Hindawi
Science and Technology of Nuclear Installations
Volume 2018, Article ID 3245604, 9 pages
https://doi.org/10.1155/2018/3245604

Research Article

A Design of Parameters with Supercritical Carbon Dioxide Brayton Cycle for CiADS

Yichuan He,[1] **Aihua Dong**,[1] **Min Xie**,[1] **and Yang Liu**[2]

[1] *Central Academy, Harbin Electric Corporation, Harbin 150028, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

Correspondence should be addressed to Aihua Dong; dongah@harbin-electric.com

Received 9 March 2018; Revised 9 May 2018; Accepted 16 May 2018; Published 10 June 2018

Academic Editor: Arkady Serikov

Recompression supercritical carbon dioxide (SCO_2) Brayton Cycle for the Chinese Initiative Accelerator Driven System (CiADS) is taken into account, and flexible thermodynamic modeling method is presented. The influences of the key parameters on thermodynamic properties of SCO_2 Brayton Cycle are discussed and the comparative analyses on genetic algorithm and pattern search algorithm are conducted. It is shown that the cycle parameters such as turbine inlet temperature, pressure ratio, outlet temperature at the hot end of condenser, and terminal temperature difference of regenerator 1 and regenerator 2 have significant effects on the cycle thermal efficiency. The calculation results indicate that pattern search algorithm has better optimization performance and quicker calculating speed than genetic algorithm. The result of optimization of the parameters for CiADS with supercritical carbon dioxide Brayton Cycle is 35.97%. Compared with other nuclear power plants of SCO_2 Brayton Cycle, CiADS with SCO_2 Brayton Cycle does not have the best thermal efficiency, but the thermal efficiency can be improved with the reactor outlet temperature increases.

1. Introduction

The accelerator driven subcritical reactor system (ADS) is a new kind of nuclear reactor which has been regarded as the most promising approach to burn minor actinide waste products with inherent safety features. Lead-bismuth eutectic (LBE) with a high atomic number has good thermophysical property which is the suitable coolant and spallation target material for ADS. In response to the urgent need for the sustainable development of nuclear energy, the Chinese Academy of Sciences (CAS) launched the ADS program in 2011 for the first five years [1]. A research facility, CiADS, will be designed and built by 2022 [2].

The Rankine cycle is used as the energy conversion system in most of the nuclear power plants [3, 4]. The high temperature gas cooled reactor constructed in china used helium gas as the working substance [5]. However, the low density of helium leads to high power consumption of the helium compressor, which reduces the net efficiency of the reactor. Therefore, it is necessary for the helium cooled reactor core to have a high outlet temperature (about 800~1000°C) to ensure its economic efficiency [6].

Using supercritical fluid as core coolant and using supercritical fluid in critical region property mutation phenomenon, set the compressor running point near the pseudocritical temperature of big density area, set the reactor operating point after the pseudocritical temperature of low density area, under the premise of the gas that can be cooled, reduce the power consumption of the compression, and implement mediums to achieve a higher efficiency under the outlet temperature of the core [7]. Due to its relatively moderate critical pressure, carbon dioxide has good stability and nuclear physical properties, and it has high density and no phase change in the operating parameters of nuclear reactors. The specific heat of carbon dioxide varies greatly near the pseudocritical point, as shown in Figure 1. Therefore, SCO_2 Brayton Cycle is considered to be one of the most promising energy transfer and energy conversion schemes in nuclear reactors. The SCO_2 Brayton Cycle was first proposed by Sulzer [8] and later reintroduced by Feher

Table 1: Overall design parameter of CiADS [2, 22].

Parameters	Design	Value
ADS		
Total power (reactor + beam), MW	10	10
Full power run time, a	3	Less than 3
Annual running time, mo	3	Less than 3
Accelerator		
Particle	Proton	Proton
Energy, MeV	500	500
Maximum beam power, MW	2.5	2.26
operation mode	CW/pulse	CW/pulse
Target		
Maximum acceptable beam power, MW	2.5	2.26
Subcritical reactor		
Energy spectrum	Fast neutron	Fast neutron
Maximum thermal power, MW	8	7.74

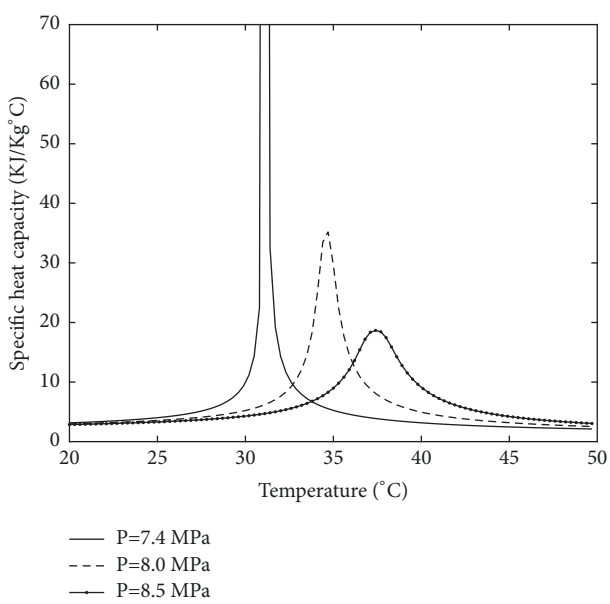

Figure 1: The relations of specific heat of carbon dioxide with temperature.

[9]. In recent years there are some successful developments concerning this concept, which is mainly conducted at the research institutions like Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), Sandia National Laboratories (SNL), Argonne National Laboratory (ANL), Tokyo Institute of Technology (TIT), South Korea Atomic Energy Research Institute (KAERI), Czech Technical University (CTU), Nuclear Power Institute of China (NPIC), Xi'an Jiao tong University, and so on [10–21].

This paper is based on the thermal cycle of supercritical carbon dioxide for an accelerator driven subcritical system. The thermal performance of the SCO_2 Brayton Cycle is studied. Genetic algorithm and pattern search algorithm are used to optimize the parameters of supercritical carbon dioxide and compared with each other.

2. System

2.1. CiADS Overall Design Scheme. CiADS engineering uses technical route with superconducting linear accelerator, high power dispersive target, and subcritical reactor. According to the construction and operation experience of the international analogies, CiADS adopts the phased construction mode. The subcritical reactor is a liquid lead-bismuth cooled fast reactor with the semipool semiloop type arrangement mode. Reactor coolant system works at the 0.05Mpa with the inlet temperature 280°C, outlet temperature 380°C, and coolant flow rate 533kg/s [2, 23]. Table 1 shows overall design parameter of CiADS.

2.2. The Layout of the Brayton Cycle. In the energy conversion system of the nuclear reactor system, supercritical carbon dioxide is used as the circulating medium which requires multiple regenerator. If only one regenerator is used, because the low-pressure side of the regenerator's specific heat capacity is relatively small, the temperature rise of the high pressure side fluid will not be enough in the heat exchange, which would lead to a pinch point of the heat exchanger. The recompression cycle layout has the advantages of simplicity and high efficiency to make the heat better used.

3. Solution Procedure

3.1. System Model. The thermodynamic model uses the recompression Brayton Cycle, for instance, as shown in Figure 2(a). In the process of thermodynamic modeling, mass conservation and energy conservation are the main factors to be considered. The main formulas are as follows [21]. The temperature-entropy diagram for the system is shown in Figure 2(b). During the circulation, the SCO_2 receives heat from the LBE-CO_2 heat exchanger (6-7) and enters the turbine to generate power (7-8). The SCO_2 of the turbine flows through regenerator 1 (8-9) and then through regenerator 2 (9-10) and recovers its energy from the flow out of the turbine. The flow is then split into two flow streams.

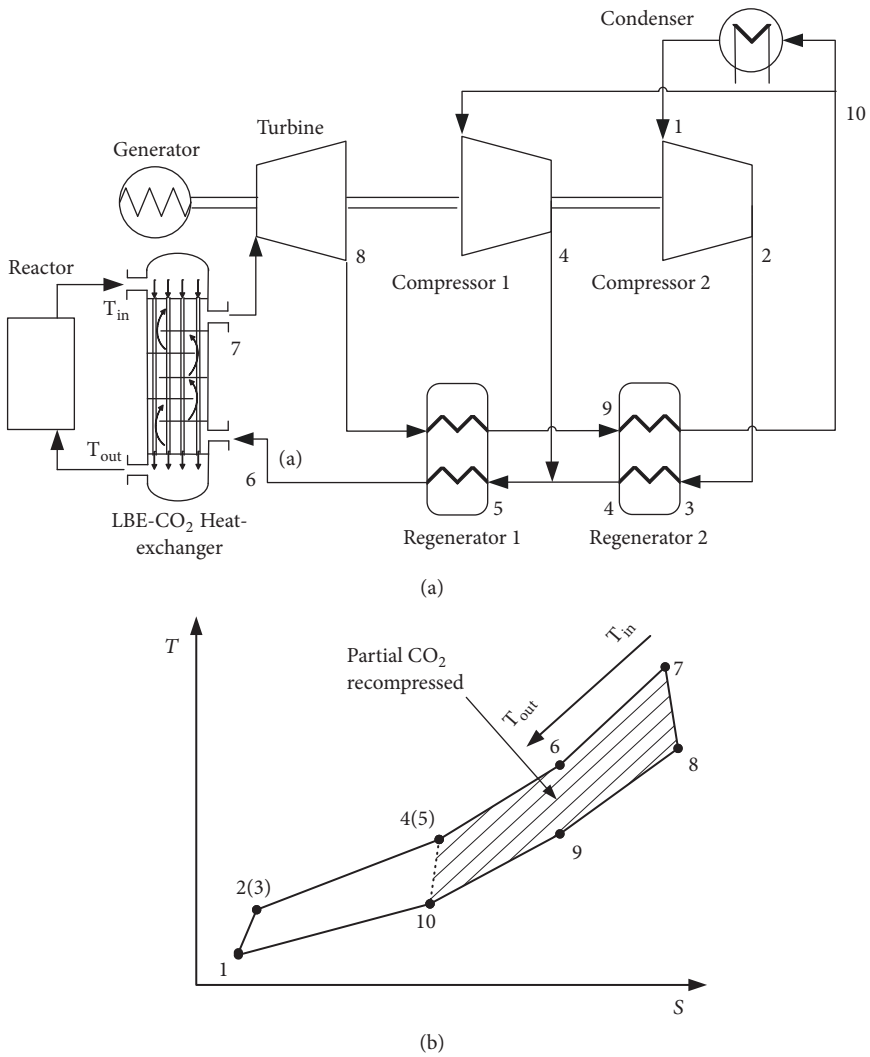

Figure 2: (a) System diagram of recompression Brayton Cycle. (b) The temperature-entropy diagram of the system.

One stream flows through a condenser (10-1) and then through the compressor 2 (1-2), while the other stream flows through the compressor 1 (10-4). The flow out of compressor 2 enters regenerator 2 and is preheated to the same temperature as the outlet of compressor 1 (3-4). Then, the flow stream from regenerator 2 merges with the flow stream from compressor 1 (point 5), and the combined flow stream is further preheated in the regenerator 1 to the LBE-CO_2 heat exchanger inlet temperature (5-6) to complete the cycle.

The compression and expansion process of main and recompression compressors and turbines are nonisentropic processes and can be expressed, respectively, as follows:

$$h_{co} = \frac{h_{co,\text{is}} - h_{ci}}{\eta_c} + h_{ci} \tag{1}$$

$$h_{to} = \left(h_{to,\text{is}} - h_{ti}\right) \cdot \eta_t + h_{ti} \tag{2}$$

Heat exchanger uses Printed Circuit Heat Exchanger (PCHE) which can work under high pressure and high temperature [24, 25]. The lower end temperature difference and higher efficiency can be achieved under the condition of controlling the volume of heat exchanger. The LBE-CO_2 heat exchanger is considered to be used in the two-loop cooling systems of ADS [26].

In the heat source, the energy balance equation is

$$m_8 \left(h_{in} - h_{out}\right) = m \left(h_7 - h_6\right) \tag{3}$$

The net power and thermal efficiency of the Brayton Cycle are defined as

$$W_{sys} = W_{turbine} - W_{compressor1} - W_{compressor2} \tag{4}$$

$$\begin{aligned} \eta &= \frac{W_{sys}}{m\left(h_7 - h_6\right)} \\ &= \frac{m \cdot \left[h_7 - h_8 - x\left(h_2 - h_1\right) - (1 - x)\left(h_4 - h_{10}\right)\right]}{m\left(h_7 - h_6\right)} \end{aligned} \tag{5}$$

In the process, the value of "x" was calculated by the other cycle parameters. And x changes with the cyclic conditions.

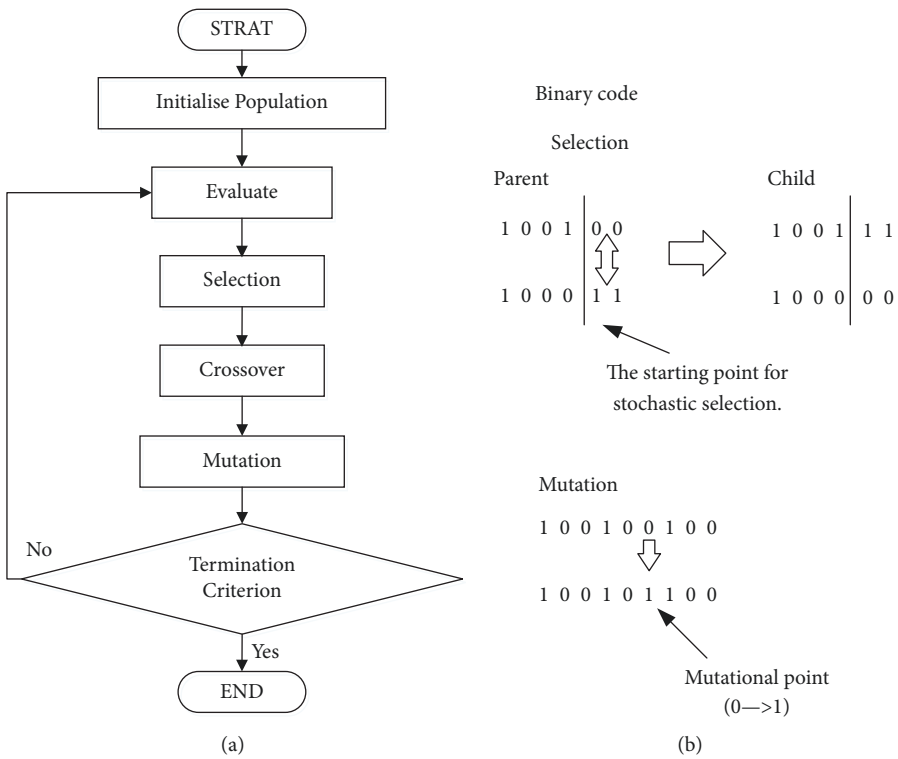

Figure 3: (a) Optimization flowchart of genetic algorithm. (b) Process diagram of selection and mutation.

3.2. Algorithm Model

3.2.1. Genetic Algorithm. Genetic algorithm (GA) is a kind of common optimization algorithm which can draw lessons from the evolutionary laws of the biological world [27]. This algorithm was first proposed by American professor J. Holland in 1975. The main idea is to simulate Darwinian theory of biological evolution of natural selection and Mendelian genetic mechanism of biological evolution process as the basis, through the simulation of "survival of the fittest." The natural evolution process and genetic mechanism of "survival of the fittest" method to search the optimal solution laid an important foundation for the research of the theory and method of genetic algorithm.

Generally speaking, we first need to simplify the problem studied. In genetic algorithm, after the initial generation population is generated by binary coding, the optimal solution is searched according to the natural evolution principle. In each generation, individuals are selected by fitness in the problem domain and combined crossover and variation of individuals by genetic operators in genetic mechanism; thus new populations are generated. Through the above process, the first generation population, like natural evolution, is more adaptable to the external environment than the previous generation population, evolving generation by generation and constantly approaching the optimal generation population. To complete the process of survival of the fittest, finally, the approximate optimal solution of the problem is obtained by decoding the optimal individuals of the last population. Its specific flowchart is shown in Figure 3(a).

For the three genetic operators of selection, crossover, and mutation, the operation of individual is carried out under the condition of random disturbance, and the process diagram of selection and mutation is shown in Figure 3(b). In the process of selection, we use stochastic uniform function to simulate biochemical events. Dependent constraint is used in the crossover function and mutation function, so the rule of individual migration to the optimal solution in each generation of population is also random. The difference between this random operation and the common random search method is that the probabilistic random rules of genetic optimization process are efficient and directional, while the ordinary random search method is undirected search. Moreover, the operation probability, coding method, initial population, and fitness function of genetic operator will directly affect the effect of genetic operation.

Genetic algorithm has the following advantages: the object of study is the individual variable, not the decision-making process. The iterative process of genetic optimization starts with a population, which has good inherent implicit parallelism, and the performance of global search optimization is better. Genetic algorithm is less affected by initial value and has high accuracy. The population of the research object is operated directly and the fitness evaluation result is used as the search information without the need of other information such as derivative. Genetic optimization is a self-organizing, adaptive, and self-learning probabilistic optimization process, which can guide the search space through the information obtained from the evolutionary process without the help of other determined rules. The optimization direction

Table 2: Initial parameters for simulation and analysis of system.

Initial parameters	Values
LBE mass flow rate	533kg/s
Inlet temperature of LBE-SCO_2 heat exchanger LBE side	380°C
Outlet temperature of LBE-SCO_2 heat exchanger LBE side	280°C
Isentropic efficiency for compressor, η_c	0.85
Isentropic efficiency for turbine, η_t	0.87

can be adjusted adaptively and the population with better performance can be obtained. Because of the advantages and characteristics, genetic algorithm has been widely used in machine learning, combinatorial optimization, function optimization, signal processing, job shop scheduling, and other different fields. It is used to solve various kinds of complex objective optimization problems and provide the theoretical basis for modern intelligent computing and other technologies.

3.2.2. Pattern Search Algorithm. Pattern search algorithm was proposed by Hooks and Jeeves in 1960s [28]. It is a direct method for solving optimization problems. The algorithm is similar to the intelligent optimization algorithm and does not need the derivative information of the objective function in the optimization process. Therefore, it has very outstanding advantages and good optimization performance for the optimization problems related to the nondifferentiable function and the complex function.

The main idea of the search algorithm is to search for the feasible descent direction by exploring the movement of the current search points according to the fixed mode and step size. Starting from the initial base point, the algorithm completes the iteration alternately with the axial movement and the mode movement. In order to find a new base point and a favorable direction of descent, the axial search is carried out in turn along the direction of n coordinates. The pattern search is carried out in the direction of the two basis points adjacent to the line, which is to accelerate the movement along the function value in the favorable direction of descent.

In the iterative process of the pattern search algorithm, if we find a point with better quality than the current point, the step size will increase, and the next iteration will start from this point at the same time. If the quality of the point being searched is not as good as the current point, the step size decreases and the search continues at the current point. When the search reaches the set termination condition, the last point is used as the optimal solution.

The pattern search algorithm is easy to realize and the optimization effect is good. At present, it is applied in many fields, such as the missile target allocation method and the power system unit combination problem, which can be optimized and analyzed by the mode search method. However, due to its optimization principle, pattern search algorithm has a large amount of calculation in the search process, and the choice of initial value has a great impact on the final solution. At the same time, the convergence speed and global search ability under the step size should be investigated when determining the search step size.

4. Results and Discussion

The thermodynamic effects of inlet temperature, pressure ratio, outlet temperature at the hot end of condenser, and terminal temperature difference of regenerator 1 and regenerator 2 on the SCO_2 Brayton Cycle are studied. The initial parameters for simulation and analysis of system performance are shown in Table 2.

The constraint conditions for the SCO2 Brayton Cycle are as follows:

(1) Maximum pressure of SCO2 Brayton Cycle system is between 15MPa and 25MPa.

(2) Minimum pressure of SCO2 Brayton Cycle system is between 7.38MPa and 12MPa.

(3) Outlet temperature at the hot end of condenser T1 is between 31.2°C and 50°C.

(4) Turbine inlet temperature T7 is between 200°C and 370°C.

(5) Terminal temperature difference of regenerator 1 $\Delta T1$ is between 3°C and 50°C.

(6) Terminal temperature difference of regenerator 2 $\Delta T2$ is between 3°C and 50°C.

The influences of some key parameters on SCO_2 Brayton Cycle thermodynamic performance have been discussed, such as condenser outlet temperature, cycle pressure ratio, and terminal temperature difference of regenerators. The study on the thermal efficiency variation with pressure ratio at different turbine inlet temperature from the modeling has been conducted, as shown in Figure 4. It can be observed that the turbine inlet temperature has a significant influence on cycle thermodynamic performance, and there are optimal pressure ratios at different turbine inlet temperature. Furthermore, the thermal efficiency and optimal pressure ratio will increase with the increasing of turbine inlet temperature. With increasing pressure ratio, the thermal efficiency rises rapidly to the maximum and then gently decreases, at a definite turbine inlet temperature, for the reason that turbine output work firstly increases faster than the total consumption of the main and recompression compressor; after that the opposite happens.

As shown in Figure 5, with the decrease of the terminal temperature difference, the thermal efficiency increases

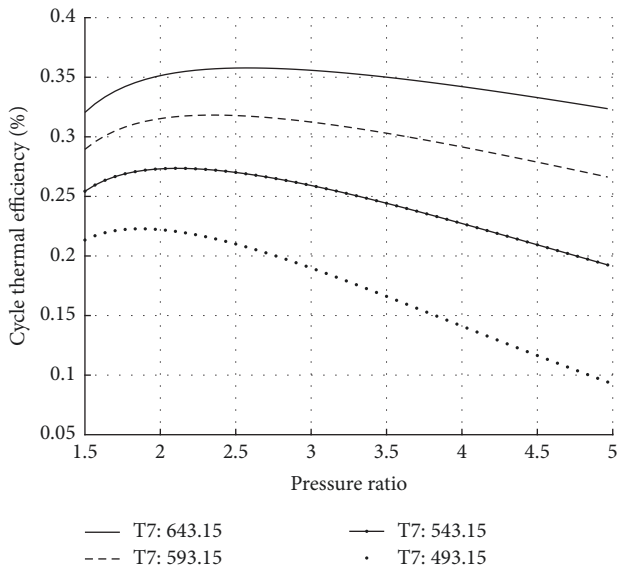

Figure 4: Effect of cycle pressure ratio on the thermal efficiency for different turbine inlet temperatures.

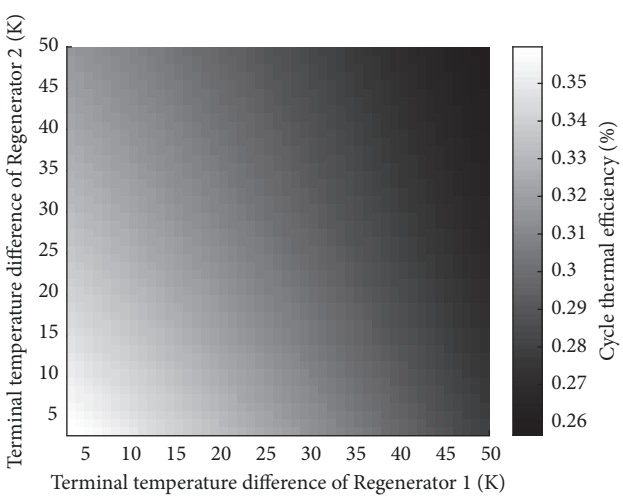

Figure 5: Effect of terminal temperature difference of regenerators on the thermal efficiency.

for the SCO_2 Brayton Cycle from the modeling. Terminal temperature difference of regenerator 1 makes more increases than terminal temperature difference of regenerator 2, because the flow rate of regenerator 1 is large and the temperature difference between the cold and the hot ends has better heat transfer conditions; the heat transfer is also larger. Moreover, regenerator 1 and regenerator 2 have better thermal efficiency when the terminal temperature difference is small, but the smaller terminal temperature difference will increase the difficulty of design and manufacture when the heat exchanger is designed and manufactured, and the specific items may need to be considered in detail.

It can be noticed from Figure 6 that the thermal efficiency is reducing as the condenser outlet temperature increases for different cycle pressure ratio, but, with the 1.5 pressure

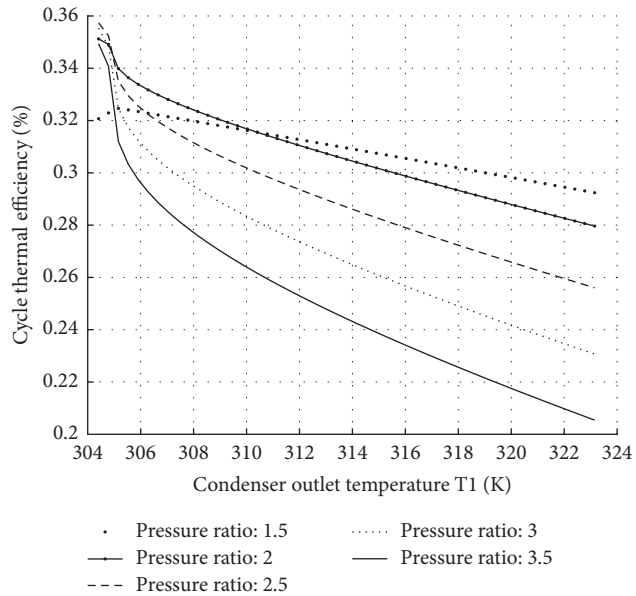

Figure 6: Effect of condenser outlet temperature on the thermal efficiency for different cycle pressure ratio.

ratio, the thermal efficiency increases rapidly first and then increases gently and even decreases at each condenser outlet temperature. At the low condenser outlet temperature of 304.35K, working at pressure ratio 2.5 has better thermal efficiency than working at pressure ratio 3. Working at pressure ratio 2 and working at pressure ratio 3.5 also have good thermal efficiency, but with the increasing of condenser outlet temperature working at pressure ratio 2 has better thermal efficiency than others. Because the specific heat of carbon dioxide near the critical point has a great change, the performance of condenser outlet temperature at different cycle pressure ratio has great changes.

In order to study the optimization design of parameters of SCO_2 Brayton Cycle, the objective optimization is conducted, based on the thermodynamic models, genetic algorithm, and pattern search algorithm. Genetic algorithm is used to optimize the parameters. The size of population is set to 50, and the population type is double vector. The crossover fraction is set to 0.8; mutation fraction is 0.2. Genetic algorithm is used to optimize the parameters with mesh initial size of 1, expansion factor of 2, and contraction factor of 0.5.

Because the algorithm belongs to the random class algorithm, it needs many operations; the result reliability is poor and cannot get the solution stably. We use genetic algorithms for multiple computations. Optimization of parameters by genetic algorithm and pattern search algorithm is shown in Table 3. The genetic algorithm curve is shown in Figure 7 as the sixth convergence curve, and Figure 8 shows the convergence curve of thermal efficiency with iterations by pattern search algorithm. As the figure shows, with the increase of generations, the thermal efficiency of the system increases rapidly and tends to stabilize quickly and finally reaches the maximum value. Genetic algorithm involves a large

Table 3: Optimization of parameters by genetic algorithm and pattern search algorithm.

	Pmax (kPa)	Pmin (kPa)	T1 (°C)	T7(°C)	ΔT1 (°C)	ΔT2 (°C)	generation number	Thermal efficiency %	Pressure ratio	Times (s)
Genetic algorithm										
1	24095.72	8318.25	31.23	369.99	3.04	3.03	105	35.907	2.896	197.4
2	23691.89	8444.36	31.31	369.99	3.7	3.03	102	35.903	2.805	191.8
3	22715.83	8063.99	31.31	369.98	3.01	3.02	103	35.925	2.816	193.6
4	23331.59	8328.26	31.23	369.96	3.05	3.02	147	35.927	2.801	276.4
5	21399.94	8174.63	31.26	369.99	3	3	143	35.932	2.617	268.8
6	23105.48	8209.23	31.32	369.99	3.12	3.04	162	35.928	2.741	318.3
Pattern search algorithm										
Start Point	20000	8000	35	300	10	10	/	25.25	2.5	
Value	21755.74	8002.80	31.2	370	3	3	601	35.970	2.719	31.8

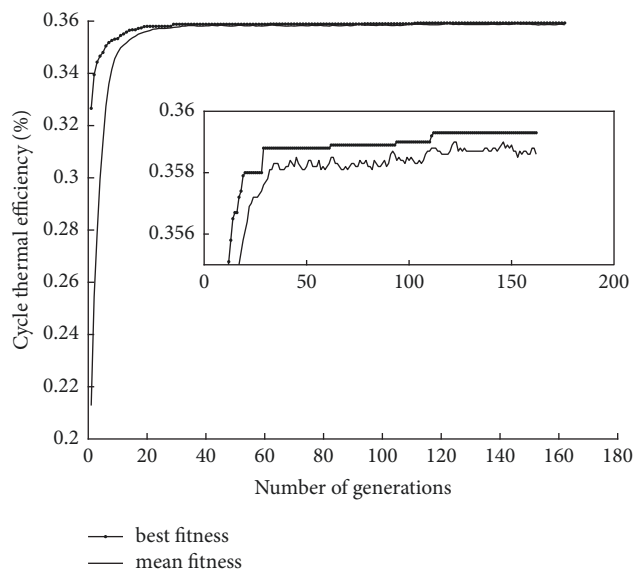

Figure 7: Convergence curve of thermal efficiency with generation by genetic algorithm.

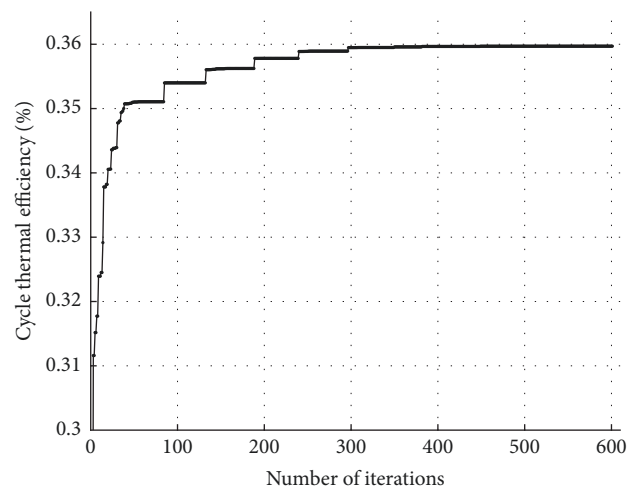

Figure 8: Convergence curve of thermal efficiency with iterations by pattern search algorithm.

number of individual calculations. When more parameters are involved, the computational time has a great disadvantage compared with the pattern search algorithm. And because the genetic algorithm belongs to the random class algorithm, it needs many operations; the result reliability is poor and cannot obtain the solution stably. And the parameter setting requirement is high; it needs better parameter setting to get the global optimal solution; otherwise, the local optimal solution may be obtained. Through the comparison of the two algorithms, it can be seen that the pattern search algorithm has a better calculation time of 31.8s in optimizing the parameters of the supercritical carbon dioxide system and a better calculation result.

Compared with other nuclear power plants, when supercritical carbon dioxide is used as a circulating working medium in energy conversion, the thermal efficiency of lead-cooled fast reactor is the highest, up to 53.8%, and the lowest thermal efficiency for heavy water reactor is 29.3% [29]. The efficiency of pressurized water reactor and sodium-cooled fast reactor was 33.5% and 46.4% [30], respectively. The thermal efficiency for CiADS is 35.97%, and with the reactor outlet temperature increases the thermal efficiency can be improved.

5. Conclusions

The main purpose of this paper is to study thermodynamic properties of SCO_2 Brayton Cycle for CiADS. The influence of the key parameters on the thermodynamic properties of the cycle was investigated. On the basis of thermodynamics and algorithm, genetic algorithm and pattern search algorithm are used to compare and analyze the maximum thermal efficiency of SCO_2 Brayton Cycle.

The main conclusions drawn from the present study are summarized as follows:

(1) For the SCO_2 Brayton Cycle, the key cycle parameters such as turbine inlet temperature, pressure ratio, outlet temperature at the hot end of condenser, and terminal temperature difference of regenerator

temperature have great effects on the cycle thermodynamic properties. In addition, with the increase of turbine inlet temperature and the decrease of temperature difference at terminal temperature difference of regenerator, the thermal efficiency also increases.

(2) Two algorithms are used in parameter optimization of SCO_2 Brayton Cycle. The optimal thermal efficiency of the system obtained by genetic algorithm and pattern search algorithm is 35.932% and 35.970%. Compared with other nuclear power plants of SCO_2 Brayton Cycle, CiADS with SCO_2 Brayton Cycle does not have the best thermal efficiency, but with the reactor outlet temperature increases the thermal efficiency can be improved.

(3) In the optimization calculation, both of the two optimization algorithms can get better optimization results. However, the computational thermal efficiency of genetic algorithm is worse than that of pattern search algorithm. The genetic algorithm needs longer calculation time with the higher requirement of parameter setting. Therefore, the pattern search algorithm is better in this calculation.

Data Availability

The data used to support the findings of this study were provided by Harbin Electric Corporation under license and so cannot be made freely available. Access to these data will be considered by the author upon request, with permission of Harbin Electric Corporation.

Conflicts of Interest

The authors declared that they have no conflicts of interest related to this work. They do not have any commercial or associative interests that represent conflicts of interest in connection with the work submitted.

Acknowledgments

This study was financially supported by Research Fund of Harbin Electric Corporation Central Academy of China, no. 17-11004. The authors are grateful to CW Zhang, Dr. YT Wang, ZL Sun, S Chen, and BL Dai of Harbin Electric Corporation Central Academy and Dr. YH Xie of Xi'an Jiaotong University.

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