Exergy and Exergoeconomic Analyses Based on Recompression Cycle of the Supercritical CO$_2$ Brayton Cycle for Sodium-cooled Fast Reactor

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Abstract

An exergy and exergoeconomic analysis program is improved for the supercritical CO$_2$ (sCO$_2$) cycle with Sodium-cooled Fast Reactor (SFR). The recompression cycle is calculated with sensitivity analyses. And the optimized results with the highest of exergy cycle efficiency are presented. The recompression cycle is well worked with SFR. Based on the sensitivity analysis, with the setting ranges of parameters in this paper, the cycle exergy and energy efficiencies and the cycle total cost rate could affect significantly by the compressor pressure ratio, inlet temperature of main compressor and inlet temperature of turbine. Via the optimization, the exergy cycle efficiency could reach 66.58% outputting 32.50 MW net power. The minimum cycle total cost rate is 2088.88 $/h with the exergy efficiency of 64.72%.

Keywords: Exergy analysis, Exergoeconomic analysis, Supercritical CO$_2$ Brayton Cycle, Sodium-cooled Fast Reactor

Nomenclature

Symbols

- $A$: heat transfer area ($m^2$)
- $\beta$: compressor pressure ratio
- $c$: cost rate per exergy unit ($$/GJ$)
- $\dot{c}$: cost rate ($$/h$)
- $e$: specific exergy (kJ/kg)
- $\dot{e}$: rate of exergy (MW)
- $h$: specific enthalpy (kJ/kg)
- $\dot{m}$: mass flow rate (kg/s)
- $p$: pressure (MPa)
- $\dot{Q}$: rate of heat (MW)
- $W$: rate of work (MW)
- $s$: specific entropy (kJ/(kg·K))
- $T$: temperature (°C)

Subscript

- $a$: setting of environment for analysis
- cyc: cycle
- comp: compressor
- exe: exergy
- MC: Main compressor
- Na-sCO$_2$: Na-sCO$_2$ Heat Exchanger
- RC: Recompressor
- recup: Recuperators
- RHT: Recuperator HT
- RLT: Recuperator LT
- Turb: Turbine

1. Introduction

Nuclear energy is one of the viable energy sectors which are regarded as the future of sustainable energy. It encompasses the tremendous capacity, the reutilization of spent fuel, the reduction of atmospheric pollution, and the propulsion of local economy[1]. About the IV generation nuclear energy conversion system, several advance nuclear reactors are under researching and testing in the worldwide range, including gas-cooled reactor, heavy liquid metal-cooled reactor, molten salt reactor, sodium-cooled fast reactor (SFR), etc. In SFR, the coolant boiling margin is large, the thermal response time is long, the primary circuit pressure closes to atmospheric pressure, the sodium 2nd loop is used as an interface between primary circuit and conversion-system[2].

In 1968, a patent on supercritical power cycles using CO$_2$ as working fluid was granted[3]. For advanced
nuclear reactors, it is expected that utilization of a sCO₂ power cycle will result in a reduction in the nuclear power plant capital cost per unit output electrical power ($/kWe) or the levelized cost of electricity[4]. It is believed that the sCO₂ cycle can be applied on SFR, Lead-cooled fast reactors and the high-temperature gas reactors. In 1960s, a 150 kW sCO₂ recompression cycle was firstly designed, assembled, and operated with a small helium-cooled nuclear reactor[5,6]. In 1968, sCO₂ cycles were proposed on SFRs application[7]. The recuperation cycle is the basis sCO₂ layout to be discussed on SFR applications. Besides, for higher efficiency, the recompression cycle, the partial cooling cycle and their improved layouts were proposed[8]. The sCO₂ cycle is well matched with SFR as conventional system and could have multiple benefits[9]. The primary sodium coolant temperature rises in the core is about 150 °C, which approximately equals the CO₂ temperature drop of about 113°C as it expands from a high pressure of about 20 MPa to a low pressure of about 7.8 MPa inside of the turbine[4]. The system pressure ratio, the turbine inlet temperature and the sCO₂ mass flow affect the system efficiency[10]. At present, the AFR-100 (100-MW-class SFR) with optimization could hit a gross efficiency of 42.3% with 104.9 MW output[9].

In our previous work, a thermal balance model with energy and exergy analysis function has been built. Via the energetic and exergetic analyses, the recompression cycle and the partial cooling cycle show better system performance than the recuperation cycle with higher cycle efficiencies[11]. With further research, the exergoeconomic investigation is essential as the guideline for the technical application. A comprehensive exergoeconomic study on sCO₂ power conversion cycle with SFR, to our knowledge, has not yet been performed.

Therefore, this paper focuses on the exergy and exergoeconomic analyses of the sCO₂ power conversion cycle with SFR. Firstly, the recompression cycle is analyzed, and the optimized results with the highest cycle efficiency of exergy are presented. Then the sensitive analyses of the cycle efficiencies and the cycle cost rate are discussed considering the variations of pressure ratio, the inlet temperature of main compressor, and the inlet temperature of turbine. It is expected that the findings of present work could guide to an efficient and economical sCO₂ power conversion cycle with SFR.

2. Analysis methods

2.1 Exergoeconomic analysis

In the previous work of this topic, the energetic and exergetic analyses have been introduced[11], therefore, only exergoeconomic analysis would be explained in this section.

The economic analysis plays a major role in the technical application. Exergoeconomics is on the basis of the principles of exergy and economic analysis at the level of system components[12]. There are multiple approaches which could be used to calculate the exergoeconomics. Among of them, the specific exergy costing method[12,13,14,15] is more simple and straight than the exergy cost[16] and the average cost approach[17] logically. Therefore, the specific exergy costing method is employed in this paper based on the calculation of energy and exergy mentioned in Section 2.2 and Section 2.3.

First of all, the cost balance equation for the kth component in a power conversion system as following[12]:

$$\sum (c_{out} \dot{E}_{out})_k + c_{W,k} \dot{W}_k = \sum (c_{in} \dot{E}_{in})_k + c_{q,k} \dot{E}_{k} + \dot{Z}_k$$ (1)

where $$\sum (c_{out} \dot{E}_{out})_k$$ and $$\sum (c_{in} \dot{E}_{in})_k$$ are the cost rates from and into the component, respectively, $$c_{W,k} \dot{W}_k$$ is the cost rate associated with the output power from the component, $$c_{q,k} \dot{E}_{k}$$ is the cost rate associated with the input heat to the component, and $$\dot{Z}_k$$ is the cost rate associated with the capital investment and operation and maintenance costs for the component, c with subscript index is the average cost per exergy unit in different parts or processes of the component, which needs to be calculated with specific system parameters.

$$\dot{Z}_k$$ equals the annual levelized capital investment ($$\dot{Z}^{CI}_k$$) plus the annual levelized operating and maintenance cost ($$\dot{Z}^{OM}_k$$), and it is presented as:

$$\dot{Z}_k = \dot{Z}^{CI}_k + \dot{Z}^{OM}_k = \frac{(CRF)}{\tau} Z_k + \frac{\dot{Z}_k Z_k}{\tau}$$ (2)

where $$\tau$$ is the annual plant operation hours (as 8000 hours in this paper), $$\gamma_k$$ is the maintenance factor (as 0.06), CRF is capital recovery factor and can be calculated as:

$$CRF = \frac{i_r (1+i_r)^n}{(1+i_r)^n-1}$$ (3)

where $$i_r$$ is the interest rate (12%), n is number of operation years (as 20 years) [12]. And $$Z_k$$ is presented the capital investment cost. Its function depends on each system component as summarized in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor core</td>
<td>$$\frac{e_{core} \cdot Q_F}{0.93 - \eta_{Pr}} \cdot \ln(\frac{PRc}{Pc})$$</td>
</tr>
<tr>
<td>Turbine</td>
<td>479.34 $$\frac{m_{in}}{0.93 - \eta_{Pr}} \cdot \ln(\frac{PRc}{Pc})$$</td>
</tr>
<tr>
<td>Compressors</td>
<td>71.1 $$\frac{m_{in}}{0.93 - \eta_{Pr}} \cdot \ln(\frac{PRc}{Pc})$$</td>
</tr>
<tr>
<td>Recuperators</td>
<td>2681 A^0.59</td>
</tr>
<tr>
<td>Coolers</td>
<td>2143 A^0.544</td>
</tr>
</tbody>
</table>
The cost rate of overall system ($\dot{C}_{\text{total}}$) is the sum of capital investment, operation and maintenance costs ($\dot{Z}$) and the cost from exergy loss and destruction ($\dot{C}_{\text{L+D}}$) as:

$$\dot{C}_{\text{total}} = \dot{Z} + \dot{C}_{\text{L+D}}$$  \hspace{1cm} (4)

The layout of recompression cycle is shown in Figure 1. The fuel of a component is defined as all exergy additions to it and the product is all exergy removals from it. Therefore, with the recompression cycle, the fuel and product for each component are list in Table 2. And the cost balance equations along with the auxiliary equations for each component are summarized in Table 3.

![Image](image.png)

Figure 1: SFR with sCO2 recompression cycle and optimal simulation results

<table>
<thead>
<tr>
<th>Component</th>
<th>Fuel Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor core</td>
<td>$E_c + E_{fuel}$</td>
</tr>
<tr>
<td>Turbine</td>
<td>$E_a - E_e$</td>
</tr>
<tr>
<td>Recuperator HT</td>
<td>$E_a = E_i$</td>
</tr>
<tr>
<td>Recuperator LT</td>
<td>$E_i - E_f$</td>
</tr>
<tr>
<td>Cooler</td>
<td>$E_B = E_A$</td>
</tr>
<tr>
<td>Main Compressor</td>
<td>$W_{MC}$</td>
</tr>
<tr>
<td>Re-compressor</td>
<td>$W_{RC}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Balance equation</th>
<th>Auxiliary equation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor core</td>
<td>$\dot{C}<em>d = \dot{C}</em>{\text{fuel}} + \dot{C}<em>c + \dot{Z}</em>{\text{core}}$</td>
<td>-</td>
</tr>
<tr>
<td>Turbine</td>
<td>$\dot{C}_e + \dot{C}_T = \dot{C}_c + \dot{Z}_T$</td>
<td>$\dot{C}_e/\dot{E}_e = \dot{C}_d/\dot{E}_d$</td>
</tr>
<tr>
<td>Recuperator HT</td>
<td>$\dot{C}_i + \dot{C}_c = \dot{C}<em>i + \dot{Z}</em>{\text{HT}}$</td>
<td>$\dot{C}_i/\dot{E}_i = \dot{C}_d/\dot{E}_d$</td>
</tr>
<tr>
<td>Recuperator LT</td>
<td>$\dot{C}_r + \dot{C}_c = \dot{C}<em>r + \dot{Z}</em>{\text{LST}}$</td>
<td>$\dot{C}_r/\dot{E}_r = \dot{C}_d/\dot{E}_d$</td>
</tr>
<tr>
<td>Cooler</td>
<td>$\dot{C}<em>a + \dot{C}</em>{\text{cooler}} = \dot{C}<em>g + \dot{Z}</em>{\text{cooler}}$</td>
<td>$\dot{C}_a/\dot{E}_a = \dot{C}_g/\dot{E}_g$</td>
</tr>
<tr>
<td>Main Compressor</td>
<td>$\dot{C}<em>b = \dot{C}</em>{MC} + \dot{C}<em>a + \dot{Z}</em>{MC}$</td>
<td>$\dot{C}<em>{MC}/\dot{W}</em>{MC} = \dot{C}_T/\dot{W}_T$</td>
</tr>
<tr>
<td>Re-compressor</td>
<td>$\dot{C}<em>a = \dot{C}</em>{RC} + \dot{C}<em>a + \dot{Z}</em>{RC}$</td>
<td>$\dot{C}_b/\dot{E}_b = \dot{C}_a/\dot{E}_a$</td>
</tr>
</tbody>
</table>

There is a simplification on the ‘Reactor core’. In the exergoeconomic calculation, the primary circuit, the 2nd loop and the Na-sCO2 heat exchanger are categorized as ‘Reactor core’. $\dot{C}_{\text{fuel}}$ presents the fuel cost rate in this whole part. $\dot{C}_{\text{fuel}}$ can be calculated as:

$$\dot{C}_{\text{fuel}} = \dot{C}_{\text{fuel}}Q_{\text{core}}$$  \hspace{1cm} (5)

Where $\dot{C}_{\text{fuel}}$ is the fuel cost ($/(\text{MW} \cdot \text{h})$). Unfortunately, only $\dot{C}_{\text{fuel}}$ with the gas turbine-modular helium reactor was found from references[12,15,21] as 7.4 $/(\text{MW} \cdot \text{h})$. But, the Advanced Fuel Cycle Cost Basis - 2017 Edition shows the constant dollar unit costs for the fast reactors is closed to the gas-cooled reactor (as 4,700 $/\text{kW(e)}$ and 5,170 $/\text{kW(e)}$ as the mean values respectively)\(^{[22]}\). Therefore, $c_{\text{fuel}}$=7.4 $/(\text{MW} \cdot \text{h})$ is used in this paper.

2.2 Optimize analysis

The optimize analysis is done by following rules:

1. $T_{\text{core,in}} \geq 330\,^\circ\text{C}$
2. $\text{max}\{\eta_{\text{exe,cyc}}\}$ or $\text{max}\{\dot{C}_{\text{total}}\}$
3. $p_H \in [15.00, 28.00]$ MPa ($p_H$ is the highest pressure of cycle)
4. $p_L \in [8.00, 12.00]$ MPa ($p_L$ is the lowest pressure of cycle)
5. $m_{\text{CO2}} \in [300.00, 450.00]$ kg/s
6. $T_{\text{max}} \in [430.00, 480.00]$\,°C ($T_{\text{max}}$ is the highest temperature of cycle, as the inlet temperature of turbine)
7. $T_{\text{min}} \in [32.00, 38.00]$\,°C ($T_{\text{min}}$ is the lowest temperature of cycle, as the inlet temperature of main compressor)

The genetic algorithm is used to find the optimal solution (flowchart shown in Figure 2). To ensure the correctness of genetic algorithm, the enumeration method is also selected and compared with the genetic algorithm. The calculating length of genetic algorithm is much shorter than the enumeration method, and results by the enumeration method agree with by the genetic algorithm.

![Image](image.png)

Figure 2: Flowchart of genetic algorithm in optimize analysis

In this paper, pipes and valves would not be considered. Since the effect tendencies of pipes and valves to the system performance are same, this simplified model still can guide the system design.
3. Results and Discussions

3.1 System performance of cycles

Figure 1 shows the optimal simulation results of recompression sCO2-SFR. Via the optimization, \( \eta_{\text{exe, cyc}} \) can reach 66.58% with outputting 32.50 MW net power. The exergy losses are summarized in Table 4. 48.82 MW exergy goes into the Na-sCO2 heat exchanger (\( \Delta E_{\text{Na-sCO2,in}} \)), and 16.10 MW exergy loses in the process of system. There are 2.06 MW exergy loss from Na-sCO2 exchanger (\( \dot{E}_{\text{loss, Na-sCO2}} \), 4.23% of \( \Delta E_{\text{Na-sCO2,in}} \)), 5.02 MW exergy loss from the recuperators (\( \dot{E}_{\text{loss,recup}} \), 10.28% of \( \Delta E_{\text{Na-sCO2,in}} \)), 3.17 MW exergy loss from the Cooler (\( \dot{E}_{\text{loss,cool}} \), 6.49% of \( \Delta E_{\text{Na-sCO2,in}} \)), 3.48 MW exergy loss from the Turbine (\( \dot{E}_{\text{loss,turbine}} \), 7.13% of \( \Delta E_{\text{Na-sCO2,in}} \)), 2.37 MW exergy loss from the compressors (\( \dot{E}_{\text{loss,comp}} \), 4.85% of \( \Delta E_{\text{Na-sCO2,in}} \)).

<table>
<thead>
<tr>
<th>Items</th>
<th>Power(MW)</th>
<th>Ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{E}_{\text{loss,Na-sCO2}} )</td>
<td>2.06</td>
<td>4.23</td>
</tr>
<tr>
<td>( \dot{E}_{\text{loss,recup}} )</td>
<td>5.02</td>
<td>10.28</td>
</tr>
<tr>
<td>( \dot{E}_{\text{cool}} )</td>
<td>3.17</td>
<td>6.49</td>
</tr>
<tr>
<td>( \dot{E}_{\text{loss,turbine}} )</td>
<td>3.48</td>
<td>7.13</td>
</tr>
<tr>
<td>( \dot{E}_{\text{loss,comp}} )</td>
<td>2.37</td>
<td>4.85</td>
</tr>
</tbody>
</table>

3.2 Exergoeconomic analysis

The effect of compressor pressure ratio (\( \beta \)) on the total cost of recompression cycle (\( C_{\text{total}} \)) is shown in Figure 3. The range of \( \beta \) is decided in [2.00, 3.50] with the \( P_{\text{comp,in}} = 8.00 \text{ MPa} \), \( T_{\text{min}} = 35.00 ^\circ \text{C} \), \( T_{\text{max}} = 480.00 ^\circ \text{C} \), and \( m_{\text{CO2}} = 428.57 \text{ kg/s} \). The increasing \( \beta \) up to around 2.75 reduces \( C_{\text{total}} \) from 2168.78 $/h to 2088.88 $/h. Then with the further increasing of \( \beta \) to 3.5, \( C_{\text{total}} \) climbs to 2120.50 $/h. As explained in Section 2, the \( C_{\text{total}} \) is the sum of capital investment, operation and maintenance costs (\( Z \)) and the cost from exergy loss and destruction (\( C_{\text{L+D}} \)).

Figure 4: Effects of compressor pressure ratio (\( \beta \)) on the capital investment, operation and maintenance costs (\( Z \)) and the cost from exergy loss and destruction (\( C_{\text{L+D}} \)).

The effect of the inlet temperature of compressor (\( T_{\text{min}} \)) on the total cost of recompression cycle (\( C_{\text{total}} \)) is shown in Figure 5. The range of \( T_{\text{min}} \) is decided in [32.00, 38.00]°C with the \( \beta = 2.75 \), \( P_{\text{comp,in}} = 8.00 \text{ MPa} \), \( T_{\text{max}} = 480.00 ^\circ \text{C} \), and \( m_{\text{CO2}} = 428.57 \text{ kg/s} \). \( C_{\text{total}} \) declines from 2142.34 $/h to 2088.88 $/h with the rising of \( T_{\text{min}} \), then maintains around 2100 $/h when \( T_{\text{min}} \) is in [36.00, 37.00]°C, then rises slightly to 2126.06 $/h at \( T_{\text{min}} = 38.00 ^\circ \text{C} \).

Figure 5: Effects of inlet temperature of main compressor (\( T_{\text{min}} \)) on the thermal efficiency (\( \eta_{\text{cyc}} \)), exergy efficiency (\( \eta_{\text{exe,cyc}} \)) and total cost rate (\( C_{\text{total}} \)).

The effects of inlet temperature of compressor (\( T_{\text{min}} \)) on the capital investment, operation and maintenance costs (\( Z \)) and the cost from exergy loss and destruction (\( C_{\text{L+D}} \)) are shown in Figure 6. \( Z \) barely changed with
the variation of $T_{\text{min}}$, $\dot{C}_{L+D}$ indicates the same tendency as $\dot{C}_{\text{total}}$. $\dot{C}_{L+D}$ declines from 589.71 $$/h to 522.89 $$/h with the rising of $T_{\text{min}}$, then maintains around 543 $$/h when $T_{\text{min}}$ is in [36.00, 37.00]°C, then rises slightly to 2126.06 $$/h at $T_{\text{min}} = 38.00$°C. At $T_{\text{min}} \in [32.00, 35.00]$°C, higher $T_{\text{min}}$ does not cause more exergy loss and destruction in the whole system (as shown in Figure 5), even leads to lower exergy loss in the cooler. However, when $T_{\text{min}}$ is larger than 35.00°C, the exergy loss from the system gets larger with the $T_{\text{min}}$ rising, which causes higher $\dot{C}_{L+D}$.

Figure 7: Effects of inlet temperature of turbine ($T_{\text{max}}$) on the cycle efficiency ($\eta_{\text{cy}}$), exergy efficiency ($\eta_{\text{exe,cyc}}$) and total cost rate ($\dot{C}_{\text{total}}$).

Figure 8: Effects of inlet temperature of turbine ($T_{\text{max}}$) on the capital investment, operation and maintenance costs ($Z$) and the cost from exergy loss and destruction ($\dot{C}_{L+D}$).

4. Conclusions

The present paper improved an exergy and exergoeconomic analysis program for sCO$_2$ power conversion cycle with SFR. The recompression cycle has been analyzed, and the optimized results with the highest of exergy were presented. This layout was evaluated based on the exergy and exergoeconomic analysis. The sensitive analyses of the cycle efficiencies and the cycle cost rate also were discussed considering the variations of pressure ratio ($\beta$), inlet temperature of main compressor ($T_{\text{min}}$), and inlet temperature of turbine ($T_{\text{max}}$).

The recompression cycle is well worked with SFR. Via the optimization, the $\eta_{\text{exe,cyc}}$ of recompression cycle could reach 66.58% with outputting 32.50 MW net power. The $\eta_{\text{cy}}$ and $\eta_{\text{exe,cyc}}$ are sensitive to $T_{\text{max}}$, and increasing $T_{\text{max}}$ is the major approach to gain higher efficiencies of system.

Based on the sensitivity analysis, with the setting ranges of parameters in this paper, the cycle efficiencies ($\eta_{\text{exe,cyc}}$, $\eta_{\text{cy}}$) and the cycle total cost rate ($\dot{C}_{\text{total}}$) could affect significantly by $\beta$, $T_{\text{min}}$ and $T_{\text{max}}$. For the recompression cycle, $\beta=2.75$, $T_{\text{min}} = 35.00$°C, $T_{\text{max}} = 480.00$°C could get the minimum $\dot{C}_{\text{total}}$ as 2088.88 $$/h with $\eta_{\text{exe,cyc}}=64.72\%$.

Reference

Klaus Brun, Peter Friedman, Richard Dennis, editors. Fundamentals and Applications of Supercritical Carbon Dioxide (sCO\textsubscript{2}) Based Power Cycles, Duxford: Woodhead Publishing; 2017, p. 339-391