Optimization Research of S-CO₂ Compound Brayton Cycle Based on Genetic Algorithm

Yuanjian Dang¹, Lei Sun², Tao Lin², Yonghui Xie²* and Yongqing Wang¹

¹State Grid Shaanxi Electric Power Research Institute, Xi’an, China
²Shaanxi Engineering Laboratory of Turbomachinery and Power Equipment, School of Energy and Power Engineering, Xi’an Jiaotong University, Xi’an, China
*Email: yhxie@mail.xjtu.edu.cn

Abstract. Supercritical carbon dioxide (S-CO₂) has the advantages of large density and small viscosity. Being used in the power circulation system, it can make the system compact and reduce the cost, so it has great potential in engineering application. In this paper, the residual heat recycling system with S-CO₂ as the working material is studied. The computational model of S-CO₂ Brayton cycle is built to analyse its characteristics. The cycle efficiency, output network and other parameters of the bottom cycle under the standard working conditions are obtained. Meanwhile, the parameters of the inlet and outlet of the components are optimized by genetic algorithm, and the parameters of the system components are obtained when the best cycle network is achieved. This study provides some reference for the field of residual heat utilization, including the gas turbine exhaust.

1. Introduction
Supercritical fluid is a state between the gas state and the liquid state, with low compressibility near the liquid state and high viscosity near the gas state [1]. The critical temperature of S-CO₂ is 31.1°C, and the critical pressure is 7.38MPa [2]. It is a kind of supercritical fluid which is easier to reach the critical condition. S-CO₂ has a series of excellent characteristics, such as non-toxic, non-flammable, explosive and cheap, and it has been widely applied in food, medical, refrigeration and air separation industries.

In recent years, the research on the application of supercritical carbon dioxide in Brayton cycle has been widely concerned and promoted, including system design and core components analysis. S-CO₂ Brayton cycle has the following significant advantages: small viscosity contributes to high system thermal efficiency, large density makes system structure compact, also the system structure is simple and the number of parts is small [3]. Dyreby [4], Muto [5], Utamura [6], Bae [7], Jeong [8], Moullec [9] and so on have made detailed research on the S-CO₂ Brayton cycle and achieved valuable results. In all, S-CO₂ Brayton cycle has great prospects for engineering application.

However, most of the studies focus on heat source of constant temperature, so there is less on that of variable temperature. Besides, as most of the studies are made for the design of S-CO₂ Brayton cycle types, there are few records of optimizing the cycle parameters. In actual situations, the common heat source for residual heat utilization is that of variable temperature, and the optimization of cyclic parameters is also the most important part of the system research.

In this paper, the related cycle types of residual heat utilization are studied, and a recompression-simple compound Brayton cycle model is constructed. Meanwhile, genetic algorithm is used to optimize the parameters of the cycle, and the optimal cycle structure parameters are obtained, also the optimization results are compared and discussed.
2. Brief introduction of principles
In this paper, GA-based optimization method is used to solve the problem [10]. The primary task is to determine the objective function and variables of the research object. Then we need to encode variables for that genetic control is an operation for strings. Binary number coding is generally adopted, and the formula for converting binary numbers to decimal numbers is defined as follows:

\[
F(b_{i1}, b_{i2}, \ldots, b_{il}) = R_i + \frac{T_i - R_i}{2^{l-1}} \sum_{j=1}^{l} b_{ij} 2^{j-1}
\]  

(1)

where: \( b_{i1}, b_{i2}, \ldots, b_{il} \) — Section \( i \) of an individual; \( l \) — section length; \( b_{ik} = 0 \) or \( 1 \); \( X_i \) — component of section \( i \); \( T_i \) — The upper limit of domain \( X_i \); \( R_i \) — The lower limit of domain \( X_i \).

The specific flow chart is shown in Figure 1.

![Figure 1. Optimization flow chart](image)

3. Calculation model
The circulatory system studied in this paper is shown in Figure 2. Exhaust or other forms of residual heat are divided into two heat sources at high temperature and low temperature as the energy source of the whole system. The recompressing Brayton cycle is constructed on the basis of high temperature heat source, and the simple Brayton cycle is built on the basis of low temperature heat source.

![Figure 2. Supercritical CO2 compound cycle layout](image)
The function includes the main part, the compressor subroutine, the turbine subroutine and the heat exchanger subroutine. Carbon dioxide properties are interpolated directly from the existing physical data points.

3.1. Turbine subroutine
The input parameters of the subroutine include inlet pressure, inlet temperature, outlet pressure, turbine entropy efficiency and turbine power; the output parameters include the outlet temperature and mass flow. Isentropic expansion multiplying by adiabatic efficiency is taken as calculation method and the formula used follows:

\[ S'_{\text{out}} = S_{\text{in}} \left( \frac{p_{\text{in}}}{p_{\text{in}}} \right) \]

where: \( S'_{\text{out}} \) —— Turbine export entropy in isentropic expansion \( /J \cdot K^{-1} \); \( S_{\text{in}} \) —— Turbine entrance entropy \( /J \cdot K^{-1} \); \( p_{\text{in}} \) —— Turbine inlet pressure/ Pa; \( T_{\text{in}} \) —— Turbine inlet temperature/ K.

3.2. Compressor subroutine
The input parameters of the subroutine include inlet pressure, inlet temperature, outlet pressure, compressor entropy efficiency and mass flow; the output parameters include the outlet temperature and compression power consumption. The formula used follows:

\[ S'_{\text{out}} = S_{\text{in}} \left( \frac{p_{\text{in}}}{p_{\text{in}}} \right) \]

where: \( S'_{\text{out}} \) —— Compressor export entropy in isentropic compression \( /J \cdot K^{-1} \); \( S_{\text{in}} \) —— Compressor entrance entropy \( /J \cdot K^{-1} \); \( p_{\text{in}} \) —— Compressor inlet pressure/ Pa; \( T_{\text{in}} \) —— Compressor inlet temperature/ K.

3.3. Heat exchanger subroutine
In this paper, the supercritical carbon dioxide recompression Brayton cycle is considered as ideal calculation, so the actual structure and heat transfer efficiency are not considered in the heat exchanger subroutine. In addition, in order to improve the effectiveness of heat transfer and take into account the minimum temperature difference of the heat exchanger, the minimum temperature difference of the heat exchanger between the hot and cold side is set as 10°C. The formula used follows:

\[ M_{\text{heat}} (H_{\text{heat in}} - H_{\text{heat out}}) = M_{\text{cold}} (H_{\text{cold out}} - H_{\text{cold in}}) \]

where: \( H_{\text{heat in}} \) —— Heat fluid inlet enthalpy of heat exchanger \( /J \cdot kg^{-1} \); \( H_{\text{heat out}} \) —— Heat fluid outlet enthalpy of heat exchanger \( /J \cdot kg^{-1} \); \( H_{\text{cold out}} \) —— Cold fluid outlet enthalpy of heat exchanger \( /J \cdot kg^{-1} \); \( H_{\text{cold in}} \) —— Cold fluid inlet enthalpy of heat exchanger \( /J \cdot kg^{-1} \).

The main part of the function: The sub functions of each component above are calculated according to the circulation process, so the mapping relation of the cost function from the input to the output can be obtained. By the way, in this study, there is no distinction between the inlet and outlet pressure of the turbine end of two cycle systems. The input and output of the cost function and the fixed amount are detailed in Table 1. The optimizations of the same exhaust temperature, exhaust flow, turbine compressor efficiency and regenerator end difference are studied in this paper. And the inlet pressure and the outlet pressure of the turbine, the inlet temperature of the main compressor are selected as the input of the cost function. Meanwhile, the net work of the circulatory system is taken as the output of the cost function, namely the optimization target.
Table 1. Cycle parameters table

| fixed parameters                      | inputs                                               | outputs                                                 |
|---------------------------------------|------------------------------------------------------|---------------------------------------------------------|
| Heat source temperature               | Inlet pressure of the turbine                        | Net work                                               |
| Heat source mass flow                 | Outlet pressure of the turbine                       |                                                         |
| Turbine isentropic efficiency         | Inlet temperature of the main compressor             |                                                         |
| Compressor isentropic efficiency      |                                                      |                                                         |
| Regenerator end temperature difference |                                                      |                                                         |

4. Results and discussion

4.1. Initial state and recompression cycle results
After the establishment and construction of the equation above, the initial state parameters, which are not optimized, are calculated first, and the corresponding fixed variable parameters is shown in Table 2.

Table 2. Parameter value table

| Term                              | Value       | Term                              | Value       |
|-----------------------------------|-------------|-----------------------------------|-------------|
| Heat source temperature           | 500 °C      | Turbine inlet pressure            | 20 MPa      |
| Heat source pressure              | 101.8 KPa   | Turbine outlet pressure            | 8 MPa       |
| Heat source mass flow             | 80 Kg·s⁻¹   | Main compressor Inlet temperature | 35 °C       |
| Regenerator end temperature difference | 10°C      | Turbine isentropic efficiency     | 0.85        |
|                                   |             | Compressor isentropic efficiency  | 0.80        |

According to the fixed variables mentioned above, we get the system parameters that only use the recompression cycle and the initial state parameters before the optimization of the compound Brayton cycle, as are shown in Table 3 and Table 4.

Table 3. Recompression cycle results table

| Term                              | Value       | Term                              | Value       |
|-----------------------------------|-------------|-----------------------------------|-------------|
| Power output of turbine           | 8.14 MW     | Exergy input                      | 12.65 MW    |
| Power consumption of compressor   | 3.45 MW     | Exergy efficiency                 | 37.05%      |
| Net power output                  | 4.69 MW     | Minimum temperature of heat       | 359.86 °C   |

Table 4. Compound Brayton cycle results table

| Term                              | Value       | Term                              | Value       |
|-----------------------------------|-------------|-----------------------------------|-------------|
| Power output of turbine           | 13.64 MW    | Exergy input                      | 27.16 MW    |
| Power consumption of compressor   | 5.49 MW     | Exergy efficiency                 | 30.00%      |
| Net power output                  | 8.15 MW     | Minimum temperature of heat       | 182.85 °C   |

4.2. Optimization results
The genetic algorithm (GA) is used to optimize the compound cycle, with a population size of 50 and an iteration number of 100. As a result, the evolution curve of the best fitness value obtained by GA algorithm is shown in Figure 3.
The change of the optimized input variable is shown in Table 5.

Table 5. Optimization parameters table

| Term                          | Optimization interval | Before | After |
|-------------------------------|-----------------------|--------|-------|
| Turbine inlet pressure /MPa  | (15,25)               | 20     | 24.95 |
| Turbine outlet pressure /MPa | (7.5,12)              | 8      | 8.15  |
| Main compressor Inlet temperature /°C | (32,40) | 35     | 32.03 |

The performance parameters of the optimized system are shown in Table 6.

Table 6. Cycle after optimization parameters table

| Term                          | Value   | Term                        | Value       |
|-------------------------------|---------|-----------------------------|-------------|
| Power output of turbine       | 14.83 MW| Exergy input                | 30.30 MW    |
| Power consumption of compressor | 5.33 MW| Exergy efficiency           | 31.35%      |
| Net power output              | 9.50 MW | Minimum temperature of heat | 146.04 °C   |

The comparison of network and system efficiency among the recompression cycle, the compound cycle before optimization and the optimized cycle is shown in Figure 4. It can be found that although the compound cycle has a higher system network (better utilization of residual heat) than the recompression cycle, the system efficiency is reduced because of the increase in the complexity of the system. In addition, the network and net efficiency of the circulatory system have been significantly improved after optimization.
5. Conclusions
In this paper, the optimization of the S-CO$_2$ compound Brayton cycle in the residual heat utilization is studied, in which the GA single objective optimization algorithm is used to process some parameters, and finally the optimization results chart is obtained. Conclusions are as follows:

1. S-CO$_2$ compound Brayton cycle has a higher system network than the single recompression cycle, but the system efficiency is reduced because of the increase in the complexity of the system. Therefore, it is necessary to consider the relationship between the cost of adding a circular structure and the income.

2. The method of optimizing the S-CO$_2$ Brayton cycle based on GA algorithm has many great characteristics such as fast convergence and good optimization results. This method is not only limited to the optimization of some kind of thermodynamic cycle, but also has a certain mobility.

3. Due to the nature of heat source and the diversity of the energy level, it is necessary to consider the correlation characteristics of the residual heat in order to select the working material of thermal cycle and its structure.

In conclusion, the system optimization based on genetic algorithm can effectively optimize the supercritical carbon dioxide compound Brayton cycle system, and this research can help the development of residual heat utilization and other engineering fields.

6. References
[1] Tanaka H, Nishiwaki N, Hirata M, et al. FORCED CONVECTION HEAT TRANSFER TO FLUID NEAR CRITICAL POINT FLOWING IN CIRCULAR TUBE[J]. International Journal of Heat and Mass Transfer, 1971, 14 (6): 739-74.
[2] Gil L, OtinS. F, Embid J.M, et al. Experimental setup to measure critical properties of pure and binary mixtures and their densities at different pressures and temperatures Determination of the precision and uncertainty in the results [J]. Journal of Supercritical Fluids, 2008, 44 (2): 123-138.
[3] Dostal V, Hejzlar P, Driscoll M.J. High-performance supercritical carbon dioxide cycle for next-generation nuclear reactors [J]. Nuclear Technology, 2006, 154 (3): 265-282.
[4] Dyreby J J, Klein S A, Nellis G F, et al. Design considerations for supercritical carbon dioxide Brayton cycles with recompression. Journal of Engineering for Gas Turbines and Power, 2014, 136(10): 101701.
[5] Muto Y, Ishiyama S, Kato Y, et al. Application of supercritical CO$_2$ gas turbine for the fossil fired thermal plant. Journal of Energy and Power Engineering, 2010, 4 (9): 7-15.
[6] Utamura M. Thermodynamic analysis of part-flow cycle supercritical CO$_2$ gas turbines. Journal of Engineering for Gas Turbines and Power, 2010, 132 (11): 111701.
[7] Bae S J, Lee J, Ahn Y. Preliminary studies of compact Bryton cycle performance for small modular high temperature gas-cooled reactor system. Annals of Nuclear Energy, 2015, 75: 11-
[8] Jeong W S, Lee J I, Jeong Y H. Potential improvements of supercritical recompression CO₂ Brayton cycle by mixing other gases for power conversion system of a SFR. Nuclear Engineering and Design, 2011, 241(6): 2128-2137.

[9] Moullec Y L. Conceptual study of a high efficiency coal-fired power plant with CO2 capture using a supercritical CO₂ Brayton cycle. Energy, 2013, 49: 32-46.

[10] Goldberg D E. Genetic algorithms in search, optimization, and machine learning. Addison-Wesley Publishing Co. 1989.