Optimization of supercritical nuclear power system based on sodium cooled fast reactor

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Abstract. By modeling the supercritical carbon dioxide Brayton recompression cycle on sodium-cooled fast reactor, the effects of parameters on cycle characters were studied. The high-efficiency and wide-range Brayton cycle was optimized. The results show that the assumptions of constant temperature or constant power cannot reflect the real efficiency variation of S-CO2 Brayton cycle. The supercritical cycle and the transcritical cycle have different requirements for operating parameters. The downward turning point of the turbine output power corresponds to the peak of cycle efficiency for S-CO2 Brayton cycle. The different split rates are corresponding to different optimal mass flow rates.

1. Introduction
At present, the nuclear power plants in the world usually use the Rankine cycle as an energy conversion system. Supercritical CO2 (S-CO2), as a working fluid, exhibits excellent thermal physical properties. The S-CO2 Brayton Cycle has become one of the alternative energy conversion system for the fourth generation nuclear energy systems. In fourth-generation nuclear energy systems, the energy conversion system can be adopted except the supercritical water reactor (SCWR) [1, 2]. The S-CO2 cycle can utilize the physical properties of CO2 near the critical point to reduce the compression work and improve the heat recovery efficiency.

Feher [3] proposed a circulation scheme in which the compression process runs in the subcritical zone. It is pointed out that if the cycle parameters are not properly selected, the scheme will face the regenerator invalid problem to cause the drop in cycle efficiency. Angelino [4, 5] recognized the applicability of CO2 cycle to the high temperature heat source of nuclear reactors earlier, and proposed a solution of recompression cycle. Dostal et al. [6] have adopted the recompression scheme, and the working fluid is in a supercritical state throughout the cycle to avoid condensation process. The scheme makes full use of the good compressibility of S-CO2, and can greatly reduce the compression work. Based on the recompression cycle, Hejzlar et al. [7] carried out optimization research on cycle parameters. These work shows that the S-CO2 recompression scheme is a more suitable scheme for the fourth generation of nuclear energy systems [8].

At present, most of the research on S-CO2 Brayton cycle has no clear application object, and the research results are not very instructive for engineering application [9-11]. The actual nuclear power system design is limited by the reactor parameters. The operating parameters of the conversion system must be matched with the reactor parameters. At present, the most mature fourth-generation reactors are sodium-cooled fast reactor and high-temperature gas-cooled reactor. Sodium-cooled fast reactor is the most mature fourth generation reactor.
full power in December 2014, the power of turbo-generator reached 14.2 MW. CEFR is a pool type reactor with a three-circuit of sodium-sodium-water of the heat transfer system. Therefore, this study will carry out the system analysis and optimization of S-CO₂ Brayton cycle for CEFR. The main parameters are core inlet/outlet temperature of 360°C /530°C and thermal power of 65MW[12].

2. S-CO₂ Brayton recompression cycle
The improvement method of the Brayton cycle is to enhance the system heat recovery and reduce the compressor power consumption. For the actual nuclear power generation system, the cost of adding a core device is much higher than the cost of increasing a device power. The most representative circulation mode is recompression cycle[13]. As shown in Figure 1, the recompression cycle has the advantage of the device number, which can achieve a balance between cycle efficiency and system complexity.

![Figure 1. Recompress Brayton cycle system.](image)

3. Mathematical modeling method
According to the system methodology, complex system can be considered as composed of some typical modules. By establishing the module mathematical model, the modules are organically combined according to entire system. For the Brayton system, the mathematical model consists of equipment such as compressors, heat exchangers, turbines and reactors. Based on the structure module information, the output stream variable is calculated by the unit module that accepts the stream.

For the closed Brayton cycle, the classical bounded Wegstein method is usually the quickest and most reliable method for tear stream convergence. It is an extrapolation of Direct substitution iteration.

The Wegstein iterative formula for solving the algebraic equations \( X = G(x) \) is as follows[14]:

\[
X^{(k+1)} = qG(X^{(k)}) + (1 - q)X^{(k)}
\]

where, the acceleration parameter \( q \) is calculated for each tear stream variable as follows:

\[
q = (1 - \frac{G(X^{(k)}) - G(X^{(k+1)})}{X^{(k)} - X^{(k+1)}})^{-1}
\]

The thermal efficiency is defined as

\[
\eta = \frac{Q_{\text{output}}}{Q_{\text{input}}}
\]

Since the high-temperature reactor and the cold source are basically shaped, the difference in heat exchanger mainly comes from the HTR and LTR. Therefore, the UA values of regenerators was used to assess the relative volume of nuclear power systems. The method of calculating the UA value is widely adopted by the logarithmic mean temperature difference (LMTD) method.

\[
UA = \frac{Q}{LMTD}
\]
4. Results and discussion
Because the operating parameters are complicated and relevant, some parameters were assumed to be beneficial to analyse. The mechanical efficiency is assumed as 99%, the isentropic efficiency of the compressor and turbine are assumed as 80% and 90%, and the cooling pump and reactor main pump power are not included in the cycle efficiency\[15\]. The outlet temperature of the CEFR is 360 °C, and the assumed heat exchanger end difference is not less than 5 °C. So, the outlet temperature of HTR does not exceed 355 °C.

4.1. Effect of Minimum temperature
Figure 2 shows the effects of the minimum temperature \(T_0\) on the compression power and turbine output power. When \(T_0\) is lower than the critical temperature, the compression power is significantly lower than that when \(T_0 > T_{pc}\). As the \(T_0\) increases to 31 °C, both the compressor 1 power and the compressor 2 inlet temperature increase to bring about the compression power increase. When \(T_0\) is lower than \(T_{pc}\), the supercritical \(\text{CO}_2\) has higher density and viscosity. So, the outlet temperature of compressor 1 is low to cause that the fluid in LTR can be cooled to a lower temperature. In addition, as the split flow rate increases, the power of the compressor 1 will increase significantly, but the compressor 2 power will be significantly reduced. However, the total power of the compression process is still reduced. When the split flow rate is small, the turbine output power can be maximized to 40.7 MW in most cases. When the split flow rate is high to 0.90 or the \(T_0\) is low to 30 °C, the HTR outlet temperature cannot reach 355 °C to bring about that maximized turbine power can not reach 40.7 MW. This is because the heat recovery of the system is limited by the reactor operating temperature of 360 °C/530 °C.

![Figure 2](image)

Figure 2. Effect of cycle minimum temperature on compression power and turbine power.
Left: compression power, Right: turbine output power.

Figure 3 shows the effects of \(T_0\) on cycle efficiency and UA. The cycle efficiency exhibits different distinct trends when the \(T_0\) is below or above \(T_{pc}\). When the \(T_0\) is lower than \(T_{pc}\), the cycle efficiency tends to decrease monotonously with the increase of the split flow rate. When the \(T_0\) is higher than \(T_{pc}\), the trend of the cycle efficiency is more complicated, and different \(T_0\) is corresponding to the different optimal split flow rate. It can be seen from the above phenomena that the supercritical cycle and the transcritical cycle have different requirements for the split flow rate. When the split flow rate is between 0.65 and 0.85, the cycle efficiency will have a local peak near \(T_{pc}\). As the split flow rate increases further, the cycle efficiency increases monotonously with the \(T_0\) increase. As can be seen from Figure 3, the higher the cycle efficiency is corresponding to the larger the UA value. But the change magnitude of UA is much greater than that of cycle efficiency. In order to improve the cycle efficiency of 1%, the UA may increase by more than 50%.
In order to compare with previous studies, the following assumes were used that the constant maximum temperature 514 °C (reactor power is not limited) and the constant power 65 MW (the maximum temperature is not limited). Figure 4 shows the effect of $T_0$ on efficiency in the three cases. It can be seen from Figure 4 that there are three variation trends of efficiency curves for the three assumptions. The efficiency for the Constant $Q_R$ can reach 48%, and the efficiency for the Constant $T_H$ is always larger than 36%. However, the above two assumptions can not reflect the real efficiency variation with $T_0$. So, the operating temperature and power of reactor must be considered in the analysis of S-CO$_2$ Brayton cycle.

4.2. Effect of split rate

Figure 5 shows the effects of split flow rate on turbine power and HTR outlet temperature. Due to the reactor operating temperature, HTR outlet temperature is limited to 355 °C. When the split flow rate is small, the HTR outlet temperature can be maintained at 355 °C. This allows the turbine to have a stable output power of 40.7 MW. As the split ratio increases, the HTR outlet temperature gradually decreases, even to less than 100 °C. It causes both the turbine inlet temperature and the outlet temperature to decrease. Further, the temperature of the hot fluid entering HTR decreases. Because of the constant outlet pressure and flow rate of the turbine, the turbine power depends on the turbine inlet temperature. Ultimately, the Brayton cycle cannot operate in a high temperature zone, and power capacity of turbine reduces sharply from 40MW to 16MW. The phenomenon wastes the high temperature characteristics of the reactor and leads to a sudden drop in cycle efficiency.

**Figure 3.** Effect of cycle minimum temperature on cycle efficiency.

**Figure 4.** Effect of heat source.

**Figure 5.** Effect of split flow rate on turbine power and HTR outlet temperature.

Left: turbine output power, Right: HTR outlet temperature.
Figure 6 shows the effects of split flow rate on cycle efficiency and UA. The different $T_0$ correspond to different optimal split flow rates. As $T_0$ increases, the corresponding optimal split rate increases gradually, but the peak value of cycle efficiency decreases from 43% to 35%. As $T_0$ increases, the outlet temperature of hot flow in LTR will also increase. This leads to the reduction in the heat recovery of the Brayton system. By comparison of Figure 5 and Figure 6, it is found that the downward turning point of the turbine output power corresponds to the peak of the cycle efficiency. If the split flow rate increases further, the outlet temperature of the HTR can no longer be maintained at 355°C, the turbine output power is gradually reduced from 40.7 MW. Therefore, when the outlet temperature of the HTR is maintained at the maximum value, the corresponding maximum split flow rate can reach the maximum cycle efficiency. The UA value also exhibits a single peak phenomenon as the split ratio increases, and the position of the peak almost coincides with the peak position of the cycle efficiency. The peak value of UA increases first and then decreases as the $T_0$ rises. The maximum UA appears at $T_0=32°C$, but this condition is not corresponding to the maximum cycle efficiency which appears at $T_0=28°C$. This phenomenon illustrates that the cycle efficiency is proportional to UA at the constant $T_0$. However, UA is multiple-valued for the same efficiency when the $T_0$ is variable.

4.3. Effect of circulating flow rate

Figure 7 shows the effects of system mass flow rate on cycle efficiency and UA. For the all split flow rates, the cycle efficiency increases first and then decreases as the mass flow rate increases. Because the maximum temperature of Brayton cycle is also limited to 525°C, the output power of the turbine also decreases as the mass flow rate decreases, resulting in an optimal mass flow rate. The different split rates are corresponding to different optimal mass flow rates. As the split flow rate increases, the optimal flow rate decreases, and the corresponding cycle efficiency peak value also decreases. Under the same split flow rate, the same UA may be corresponding to two mass flow rates. However, when the mass flow rate increases and exceed optimal value, UA decreases gently associated with efficiency rapid reduction. Therefore, the effects of mass flow rate on efficiency and UA need to be comprehensively considered.

4.4. Effect of parameter fluctuations

Based on the results of the Argonne National Laboratory and the previous parametric comparison analysis, CASE 0, CASE 1 and CASE 2 were proposed. CASE 0: split flow rate 0.7, mass flow rate 335kg/s. CASE 1: split flow rate 0.6, mass flow rate 375 kg/s. CASE 2: split flow rate 0.6, mass flow...
rate 368 kg/s. Figure 8 shows the corresponding change characteristics of the system efficiency when certain parameter fluctuates. The varied parameters are the cycle minimum temperature, split rate and flow rate. Taking the efficiency of 40% as the criterion, it can be seen that the CASE 2 has higher cycle efficiency and larger efficient operation area. The comparative result indicates that CASE 2 has stronger adaptability for the operating parameter fluctuation. Therefore, CASE 2 is the prioritization scheme for the China Experiment Fast Reactor.

![Figure 8](image_url)

**Figure 8.** Comparison of the operating range. (Left: minimum temperature, Middle: split flow rate, Right: flow rate fluctuate.)

5. Conclusion
In this paper, the research on supercritical carbon dioxide Brayton cycle is carried out for the sodium-cooled fast reactor. The main conclusions are as follows:

(1) Because the CEFR operating temperature of 360℃/530℃, when the split flow rate is high to 0.90 or $T_0$ is low to 30℃, the turbine power can not reach specified value of 40.7 MW.

(2) The assumptions of constant temperature or constant power can not reflect the real efficiency variation of S-CO$_2$ Brayton cycle.

(3) The supercritical cycle and the transcritical cycle have different requirements for the split flow rate. As the split ratio increases, the S-CO$_2$ cycle cannot operate in a high temperature zone.

(4) The downward turning point of the turbine output power corresponds to the peak of cycle efficiency for S-CO$_2$ Brayton cycle. Moreover, the different split rates are corresponding to different optimal mass flow rates.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| A      | heat transfer area, m² |
| HTR    | High temperature regenerator |
| LTR    | Low temperature regenerator |
| LMTD   | Logarithmic mean temperature difference, °C |
| M      | mass flow rate, kg/s |
| q      | acceleration parameter |
| Q      | heat, W |
| T      | temperature, °C |
| U      | global heat transfer coefficient, W/(m²·K) |
| W      | power, W |
| X      | algebraic equations |
| χ      | split flow rate |
| η      | thermal efficiency |

Subscripts

| Subscript | Description |
|-----------|-------------|
| 0         | cycle minimum point |
| P         | compressor |
| pc        | pseudo critical |
| T         | turbine |
| R         | reactor |

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