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Advanced Exergy and Thermoeconomic Analysis of the Supercritical Carbon Dioxide Recompression Cycle: a Comparative Study

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ABSTRACT: In this paper, the superconducting carbon dioxide cycle is re-examined and compared from the perspective of advanced and thermoconomic exergy analysis to identify real potentials and prioritize the improvement of cycle components. In advanced exergy analysis, in addition to calculating the total exogenous exergy destruction for each component, the contribution and effect of each of the other components and their combination in causing this inefficiency have also been identified. In thermoeconomic analysis of the system, the unit cost of the product, the cost of investment and the cost of destroying the exergy for the components of the system are calculated. Improvements based on advanced exergy analysis are assigned to high temperature recuperator, turbine, compressor 1, preheater, low temperature recuperator, compressor 2 and reactor, respectively. Also, based on thermoeconomic analysis, improving the turbine and reactor is not economically justified. However, the results show that even by abandoning the improvement of these two components, due to their high economic cost and by improving other components of the cycle based on the prioritization of advanced exergy analysis, , it is possible to increase the efficiency of the exergy cycle from 47.29% to 63% and cycle energy efficiency from 34.15% to 45.84%.

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1. Introduction

In recent years, researchers have focused on the concept of exergy in the analysis of energy conversion systems because exergy analysis determines the main sources of system efficiency loss. Despite the high significance of the exergy perspective, conventional exergy analysis is not able to determine the amount of interaction between system components and also determining the avoidable part of exergy destruction, which this lack of information can be fulfilled by the advanced exergy analysis [1-6].

Nowadays, the Supercritical Carbon Dioxide (SCO_2) cycle has attracted a great deal of attention due to the favorable properties of its operating fluid at the critical point. Feher [7] provided valuable information about the properties and applications of the supercritical carbon dioxide cycle. Akbary et al. [8] optimized the combined SCO_2 recompression Brayton/organic Rankine cycle. The conventional and advanced exergy analysis of SCO_2 cycle was carried out by Mohammadi et al. [9].

The SCO_2 recompression cycle has not been studied simultaneously from the viewpoint of economic and advanced exergy analysis. Advanced Exergy Analysis provides more accurate information on the impact of system components on each other and the actual potential for cycle improvement. Comparing the results of the simultaneous analysis of thermodynamic systems from the viewpoint of economic and advanced exergy analysis provides significant assistance in selecting efficient components of the system in order to minimize economic costs and exergy destruction.

2. Methodology

The mass, energy and exergy balances for the system components as control volumes can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\dot{Q} + \sum \dot{m}_i h_i = \sum \dot{m}_e h_e + \dot{W} \tag{2}$$

$$\dot{E}_Q + \sum \dot{m}_i e_i = \sum \dot{m}_e e_e + \dot{W} + \dot{E}_D \tag{3}$$

In the present work, because of the assumptions, a unique working fluid and also lack of chemical reaction only physical exergy, expressed as follows, is considered:

$$e_{ph} = \left(h - T_0 s\right) - \left(h_0 - T_0 s_0\right) \tag{4}$$

The exergy destruction in the kth component can be split into endogenous/exogenous and avoidable/unavoidable parts:

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \tag{5}$$

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN} \tag{6}$$

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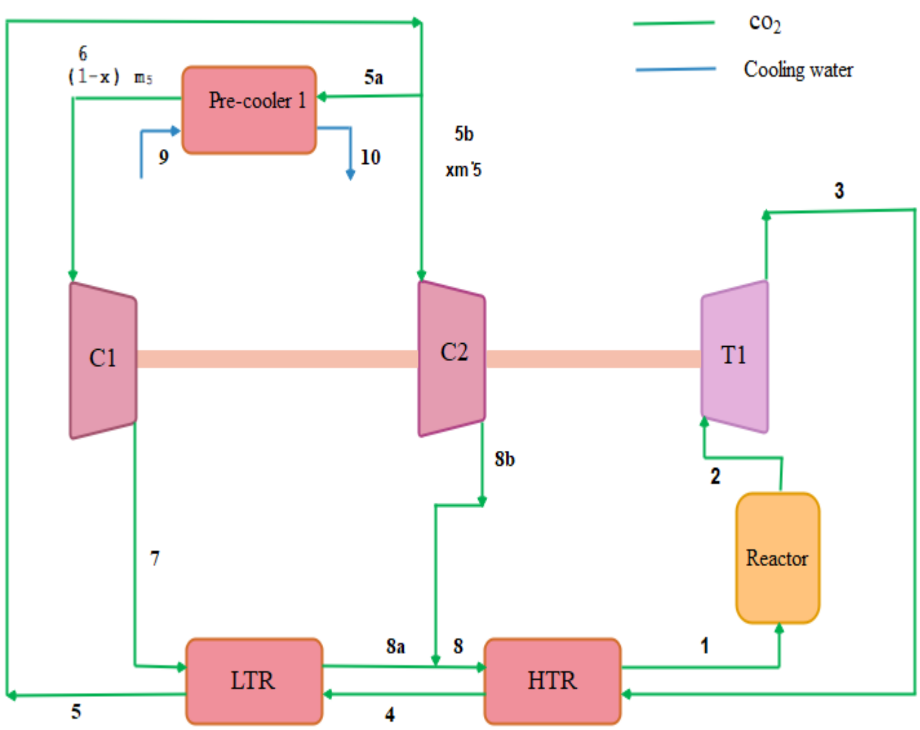

Fig. 1. Schematic diagram for the S-CO2 recompression cycle.

The endogenous and exogenous exergy destruction rates can also be split into avoidable and unavoidable parts. Similarly, the unavoidable and avoidable exergy destruction rates can be divided into endogenous and exogenous parts:

The exogenous value can also be split in order to estimate

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k}^{EX,AV} + \dot{E}_{D,k}^{EN,AV} \quad (5)$$

$$\dot{E}_{D,k}^{UN} = \dot{E}_{D,k}^{EX,UN} + \dot{E}_{D,k}^{EN,UN} \quad (6)$$

$$\dot{E}_{D,k}^{EN} = \dot{E}_{D,k}^{EN,AV} + \dot{E}_{D,k}^{EN,UN} \quad (7)$$

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{EX,AV} + \dot{E}_{D,k}^{EX,UN} \quad (8)$$

the effect of a given component on the others [10]:

$$\dot{E}_{D,k}^{mex} = \dot{E}_{D,k}^{EX} - \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{EX,r} \quad (9)$$

Cost balance for each system component is required for Exergoeconomic analysis [11].

$$\sum \dot{C}_{e,k} + \sum \dot{C}_{w,k} = \sum \dot{C}_{i,k} + \sum \dot{C}_{q,k} + \dot{Z}_k \quad (10)$$

The exergoeconomic factor is expressed as follows [11]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \quad (11)$$

3. Results and Discussion

Advanced exergy analysis, by dividing the exergy destruction into the endogenous and exogenous parts, the effect of different components of the cycle on each other is determined. Also, by dividing the exergy destruction into the avoidable and unavoidable parts, a part of the exergy destruction that can be decrease by improving the system is determined. The conventional exergy analysis suggests this order as: the reactor, the pre-cooler, the Low Temperature Recuperator (LTR), the High Temperature Recuperator (HTR) and the turbine, while the advanced exergy analysis recommends the priority as the HTR, the turbine, and the main compressor, followed by the HTR, turbine, compressor 1, pre-cooler, LTR, compressor 2 and reactor, respectively. Fig. 2 shows the priority of cycle improvement based on advanced exergy analysis.

The results of thermoeconomic analysis for each component of the S-CO_2 cycle are evaluated. The total cost of the product unit for this cycle is 10.35 \$ / h. The highest cost of exergy destruction among the cycle components is for pre-cooler, followed by the reactor, LTR, HTR, turbine, compressor 1 and compressor 2, respectively. Also, the highest investment costs are related to the reactor, turbine, compressor 1, compressor 2, LTR and HTR, respectively. Fig. 3 shows diagram of the exorcoconomic factor for different components of the SCO_2 cycle. As a result, the exogenous factor is greater for the turbine and reactor. Therefore, by choosing these two components with lower technology, the cycle investment cost can be reduced.

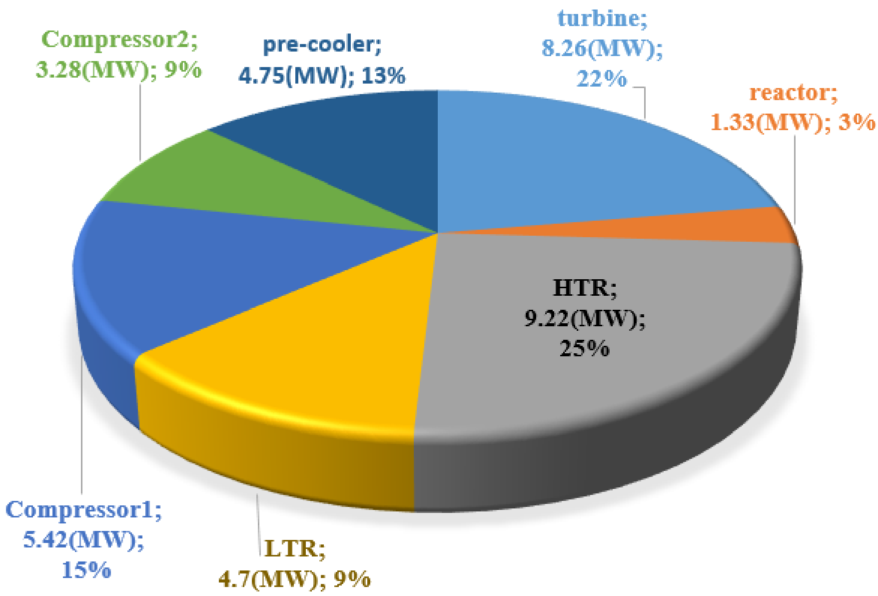

Fig. 2. The diagram of avoidable endogenous exergy destruction part for different components of the SCO_2 cycle.

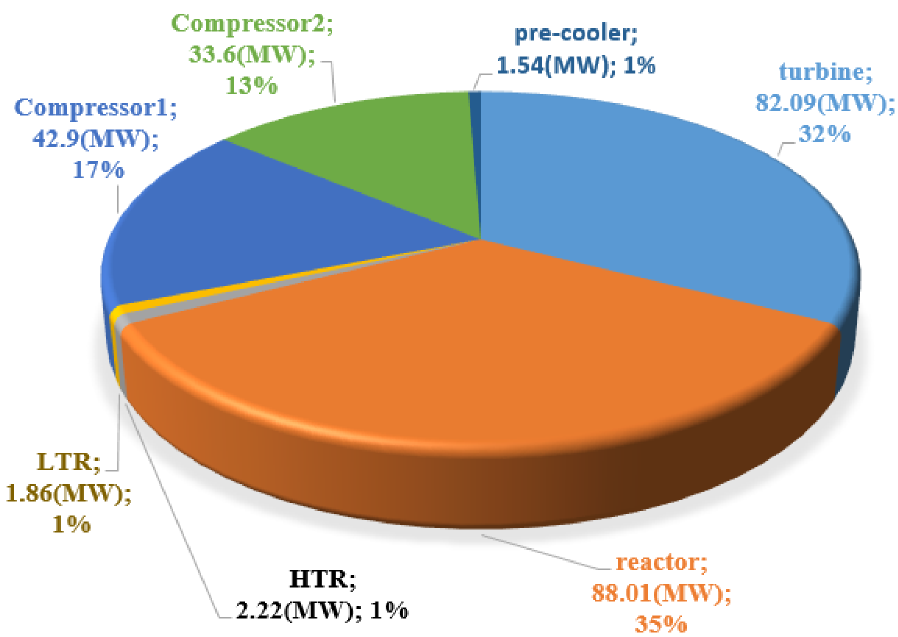

Fig. 3. The diagram of the exorcoconomic factor for different components of the SCO_2 cycle.

As a result, regardless of the improvement of the turbine and reactor, due to the high economic cost, and according to the priority of improvement of other components of the cycle based on the results of advanced exergy analysis, the total exergy of the cycle decreases 27.2% and cycle efficiency increases 26.6% .

4. Conclusions

The advanced exergy analysis recommends the different order of priority improvement from conventional exergy analysis.

The results of thermoeconomic analysis show that investing to improve the turbine and reactor is not economically justified. However, from the viewpoint of the advanced exergy analysis, the potential of reducing the exergy destruction in the turbine is high, and investing in this component improves performance. Even if the improvement of these two components is neglected due to their high economic cost and improvement of other components of the cycle is performed based on the priority of advanced exergy analysis, the cycle efficiency increases by 26.6%.

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