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Research Article

Performance analyses and optimization of a regenerative supercritical carbon dioxide power cycle with intercooler and reheater

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ABSTRACT

Supercritical CO_2 (sCO_2) power cycles play an important role in energy production as they are more efficient and more compact than conventional energy production systems. Therefore, they are widely used in different systems such as nuclear systems, renewable energy systems, heat recovery systems, fossil power plants, submarines, and some commercial and navy ships that produce a wide range of power operating in different temperature ranges. It has become very popular especially in recent years due to its widespread use and technical capabilities. This study analyses the effects of some design parameters (pressure ratio and temperature ratio) on the performance criteria (net work, thermal efficiency, back work ratio, and total entropy generation) and draws some optimum working conditions by means of the purpose of using. Results show that to obtain an optimum system according to maximum thermal efficiency or maximum net work the design range for the compression ratio for temperature ratio (α) 2, is between 5.224 and 6.449, for α=2.75, 8.408 and 12.57, and for α=3.5, the design range is between 11.35 and 16.

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INTRODUCTION

In today's world, where the need for energy is increasing day by day, the question of how and in which ways energy is provided rather than providing it comes to the fore. In this context, this question is very important especially in the field of Maritime. Considering that most of the international transportation is done by ships, it is known that the improvements to be made in this sector will affect a very wide area. The use of more environmentally friendly, more efficient, and more suitable sized systems in maritime will positively affect other areas. In addition, air-independent propulsion systems are preferred, especially in places where confidentiality is at the forefront, such as military submarines. Today, there are many air-independent propulsion systems based on different technological levels and different working principles. Supercritical CO_2 (sCO_2) cycles are one of them. From this point of view, supercritical CO_2 systems have a very common use because they are smaller in size than conventional systems and are more suitable for security, especially in the navy vessels.

Supercritical cycles have a very common usage and research area since the 1950s, when the technical foundations were laid, and especially after the 2000s. In order to show the com-

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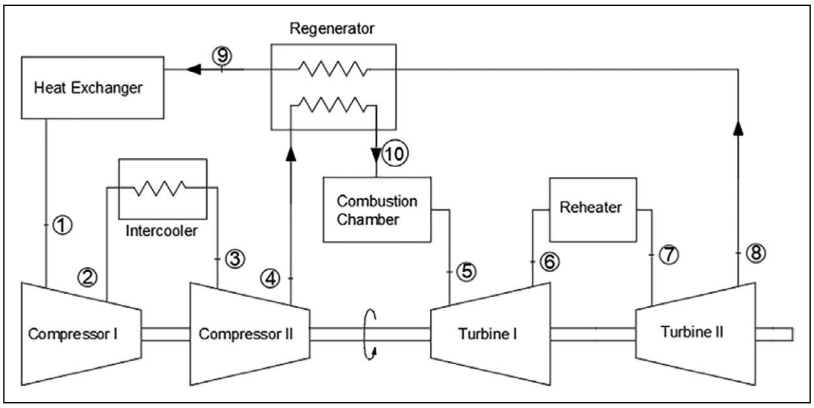

Figure 1. The schematic diagram of sCO_2 cycle with the intercooler, reheater, and regenerator.

mon and popular interest for super critical CO_2 cycles, these some detailed reviews supply very important source for researchers (Ahn et al., 2015; Wang, He, & Zhu, 2017; White, Bianchi, Chai, Tassou, & Sayma, 2021). Beside to these, many experimental and theoretical studies have been carried out in the fields of energy efficiency, economy, and environment for different application areas (Zhu, 2017). Such studies have been done for concentrated solar power applications by (Reyes-Belmonte, Sebastián, González-Aguilar, & Romero, 2017; Guelpa & Verda, 2020); for fossil power plant applications by (Guo, Li, Xu, Yan, & Ma, 2020); power cycle evaluation including sCO_2 for nuclear power plant by (Herranz, Linares, & Moratilla, 2009); for waste heat recovery by (Manente & Costa, 2020; Siddiqui & Almitani, 2020); and for marine applications by (Gumus, 2019). And also energy and exergy analyses and optimization of different kind of supercritical CO_2 power cycles have been concluded by (Bashan & Gumus, 2018; Gumus & Bashan, 2020). First law based dimensional analyses and optimization of a supercritical CO_2 power cycle have been made by (Karakurt, Bashan, & Ust, 2020). In this study, analyzes of the performance outputs (net work, back work ratio, thermal efficiency, and entropy generation rate) of a supercritical Brayton cycle with CO_2 flow will be performed according to the design parameters (pressure ration and temperature ratio).

THERMODYNAMIC MODEL

The Brayton cycle is known as a commonly used cycle in gas turbine areas. So, it has an important place in today's gas-fluid power cycles. Although it is an open system like internal combustion power cycles, for thermodynamic analysis, it is assumed that the exhaust gases are taken inside and reused after passing through a heat exchanger and are made suitable for analysis as a closed system. The schematic model of the supercritical CO_2 cycle with intercooler, reheater and regenerator operating according to the closed system principles is given in Figure 1.

In the analyzes, 305 K for temperature and 7500 kPa for pressure were chosen as initial conditions. Isentropic efficiency values of compressors and turbines were accepted as 0.70 and 0.80. While the pressure drop (ΔP) is 0.05 bar and the effectiveness is 0.90 in the heat exchangers. The compressor inlet temperatures (T_1=T_3) and turbine inlet temperatures (T_5=T_7) are considered equal among themselves.

The equations used in the analyzes were obtained in accordance with the Laws of Thermodynamics and are shared below. In this context, the amount of work consumed in the compressors and produced in the turbines are calculated with Equations 1 and 2. While the sub-indices c and t in the equations represent the compressor and turbine, the numbers represent the entry-exit points of the system elements seen in Figure 1.

$$w_c=(h_2-h_1)+(h_4-h_3) \quad (1)$$

$$w_t=(h_5-h_6)+(h_7-h_8) \quad (2)$$

The expression of the back work ratio (r_{bw}), which is the ratio of the work consumed in the compressor(s) to the work produced in the turbine(s), is defined as in Equation 3. The net work (w_{net}) of the system is defined in Equation 4 as the difference between the work produced in the turbines and the work consumed in the compressors.

$$r_{bw}=w_c/w_t \quad (3)$$

$$w_{net}=w_t-w_c \quad (4)$$

The sum of the heats given or inlet to the system (q_{in}) in the combustion chamber and the reheating section is given in Equation 5. The expression of thermal efficiency (η_{th}), which is the ratio of the net work obtained from the system to the heat supplied to the system, is also given in Equation 6.

$$q_{in}=q_{in1}+q_{in2}=(h_5-h_{10})+(h_7-h_6) \quad (5)$$

$$n_{th}=w_{net}/q_{in} \quad (6)$$

The entropy generation of system (*sys*) and environment (*env*) can be defined separately in Equations 7, 8, and 9. In the equations, the subindices sys, env and out defines the system, the environment, and the heat rejection from the system to the environment. ΔT defines the temperature differences between related environment and system points.

$$q_{out}=q_{out1}+q_{out2}(h_3-h_2)+(h_9-h_1) \tag{7}$$

$$s_{sys}=\left(\left(\frac{q_{in1}}{T_5}\right)+\left(\frac{q_{in2}}{T_7}\right)\right)-\left(\left(\frac{q_{out1}}{T_1}\right)+\left(\frac{q_{out2}}{T_3}\right)\right) \tag{8}$$

$$s_{env}=-\left(\left(\frac{q_{in1}}{T_5+\Delta T}\right)+\left(\frac{q_{in2}}{T_7+\Delta T}\right)\right)+\left(\left(\frac{q_{out1}}{T_1-\Delta T}\right)+\left(\frac{q_{out2}}{T_3-\Delta T}\right)\right) \tag{9}$$

Total entropy generation can be calculated with Equation 10 that sums of the Equations 8 and 9.

$$s_{gen}=s_{sys}+s_{env} \tag{10}$$

RESULTS AND DISCUSSION

The results obtained using the assumptions made, and the given equations in the thermodynamic model section will be shared in this section. As a result of the calculations, the pressure, temperature, and specific enthalpy values of each point in the cycle are included in Table 1.

In the parametric analyzes, 4, 8, 12, 16 values were used for the compression ratio (rp), while 2, 2.75 and 3.5 values were used for temperature ratio (α). While rp values are related to the dimensions of the system, α values are related to the material structure. The effects of these parameters on the performance criteria are shown in the figures below.

The effects of pressure ratio on the performance outputs (r_{bw}, w_{net}, η_{th}, and s_{gen}) at a constant temperature ratio are given in Figure 2. In the analyses, the temperature ratio of 2.75 was considered. In cases where the compression ratio is changed by keeping the temperature ratio constant, there is a compression ratio that maximizes the thermal efficiency and the net work, while the back work ratio increases with a linear characteristic and the entropy generation increases with an exponential characteristic. The right y axe shows the s_{gen} in kJ/kg.K unit, thermal efficiency and back work ratio. The left y axe shows the net work of the system per kg.

Table 1. The thermophysical properties of system points

i	P_i [MPa]	T_i [K]	h_i [kj/kg]	s_i [kJ/kg.K]
1	7.5	305	-152	-1.231
2	21.21	362.3	-113	-1.199
3	20.15	305	-248	-1.599
4	57	340.2	-191	-1.548
5	54.15	838.8	533.4	-0.194
6	19.14	722.7	405.3	-0.148
7	18.18	838.8	548.9	0.0453
8	7.87	748	449	0.0794
9	7.72	365	4.56	-0.751
10	55.29	595.4	208.4	-0.656

The effects of changes in temperature ratio at a constant pressure ratio on the performance outputs are given in Figure 2. In cases where the compression ratio is kept constant (rp=8) and the temperature ratio is changed, thermal efficiency and net work expressions increase with different inclination angles, while the back work ratio decreases with a linear characteristic and the entropy generation decreases with an exponential characteristic in kJ/kg.K unit.

The effects of changes in pressure and temperature ratios on net work and thermal efficiency are given in Figure 3. In cases where the compression ratio is changed by keeping the temperature ratio constant, there is a compression ratio that maximizes the thermal efficiency and net work expressions for each temperature ratio. These rates increase with the change of temperature ratio. Straight lines on the axes show the variation of pressure ratios at constant temperature ratios, while dashed lines characterize variable temperature ratios at constant compression ratio. If the temperature ratio (α) is 2, the compression ratio that maximizes the net work (59.22 kJ/kg) becomes 6.449, while the thermal efficiency value becomes 0.1665. At this temperature, the compression ratio at which the thermal

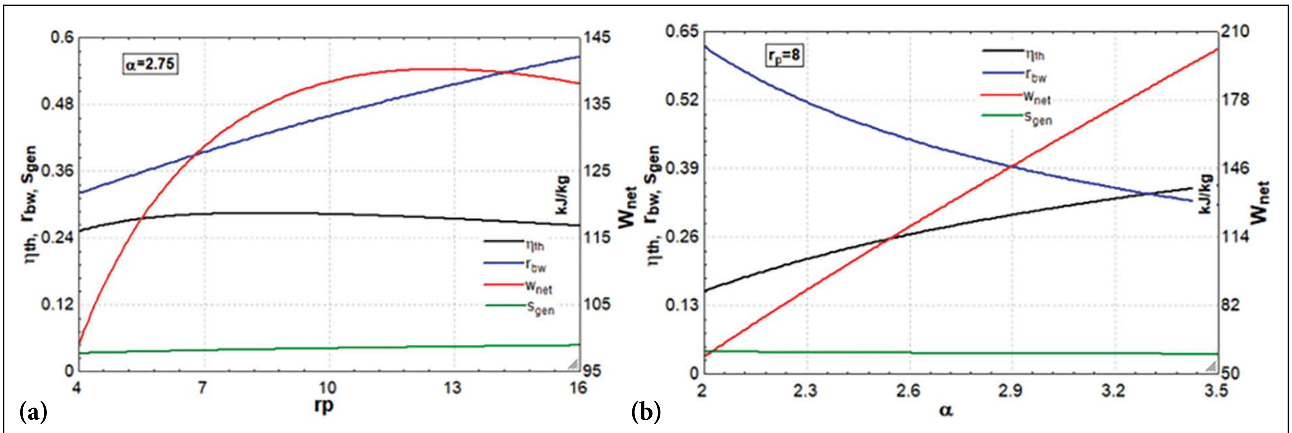

Figure 2. The effects of (a) the pressure ratio and (b) the temperature ratio on the performance outputs.

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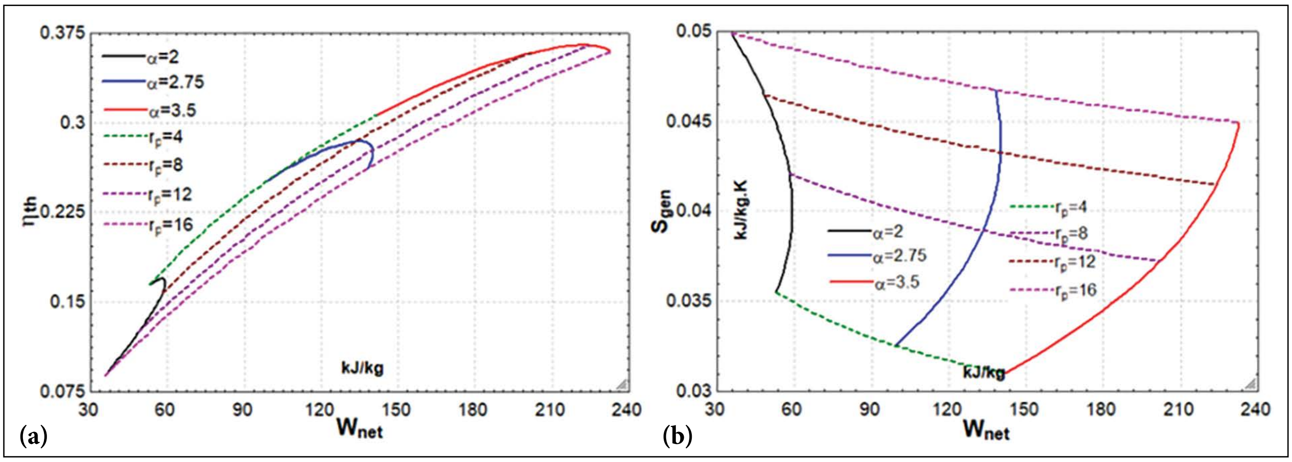

Figure 3. The effects of the temperature ratio and pressure ratio on (a) the η_{th} and w_{net} and (b) s_{gen} and w_{net}.

efficiency is maximum (0.1695) is 5.224, while the net work is 57.91 kJ/kg.

Depending on the purpose of use, the region between the points with maximum thermal efficiency or maximum net work can be determined as the operating region of the system and the operating point to be selected should be between these points. From this point of view, when the net work, thermal efficiency and compression ratios in the maximum thermal efficiency conditions are compared with the maximum net work conditions, a change of –2%, 1.8% and 19% is observed. In cases where the temperature ratio is 2.75 and 3.5, the maximum net work values increase by 137% and 293%, while the maximum thermal efficiency values increase by 70% and 120%, according to the temperature ratio being 2. If the pressure ratio is kept constant and the temperature ratio changes, both the thermal efficiency and the net work values are maximum at the same temperature ratio (α=3.5), and there is a close linear relationship between the increase in the temperature ratio and the increase in the thermal efficiency and net work. If the system size is doubled, that is, the compression ratio increases from 4 to 8, there is an increase in thermal efficiency and net work by 17% and 50%, respectively. If the compression ratio increases from 8 to 16, these increase rates decrease to 0.2% and 15%.

The entropy produced by the cycles when they are operating at an optimal level are the criteria to be considered. Considering the maximum values reached by the maximum net work and entropy according to variable temperature pressure ratios are seen in Figure 3. For α=2, there is an important point that has two different entropy generation values and two different pressure ratio for a single net work. After the maximum net work value, the increment of the pressure ratio has not positive effect that both system dimension and entropy generation increase. From this point, same explanations make for other temperature ratios with smaller range. Generally, while the net work increase with the temperature ratio increment at a constant pressure ratio, the entropy generation decreases with linear characteristics. However, at a constant temperature ratio, the increment of the pressure ratio increases the entropy generation and also reaches a maximum point for the net work values.

With the increase of the temperature ratio, the back work ratios corresponding to the maximum thermal efficiency decrease. Accordingly, if the temperature ratios increase from 2 to 3.5, the back work ratio also decreases from 0.518 to 0.373, which is due to the increase in the temperature ratio of the net work. If the temperature ratio drops from 3.5 to 2, the back work ratio takes a wider range of values. If the pressure ratio is kept constant and the temperature ratio is changed, the thermal efficiency constantly increases while the back work ratio decreases.

It can be also shown in Figure 4, increasing of the temperature ratio at a constant pressure ratio decreases both the entropy generation and back work ratio linearly. Moreover, both the entropy generation and back work ratio values increase with the pressure ratio increasing at a constant pressure ratio.

Similar comments like in the Figure 3 will be made for Figure 5 when the comparison of the entropy generation and the thermal efficiency values. For example, if α=2.75, there are two different entropy generation values (0.033 and 0.047 kJ/kg.K) and two different pressure ratio (nearly 5 and 16) for a single thermal efficiency (almost 0.26). After thermal efficiency value, the increment of the pressure ratio has not positive effect that both system dimension and entropy generation increase. For thermal efficiency values, there is a maximum or bending point at a constant temperature ratio for different pressure ratio that are 0.17 and 0.365 for α=2 and α=3.5. The corresponding entropy generation values for the maximum thermal efficiencies are 0.03795 and 0.04088 kJ/kg.K. The entropy generation value that corresponding to the maximum dimension or

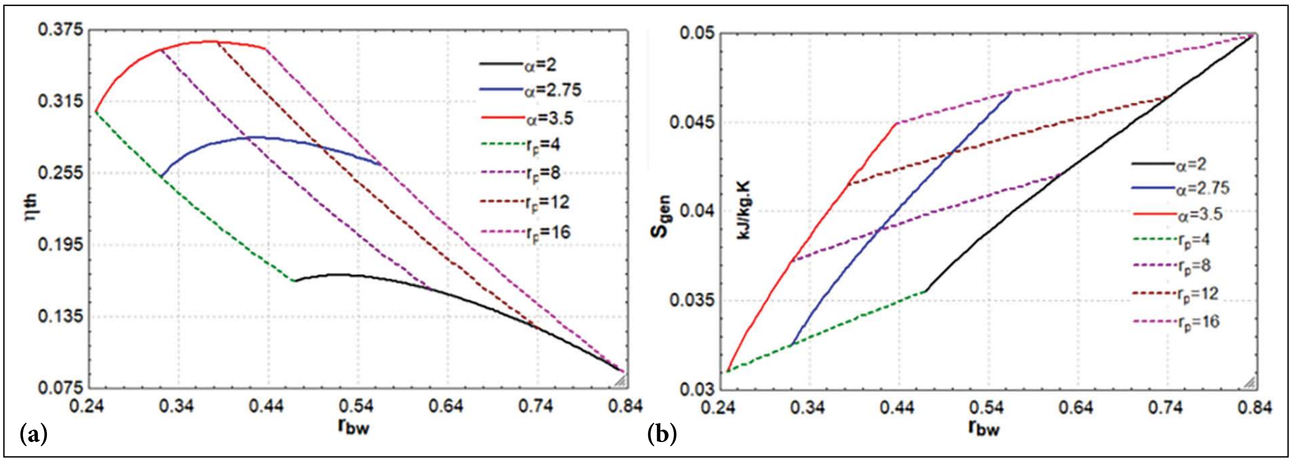

Figure 4. The effects of the temperature ratio and pressure ratio on (a) the η_{th} and r_{bw} (b) the s_{gen} and r_{bw}.

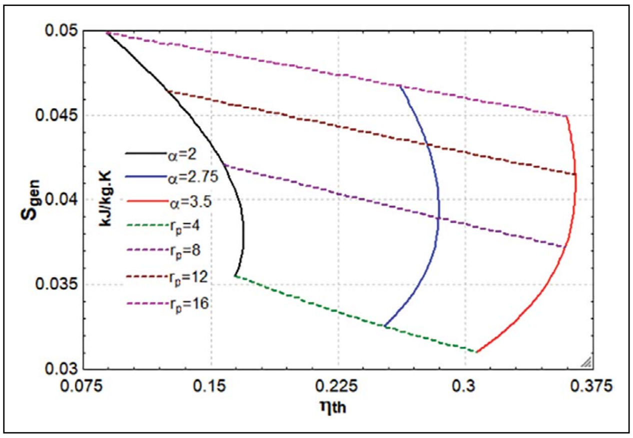

Figure 5. The effects of the temperature ratio and pressure ratio on the s_{gen} and η_{th}.

the highest pressure ratio decrease linearly for constant temperature ratios.

CONCLUSIONS

This study constitutes the initial phase of a comprehensive parametric optimization study of a supercritical Brayton cycle working with CO_2. In this framework, the outputs of the performance criteria of the system (r_{bw}, w_{net}, η_{th}, and s_{gen}) according to the First and Second Laws of Thermodynamics were obtained and their interaction with the design parameters (rp and α) was examined. With the study, an optimum working area has been determined, especially from the points where the thermal efficiency and net work criteria are maximum separately. Accordingly, the design range for the compression ratio for α=2, is between 5.224 and 6.449, for α=2.75, 8.408 and 12.57, and for α=3.5, the design range is between 11.35 and 16. A system that will operate in this region is expected to sacrifice certain outputs. In future, it is planning to develop this study with ecological and dimensional analyzes based on the Second Law of Thermodynamics.

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AUTHORSHIP CONTRIBUTIONS

In this study, Author 1 made his contributions by advising the co-authors, the evaluation, and the examination of the results. Authors 2 and 3 contributed to obtaining and evaluating the results.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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