expansion and compression processes are adiabatic.
- The cycle operates under steady-state conditions.
- The thickness of impeller blades can be considered negligible

To perform the energy analysis of the PC Brayton cycle configuration, mass, and energy balance was carried out in all component. The fist law efficiency of the power cycle is defined as:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \; x \; 100 \tag{1}$$

with:

$$\dot{W}_{net} = \sum \dot{W}_{turb} - \sum \dot{W}_{Comp} \tag{2}$$

$$\dot{Q}_{in} = \dot{Q}_{heater} + \dot{Q}_{reheater} \tag{3}$$

The energy model was validated with the result performed by Kulhánek and Dostál [10], Turchi et al.[11], and R. Vasquez [4] in their investigations. The parameters used in the validation process are shown in Table 1. All balances were written in MatLab, and Refprop V9.1 was used to obtain the thermodynamic properties of the fluid work. Typical temperature-entropy diagram for the Partial cooling (PC) $s - CO_2$ Brayton Cycle layout with rehearing at the turbine inlet temperature of 700 °C, is presented in Fig. 2

Parameters	Value
Turbine efficiency	93%
Compressor efficiency	89%
Heat exchanger effectiveness	95%
Turbine inlet temperature	500°C – 800°C
Cycle high pressure	25 MPa
Minimum Pinch Point temperature	5°C

Table 1. Input parameters used in the validation of the proposed model. Data were taken from Ref. [4].

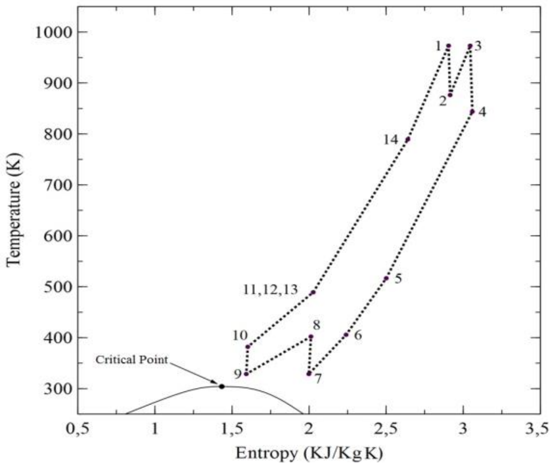

Figure 2. Temperature-Entropy diagram for Supercritical ($s - CO_2$) Partial Cooling Brayton Cycle Layout with reheat.

On the other hand, the exergy balance for each component of the $s - CO_2$ Brayton cycle, is determined as:

$$\frac{dE_{v.c.}}{dt} = \sum_j \dot{E}_{qj} - \dot{W}_{cv} + \sum_j \dot{m}_i \, b_i - \sum_o \dot{m}_o \, b_o - \dot{E}_d - \dot{E}_{loos} \tag{4}$$

with:

$$\dot{E}_q = \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j \tag{5}$$

$$b = h - h_o - T_o(s - s_o) + \frac{V^2}{2} + gz \tag{6}$$

In this research, the thermal effects produced by the thermal source that provides the input energy to the cycle is not taken into account in the analysis, since this thermal source is handled as a "black box" from which only the heat required is extracted for the operation of the proposed Brayton cycle configuration. The exergy efficiency of the cycle is calculated in two different ways with the application of equations Ec. (7) and Ec. (8) to verify the results.

$$\eta_{exergy} = \frac{\dot{W}_{net,turbina} - \dot{W}_{net,compresor}}{\dot{E}_{input}} \tag{7}$$

$$\eta_{exergy} = 1 - \frac{\sum\left(\dot{E}_{loss,comp} + \dot{E}_{d,comp}\right)}{\dot{E}_{input}} \tag{8}$$

3. Results and discussion

In this paper supercritical Partial Cooling (PC) Brayton cycle, with rehearing and without it, was modeled with the use of the Mathematical software MatLab and REFPROP V9.1 for the thermodynamic properties of the fluid work. The optimization process of the fist law was carried out with the Particle Swarm Optimization (PSO).

3.1. Case study: Validation of the model

In Fig. 3 the results of the validation, of the thermal efficiencies, of the supercritical Brayton cycle configuration analyzed, are presented. The results obtained from the proposed model agree well with the reference results [4]. With a slight error of 3,8% (maximum relative error) for all temperatures. These small deviations are (possibly) due to the database of the thermal properties used, to the optimization model and code implemented or to the processing capacity of the equipment used for the simulations

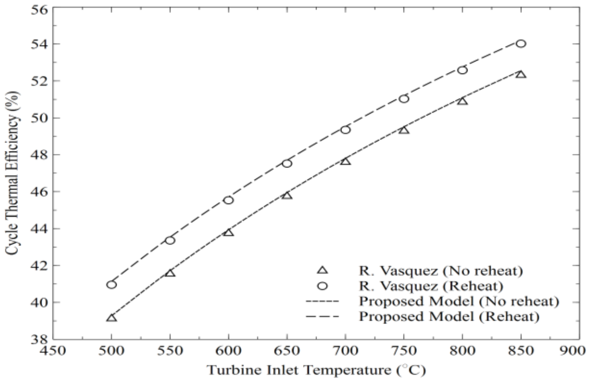

Figure 3. Validation of the proposed model with and without rehearing, according to reference. R. Vasquez [4]. Input data are given in Table 1.

3.2. Case study: First Law. Energetic Analysis

According to the fist law of thermodynamic, the thermal efficiency of the super critical CO_2 Brayton cycle increases monotonically with the temperature of the cycle, like is shown in Fig. 3 and Table 2.

ITEM	Temperature	Efficiency [%]	
#	[°C]	With Reheater	Without Reheater
1	500	41,14%	39,28%
2	550	43,55%	41,72%
3	600	45,74%	43,93%
4	650	47,75%	45,95%
5	700	49,58%	47,81%
6	750	51,27%	49,52%
7	800	52,83%	51,09%
8	850	54,28%	52,56%

Table 2. Efficiencies of the PC the $s - CO_2$ Brayton cycle with and without reheater according to Input parameters.

3.3. Case study: Exergetic Analysis

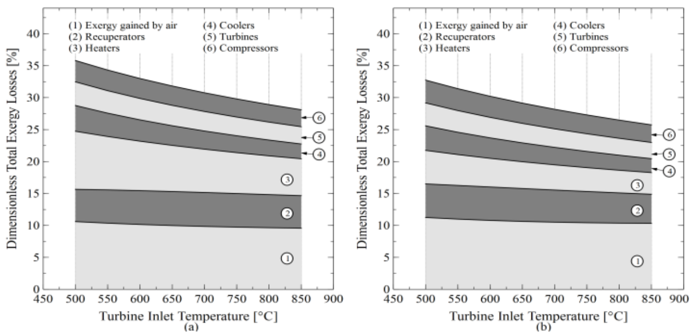

Figure 4. Dimensionless exergy losses by component for Partial Cooling S-CO2 Brayton cycle. (a) without reheat, (b) with reheat.

According to the shown above, the total exergy losses are lower in the configuration that implements the use of reheater than this one that does not use it. Fig. 4a and 4b. It can be seen that with the use of reheater the exergy losses decrease by at least 3 percentage points as the temperature increases in this configurations. Also, the use of the reheater, favors the decrease of the total exergy losses of the cycle, concerning the configuration in which this is not implemented, presenting a decrease of 3,74%.

4. Conclusions

A supercritical Brayton cycled was modeled and studied in this investigation, in a temperature range from 500 °C to 800 °C. A partial cooling layout with and without reheater with $s - CO_2$ as a fluid work was presented.
According to the thermodynamic analysis developed and the results obtained, the below conclusions are proposed:

- The addition of the reheater to the configuration of the $s - CO_2$ Brayton cycle is a hopeful option, since it helps to considerably improve the thermal efficiency of the cycle by at least 2,5 %.
- The combination of components such as the intercooler, the re-compressor, the recuperator and the re-heater used in a supercritical Brayton cycle can achieve greater thermal efficiencies, which it can reach an efficiency of around 47%.
- Based on the exergy analysis, implementation of reheater can achieve to improve the total exergy losses with the reduction of the exergy losses of 6 %.
- The component or stage with the greatest contribution in the exergy losses in the Brayton cycle configuration studied are those caused by the cooling air followed by the recuperators. While the components that contribute least to the losses of exergy are the turbines and compressors, with a minimum contribution.

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