Influence of Supercritical Carbon Dioxide Brayton Cycle Parameters on Intelligent Circulation System and Its Optimization Strategy

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Abstract. The supercritical carbon dioxide (SCO2) Brayton cycle takes advantage of the special physical properties of carbon dioxide near the critical point (31.1 °C, 7.39MPa), and has higher energy conversion efficiency than the current large-scale steam power cycle. This cycle can be widely used in the field of power generation, but a lot of research work is still needed in terms of component parameters and layout under different working conditions. In this regard, the purpose of this paper is to study the influence of supercritical carbon dioxide Brayton cycle parameters on cycle efficiency and its optimization strategy. Based on the first law of thermodynamics, this paper uses Aspen Plus software to establish S-CO2 Brayton cycle system models with different circulation arrangements. In this paper, the existing algorithm of the simulation system and the newly-built algorithm are used to build the S-CO2 shunt and recompression Brayton cycle system model, and the accuracy of the model is verified with experimental data from literature. Then this paper conducts disturbance experiments on the model to study the influence of heater heating, valve opening and precooler cooling on the system, and analyze the dynamic characteristics of the system. Experimental results show that the thermal efficiency of the simple Brayton cycle is much lower than that of the recompression Brayton cycle and the split recompression Brayton cycle under higher parameters. The compressor outlet pressure and the turbine inlet temperature have an effect on the efficiency of the recompression Brayton cycle. The impact is significant, and the optimal value of the compressor shunt coefficient is between 0.5-0.7, which provides a reference for the layout optimization method of the SCO2 Brayton cycle and the optimization of the same type of power generation cycle.

Keywords: Supercritical Carbon Dioxide, Brayton Cycle, Cycle Efficiency, Simulation Research

1. Introduction
Energy is the basic need to ensure social and economic development. Adequate energy supply guarantees sustainable economic growth, promotes the improvement of people's living standards and
promotes the development and progress of human society [1]. In recent years, with rapid population growth and rapid economic growth, environmental problems have become increasingly serious [2]. Due to the characteristics of my country's energy structure, coal-fired electricity generation will continue to be my country's main method of generating energy for some time [3-4]. Improving mineral energy efficiency and reducing pollution emissions are effective ways to solve energy and environmental problems. Because the Brayton cycle has the advantages of high efficiency cycle, simple and compact structure and short construction period [5-6], the use of the Brayton cycle is the direction of developing efficient and clean energy in the future [7].

Currently, coal-fired power plants still dominate the power generation industry in my country. Many researchers at home and abroad have conducted a lot of research on the application of S-CO2 Brayton cycle in coal-fired power generation [8]. Abroad, Siddiqui focuses on analyzing the feasibility of implementing S-CO2 cycle in new power plants, calculating the thermal efficiency of Brayton S-CO2 recirculation cycle and Brayton heat recovery compression cycle, and recommends that SO cycle CO2 will be mainly used in nuclear reactors at high temperatures [9]. In China, Zhao Xinbao introduced and analyzed the main advantages of the S-CO2 Brayton cycle applied to nuclear reactor systems. On the basis of the research on the S-CO2 Brayton cycle used in nuclear reactor systems, he suggested that the S-CO2 Brayton cycle is the development of my country's advanced nuclear energy technology. It has great potential [10].

This work mainly studies the influence of supercritical Brayton carbon cycle parameters on cycle efficiency and optimization strategies. This document first introduces the S-CO2 Brayton cycle system model with different traffic settings. Then, this article uses a simulation system to create a model of the S-CO2 branch, then compresses the Brayton cycle system and verifies the accuracy of the model. This work also analyzed the dynamic characteristics of the system, found the weak links of the system through energy distribution and energy loss distribution, and determined the direction for improvement. The study found that the Brayton decompression cycle and the Brayton decompression cycle have higher cycle efficiency, and the compressor outlet pressure and the turbine inlet temperature have a significant impact on the performance of the Brayton decompression cycle. The Brayton decompression cycle is important Reference value.

2. Technical Research on the Influence of Supercritical Carbon Dioxide Brayton Cycle Parameters on Cycle Efficiency and Optimization Strategies

2.1. Supercritical Carbon Dioxide

With the change of temperature and pressure, matter will undergo phase change. There are three phases of any substance: solid, liquid and gas. The intersection point of the two phases of gas and liquid is called the critical point. The critical point corresponds to the critical temperature and the critical pressure. Different substances have different critical states. It not only has gas-like diffusivity, but also has liquid-like density and solubility. It also has the physical properties of low viscosity and low surface tension. SCO2 is currently the most valued and most promising supercritical fluid because it has the following characteristics: carbon dioxide is inactive and difficult to react with other substances. It is a safer working fluid. Carbon dioxide reserves are abundant in nature and the cost is low. The critical pressure of CO2 is 7.39MPa, and the critical temperature is 31.1°C, which requires relatively low requirements and is easy to prepare.

SCO2 has the characteristics of good stability and thermal conductivity, and it is not easy to react with other substances even if the system fails. Because SCO2 has a density similar to a liquid, it has a good performance in material selection, compressor design and improvement of recycling economy, and CO2 has the characteristics of low price and abundant reserves. When SCO2 is used as a circulating working fluid, due to its special physical properties near the critical point, it can greatly reduce the power consumption of the compressor, thereby achieving the purpose of improving the cycle output and cycle efficiency. The SCO2 Brayton cycle uses small-size and high-speed compressors and turbines. The heat exchanger uses a highly efficient and compact printed circuit
board heat exchanger (PCHE), which greatly reduces the area. Economic benefits are good. The cost of SCO2 Brayton cycle power generation is much lower than the current cost of conventional thermal power generation. Since the cycle is fully enclosed and no pollutants are discharged, the maintenance and waste disposal costs are greatly reduced.

2.2. Establishment of Supercritical Carbon Dioxide Brayton Cycle System Model

The main components of the S-CO2 Brayton cycle system are compressors, turbines, heat exchangers, etc. In order to analyze the thermal efficiency of the system more simply and easily, and provide optimized and improved reports, it is first necessary to model each device separately. In the modeling process, some complex thermal processes will be appropriately simplified by making reasonable assumptions.

**Compressor.** The compressor in the S-CO2 Brayton cycle system adopts an isentropic model, and they all operate at a constant pressure ratio. Assuming that the inlet temperature of the i-th stage compressor is $T_{i, in}$, the compression process is a variable process, which can be regarded as a reversible adiabatic process, then the outlet temperature $T_{i, out}$ is:

$$T_{i, out} = T_{i, in} \cdot \frac{n-\gamma}{\gamma} \frac{\beta_{i,C}^{n}}{n-\gamma} \cdot \frac{1}{\eta_{i,c}} \quad (1)$$

The variability index satisfies:

$$\frac{n-\gamma}{\gamma} = \frac{\gamma-1}{\eta_{i,c}} \quad (2)$$

In the formula: $\beta_{i,C}$—i-stage compressor pressure ratio; $n$—variable index; $\gamma$—specific heat capacity ratio, which is the ratio of constant pressure specific heat capacity $C_p$ to constant volume specific heat capacity $C_v$; $\eta_{i,c}$—compressor isentropic efficiency.

**Heat exchanger.** In the calculation process of the heat exchanger in this paper, the energy conservation of the entire heat exchange process:

$$m_1 C_p(T_{1, in} - T_{1, out}) = m_2 C_p(T_{2, out} - T_{2, in}) \quad (3)$$

Where $C_p$—Hot end fluid constant pressure specific heat capacity $J/(kg \cdot k)$; $m_1$—Hot end fluid mass kg; $T_{1, in}$ and $T_{1, out}$—hot end fluid at the heat exchanger inlet and outlet temperature, $C$; $C_p$—cold end fluid constant pressure specific heat capacity, $J/(kg \cdot k)$; $m_2$—Mass of cold end fluid, kg; $T_{2, in}$ and $T_{2, out}$—temperature of cold end fluid at the inlet and outlet of the heat exchanger, $C$.

**Turbine.** The S-CO2 Brayton cycle system turbine adopts an isentropic model, and they all operate at a constant expansion ratio. The turbine outlet temperature can be expressed as:

$$T_{i, out} = T_{i, in} / \frac{n-\gamma}{n} \eta_{i,t} \beta_{i,t}^{n} \quad (4)$$

The variability index satisfies:

$$\frac{n-\gamma}{n} = \frac{\gamma-1}{\eta_{i,t}} \eta_{i,t} \quad (5)$$

Where $T_{i, out}$ and $T_{i, in}$ are the outlet and inlet temperatures of the i-stage turbine, respectively, in $C$; $\eta_{i,t}$ is the efficiency of the i-th turbine, $\beta_{i,t}$ is the expansion ratio of the i-th turbine, and $\gamma$ is the specific heat capacity ratio.

**S-CO2 simple Brayton cycle system.** The simple Brayton S-CO2 cycle is the most basic cycle device, which consists of a compressor, a turbine, a heat exchanger and a cooler. High temperature and high pressure CO2 enters the turbine for operation, and the pressure is reduced to form low pressure and high temperature CO2. In the regenerator, the low-pressure and high-temperature CO2 liquid exchanges heat with the high-pressure and low-temperature CO2 fluid to obtain low-temperature and low-temperature CO2 liquid and high-pressure and high-temperature CO2 liquid. Liquid carbon dioxide, that is, low-temperature liquid carbon dioxide, is cooled by a pre-cooler, and then enters the compressor for
amplification to form high-temperature and high-pressure carbon dioxide, forming the entire closed-loop system.

**S-CO2 recompression Brayton cycle system.** It can be seen from the simple parameters of the Brayton cycle that in the regenerator, the temperature of the cold liquid is close to the critical point (31°C), and the specific heat of the hot liquid is lower than that of the cold liquid. May cause its location to change. The final appearance of the heat exchange temperature difference heat exchanger will affect the heat exchange efficiency of the heat exchanger. After passing through the high temperature heat exchanger (HTR) and LTR, and then passing through the flow limiting device to separate the air flow, it enters the main compressor and the recompressor respectively. The working fluid passing through the main compressor is first cooled by the pre-cooler and the main compressor, the output working fluid enters the LTR for heating, and is mixed with the output working fluid of the compressor, and enters the HTR for heating. After the most active fluid passes through the heater, the temperature rises to the inlet temperature of the turbine.

3. Experimental Study on the Influence of Supercritical Carbon Dioxide Brayton Cycle Parameters on Cycle Efficiency and Its Optimization Strategy

3.1. Experimental Data
This paper compares and analyzes the efficiency of the three cycles of simple Brayton cycle, recompression Brayton cycle, and split recompression Brayton cycle under higher parameters. At this time, the total flow rate under higher parameter conditions is 3320.5kg/s, the pressure range is 9.21-20MPa, the temperature range is 45-650°C, the compressor efficiency is 80%, the turbine efficiency is 80%, and the shunt coefficient is 0.8.

3.2. Experimental Process
This article firstly compares and analyzes the efficiency of the three cycles of simple Brayton cycle, recompression Brayton cycle, and shunt recompression Brayton cycle under higher parameters. Then, this paper tests the efficiency of the recompression Brayton cycle under different compressor split coefficient values, which is used to analyze the influence of the supercritical carbon dioxide Brayton cycle parameters on the cycle efficiency and its optimization strategy.

4. Experimental Analysis of the Effect of Supercritical Carbon Dioxide Brayton Cycle Parameters on Cycle Efficiency and Optimization Strategies

4.1. Thermal Characteristics of the S-CO2 Brayton Cycle under Higher Working Conditions
In order to study the thermal characteristics of three different Brayton cycles under higher operating conditions, this paper calculated the thermal results of each cycle system under higher operating conditions, and drew a table and histogram based on the results. As shown in Table 1 and Figure 1.

**Table 1.** Thermal characteristics of Brayton cycle under higher working conditions

| Parameter                        | Simple Brayton cycle | Recompressed Brayton cycle | Shunt recompression Brayton cycle |
|----------------------------------|-----------------------|----------------------------|----------------------------------|
| Heater power (MW)                | 1014.6                | 553.2                      | 558.4                            |
| Turbine power (MW)               | 332.5                 | 374.2                      | 373.1                            |
| Compressor power consumption (MW)| 96.0                  | 102.6                      | 108.3                            |
| Regenerator heat exchange (MW)   | 1523.5                | 1903.5                     | 1882.6                           |
| Pre-cooler heat absorption (MW)  | 398.4                 | 315.7                      | 316.5                            |
| Cycle efficiency (%)             | 23.5                  | 48.6                       | 47.6                             |

Since the thermal parameters of the inlet fluid of the turbine are the same, the work done by the turbine is the same. Since the Brayton recompression cycle and the Brayton recompression separation cycle are set as waste heat recovery, the working fluid reaches a higher temperature before entering the
heat source heater, thereby significantly reducing the working temperature and the heat source consumes heat. As can be seen from Table 1, the LTR setting reduces the heat consumption of the heat source by 50%. Due to the increase in LTR, the inlet temperature of the pre-cooler is reduced, thereby reducing the power consumption of the pre-cooler, and the recompression cycle and recompression split cycle are reduced by 27.5% and 20.8%, respectively. However, the cycle performance of the Brayton suppression cycle and the Brayton split-recompression cycle are immediately improved almost twice. Compared with the recompression cycle device, the Brayton split recompression cycle has almost no effect on improving the thermal efficiency of the cycle, but the recompression split cycle has an absolute advantage in improving the size of the turbine.

![Figure 1. Thermal characteristics of Brayton cycle under higher working conditions](image)

4.2. Influence of Compressor Shunt Coefficient on Cycle Thermal Efficiency

The shunt coefficient is defined as the mass flow rate of the working fluid flowing into the main compressor in the total mass flow rate. In order to further verify the influence of the compressor shunt coefficient on the cycle thermal efficiency, in the simulation calculation process, in order to control the influence of other variables, to ensure that the heater heating power, the precooler outlet temperature, and the total cycle time are at the highest pressure in each cycle. The mass flow rate remains unchanged. Under different maximum cycle pressures, the influence of compressor shunt coefficient on cycle efficiency also changes accordingly. As shown in Table 2 and Figure 2.

| Shunt coefficient | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Maximum pressure 10MPa | 7.5 | 8 | 8.5 | 8.9 | 9.2 | 9.1 | 9 | 8.9 |
| Maximum pressure 20MPa | 15.5 | 23 | 27 | 28 | 28 | 26 | |
| Maximum pressure 25MPa | 22.5 | 27 | 33 | 31.5 | 30 |

![Figure 2. Effect of shunt coefficient on cycle efficiency](image)
It can be seen from the Figure that when the branching coefficient increases from 0.2 to 0.7, the cycle efficiency is significantly improved. But when the branching coefficient increases from 0.7 to 0.9, the cycle efficiency changes less. The analysis shows that the higher the branch coefficient, the main compressor enters, the coolant cools the working fluid, and the main compressor consumes less power than the suppressor. When the branching coefficient is greater than 0.7, the cycle efficiency will not change significantly with the increase of the branching coefficient. The main reason is that more liquid is cooled by the cooler, which reduces the inlet temperature of the heater, thereby reducing the inlet temperature. The temperature of the turbine, thereby reducing the operation of the turbine.

5. Conclusions
This work mainly studies the influence of supercritical Brayton carbon cycle parameters on cycle efficiency and optimization strategies. This article first uses Aspen Plus software to create S-CO2 Brayton cycle models with different cycle settings. Then perform perturbation experiments on the model and analyze the dynamic characteristics of the system. In addition, this paper compares and analyzes four cycle models: single cycle, recompression cycle, pre-compression cycle and partial cooling cycle to determine the direction of improvement and further increase thermal efficiency. Under higher parameters, the thermal efficiency of a single Brayton cycle is much lower than that of the Brayton recompression cycle and the gradual compression Brayton cycle. In addition, the flow rate of the compressor has a great influence on the efficiency of the Brayton compression cycle. It is of great significance to study the optimization method of Brayton SCO2 cycle layout.

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