

Thermo-economic optimization of supercritical CO₂ Brayton cycle on the design point for application in solar power tower system

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Abstract. The supercritical CO₂ Brayton cycle integrated with a solar power tower system has the advantages of high efficiency, compact cycle structure, strong scalability, and great power generation potential, which can positively deal with the energy crisis and global warming. The selection and optimization of design points are very important for actual operating situations. In this paper, the thermodynamic and economic models of the 10 MWe supercritical CO₂ Brayton cycle for application in solar power tower system are established. Multi-objective optimizations of the simple recuperative cycle, reheating cycle, and recompression cycle at different compressor inlet temperature are completed. The thermal efficiency and the levelized energy cost are selected as the fitness functions. The ranges of the optimal compressor inlet pressure and reheating pressure on the Pareto frontier are analyzed. Finally, multi-objective optimizations and analysis of the supercritical CO₂ Brayton cycle at different ambient temperature are carried out. This paper investigates the influence of the compressor inlet temperature and ambient temperature on the thermal efficiency and economic performance of the supercritical CO₂ Brayton cycle.

1 Introduction

The application of renewable energy is an important method to solve the energy crisis, deal with climate warming, and achieve sustainable development. Concentrated solar power (CSP) technology has got more and more attention. Among the common CSP technologies, the solar power tower (SPT) technology can offer high efficiency and promising scaling [1]. However, compared with the traditional coal-fired power generation plants, CSP still has no economic competitiveness [2]. Therefore, increasing the efficiency and reducing the cost for CSP plants are the future development directions [3].

Supercritical carbon dioxide (S-CO₂) Brayton cycles are applied in the fields of nuclear power, coal-fired power, waste-heat recovery, CSP and so on. It is a promising option that S-CO₂ Brayton cycles are integrated into the SPT system because of superior thermodynamic performance and compact layout [4]. The advantages of S-CO₂ Brayton cycles in the CSP system are as follows [5]: less compression work is required; compact layout structure due to small turbomachinery and heat exchangers; droughty areas can be selected as application sites by dry cooling; less corrosiveness, fewer requirements for materials.

The thermodynamic performance of the S-CO₂ Brayton cycle has received more and more attention. Turchi et al. [6] compared the thermodynamic performance of different forms of the S-CO₂ Brayton

cycle. Wang et al. [1] studied the influence of key parameters on thermal efficiency, specific work, and incorporation ability. He also compared different S-CO₂ Brayton cycle layouts integrated into the SPT system based on multi-objective optimization, in which overall efficiency and specific work are selected performance criteria [7]. For the recompression S-CO₂ Brayton cycle, Wang et al. [2] investigated the effects of key parameters on the overall SPT system and cycle exergy efficiency. Yang et al. [8,9] analysed and compared part-load and off-design thermodynamic performance of typical S-CO₂ Brayton cycles. Many scholars have also studied the economic performance of the S-CO₂ Brayton cycle. Neises et al. [10] investigated the minimize levelized cost of energy of different configurations of S-CO₂ Brayton cycles. Ma et al. [11] utilized an exergoeconomic approach to minimize the total unit exergy cost for optimal integration of main compression intercooling S-CO₂ Brayton cycles with or without reheat in the SPT system and established sensitivity analysis model. Therefore, it is essential to investigate the thermo-economic performance of the S-CO₂ Brayton cycle in the future.

In the S-CO₂ Brayton cycle integrated into the SPT system, the study of design points is still significant because the selection and optimization of design conditions are the guidance and basis for off-design or dynamic operation. In many studies, the compressor inlet temperature is set to a certain value [1,2,7-9]. The influence of the ambient temperature of design points is

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also not negligible. However, few studies on the effects of compressor inlet temperature or ambient temperature on the multi-objective optimization comprehensively consider thermodynamic and economic performance.

This paper establishes thermodynamic and economic models for the 10 MWe S-CO₂ Brayton cycle applied to the solar power tower system. The thermodynamic and economic performance are selected as fitness functions. The parameters analysis of compressor inlet temperature and ambient temperature and multi-object optimization for the simple recuperative cycle, reheating cycle, and recompression cycle are investigated. The influence of variable compressor inlet temperature and ambient temperature on the Pareto frontiers are studied.

2 Configurations

This paper selects three layouts of the S-CO₂ Brayton cycle. Among the common layouts, the simple recuperative cycle is the basic form. The reheating cycle can increase the power generation of the turbine. The recompression cycle is beneficial to heat recovery. The *T-s* diagrams are shown in Fig.1, Fig.2 and Fig.3.

The S-CO₂ Brayton cycle components generally include compressors, turbines, recuperators, heaters, and air-coolers. In the split-shaft configuration, compressors are driven by a motor, and turbines connect a generator. In the simple recuperative cycle, from state 1 to 2, the S-CO₂ is compressed to a high-pressure state. Then it is heated in the recuperator and the heater. From state 4 to 5, the S-CO₂ expands in the turbine. In the recuperator, the hot stream transfers heat to the cold stream. Finally, the S-CO₂ is cooled in the air-cooler to state 1.

The reheating cycle and recompression cycle process are similar to the simple recuperative cycle. Comparing to the simple recuperative cycle, the reheating cycle has an extra turbine and an additional reheating process in the re-heater. Comparing to the reheating cycle, the recompression cycle has an extra re-compressor.

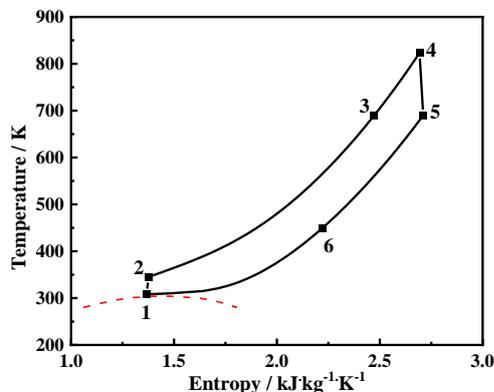


Fig. 1. Simple recuperative cycle *T-s* diagram.

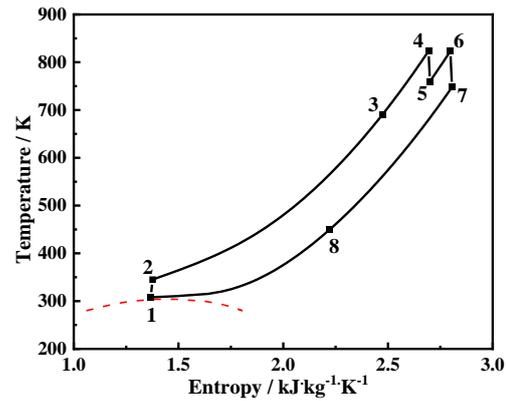


Fig. 2. Reheating cycle *T-s* diagram.

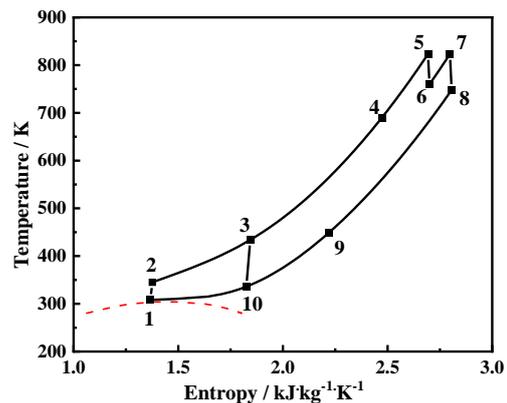


Fig. 3. Recompression cycle *T-s* diagram.

3 Calculation models

3.1 Thermodynamic models

The power output of the S-CO₂ Brayton cycle is 10 MWe in this work. The turbomachinery inlet and outlet enthalpy (*h*) values are determined based on the known temperature and pressure in the calculation process. The specific work consumed by the compressor and generated by the turbine can be indicated as follows:

$$W_{\text{com}} = m_{\text{CO}_2} \cdot (h_{\text{out,s}} - h_{\text{in}}) / \eta_{\text{com}} \quad (1)$$

$$W_{\text{tur}} = m_{\text{CO}_2} \cdot (h_{\text{in}} - h_{\text{out,s}}) \cdot \eta_{\text{tur}} \quad (2)$$

The specific work of the S-CO₂ Brayton cycle is calculated as follows:

$$W_{\text{net}} = W_{\text{tur}} \cdot \eta_{\text{generator}} - W_{\text{com}} / \eta_{\text{motor}} \quad (3)$$

The energy absorbed in the heater or re-heater can be calculated as follows:

$$Q_{\text{heat}} = m_{\text{CO}_2} \cdot (h_{\text{out}} - h_{\text{in}}) \quad (4)$$

The thermal efficiency of the S-CO₂ Brayton cycle is defined as follows:

$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_{\text{heat}} + Q_{\text{reheat}}} \quad (5)$$

3.2 Economic models

The S-CO₂ Brayton cycle components cost models are proposed [12]. The compressor and turbine cost (\$) models related to consuming or generating work (kW) are as follows:

$$C_{\text{com}} = 6898 \cdot W_{\text{com}}^{0.7865} \quad (6)$$

$$C_{\text{tur}} = 7790 \cdot W_{\text{tur}}^{0.6842} \quad (7)$$

The heater, recuperator, and air-cooler cost (\$) models related to the heat exchanger conductance (kW/K) are calculated as follows:

$$C_{\text{heater}} = 3500 \cdot UA_{\text{heater}} \quad (8)$$

$$C_{\text{recuperator}} = 1250 \cdot UA_{\text{recuperator}} \quad (9)$$

$$C_{\text{cooler}} = 2300 \cdot UA_{\text{cooler}} \quad (10)$$

The total cost of the S-CO₂ Brayton cycle is as follows:

$$C_{\text{total}} = \sum C_{\text{com}} + \sum C_{\text{tur}} + \sum C_{\text{heater}} + \sum C_{\text{recuperator}} + \sum C_{\text{cooler}} \quad (11)$$

The levelized energy cost (LEC) represents the economic performance of the cycle in this paper. Annal operation and maintenance cost (COM) is 1.65 % of the total cost, and interest (r) is 5 % [13]. The operation time (t_{op}) is 7500 h/year and the lifetime (L) is 15 years.

$$\text{LEC} = \frac{\text{COM} + C_{\text{total}} \cdot \text{CRF}}{W_{\text{net}} \cdot t_{\text{op}}} \quad (12)$$

$$\text{CRF} = \frac{r \cdot (1+r)^L}{(1+r)^L - 1} \quad (13)$$

4 Results and discussion

4.1 Performance analysis

In this part, the influence of compressor inlet temperature and ambient temperature on the thermal efficiency and economic performance are analysed.

Fig.4 shows thermal efficiency and economic performance change with the compressor inlet temperature of the simple recuperative cycle. As the compressor inlet temperature increases, the thermal efficiency decreases, and the LEC increases. Fig.5 shows the LEC of three cycle configurations changes with the ambient temperature. As the ambient temperature of the design condition increases, the air-cooler conductance and LEC increase, and the thermal efficiency does not change.

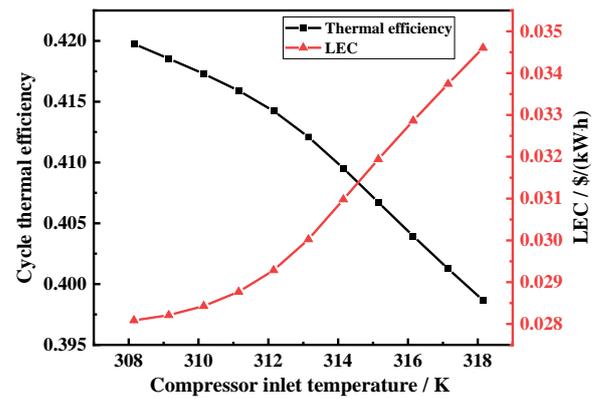


Fig. 4. Effects of compressor inlet temperature on thermal efficiency and LEC.

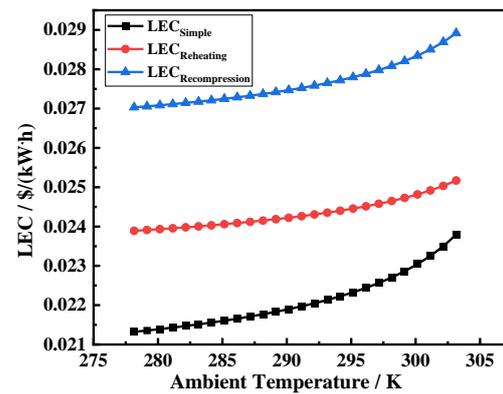


Fig. 5. Effects of ambient temperature on LEC.

4.2 Multi-objective optimization

Genetic algorithm (GA) is an optimization method that mimics the natural selection of biological evolution [14]. NSGA-II is used in this paper for multi-objective optimization. The thermal efficiency and the LEC are selected as fitness functions. The main input parameters are shown in Table 1. The decision variables are expressed as follows:

$$\begin{cases} \vec{X} = (p_{\text{min}}) & \text{Simple recuperative cycle} \\ \vec{X} = (p_{\text{min}}, p_{\text{rh}}) & \text{Reheating cycle} \\ \vec{X} = (p_{\text{min}}, p_{\text{rh}}, SR) & \text{Recompression cycle} \end{cases} \quad (14)$$

Fig.6 shows the simple recuperative cycle, reheating cycle, and recompression cycle Pareto frontiers in different compressor inlet temperature. As we can see, the recompression cycle has the highest thermal efficiency and LEC, followed by the reheating cycle and the simple recuperative cycle. The lower the compressor inlet temperature, the higher the thermal efficiency and the lower LEC. On the Pareto frontiers, the compressor inlet temperature drops by 5 °C, the thermal efficiency increases by 2 %, and the LEC decrease by 0.00176 \$/kW/h on average when another fitness function remains the same.

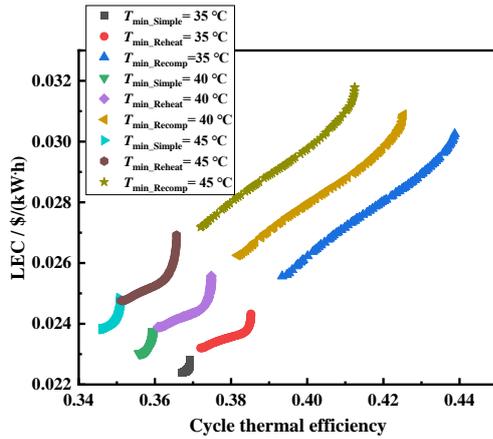
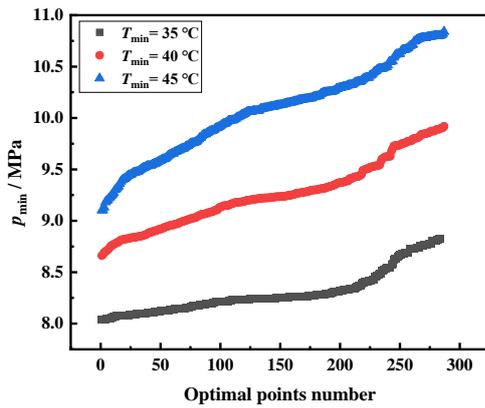
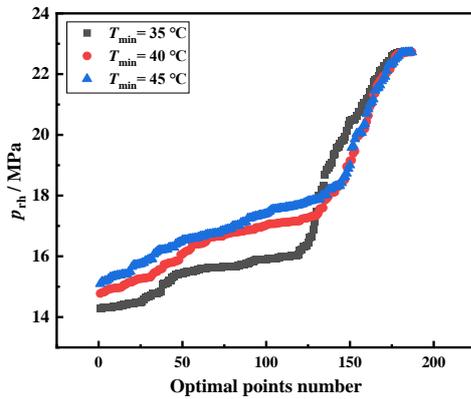


Fig. 6. The Pareto frontiers of different compressor inlet temperature for three configurations.



(a)



(b)

Fig. 7. (a) Optimum value of minimum cycle pressure and (b) Optimum value of reheating pressure.

Table 1. Main input parameters of the S-CO₂ Brayton cycle in multi-objective optimization

Parameter	Value
Power output (MWe)	10

Compressor inlet temperature (°C)	Varied
Turbine inlet temperature (°C)	550
Turbine inlet pressure (MPa)	25
Compressor isentropic efficiency (%)	89 [1]
Turbine isentropic efficiency (%)	93 [1]
Motor efficiency (%)	90
Generator efficiency (%)	97

Table 2. The highest thermal efficiency of different cycles in different compressor inlet temperature.

Compressor inlet temperature	Cycle	The highest thermal efficiency (%)	The corresponding LEC (\$/kWh)
35 °C	Simple	36.923	0.023
	Reheat	38.523	0.024
	Recompression	43.875	0.030
40 °C	Simple	35.938	0.024
	Reheat	37.481	0.026
	Recompression	42.525	0.031
45 °C	Simple	35.068	0.025
	Reheat	36.568	0.027
	Recompression	41.248	0.032

Table 3. The range of the optimal minimum cycle pressure on Pareto frontiers.

The compressor inlet temperature	The lower boundary of p_{min} (kPa)	The upper boundary of p_{min} (kPa)
35 °C	8035	8825
40 °C	8662	9919
45 °C	9102	10840

Table 2 shows the highest thermal efficiency that can be achieved in a certain compressor inlet temperature and corresponding LEC. When the compressor inlet temperature increases by 5 °C, the maximum achievable cycle thermal efficiency reduces by 1 %, and the LEC

increases by an average of 0.001 \$/kWh in the same cycle layout.

Fig.7 shows the minimum cycle pressure and reheating pressure values on Pareto frontiers points in different compressor inlet temperature. When the design compressor inlet temperature increases, the optimal minimum cycle pressure also increases (Table 3), and the optimal reheating pressure increases in the 14 MPa – 18 MPa, and then it increases rapidly.

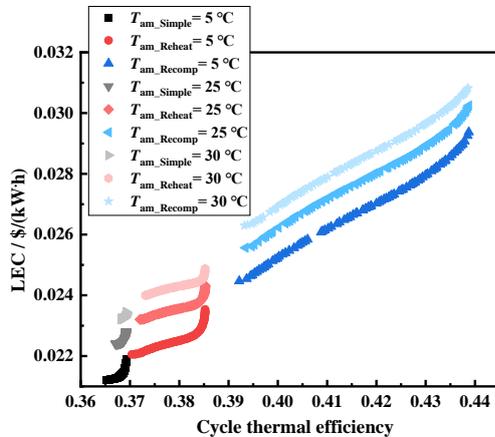


Fig. 8. The Pareto frontiers of different ambient temperature.

Fig.8 shows S-CO₂ Brayton cycles Pareto frontiers in different ambient temperature with 35 °C compressor inlet temperature. The S-CO₂ Brayton cycle has a lower LEC on the lower ambient temperature. When the ambient temperature on design points increases from 5 °C to 25 °C, the LEC increases by 0.001 \$/kWh. And the ambient temperature on the design point increases from 25 °C to 30 °C, the LEC increases by 0.0007 \$/kWh.

5 Conclusions

This paper studies the multi-objective optimization of the simple recuperative cycle, reheating cycle, and recompression cycle in different compressor inlet temperature and ambient temperature. The thermal efficiency and economic performance are the fitness functions. The main conclusions are listed as follows: (1) The lower the compressor inlet temperature, the higher the thermal efficiency, and the lower the LEC. The lower the ambient temperature of design conditions, the lower the LEC. The ambient temperature does not affect the cycle thermal efficiency. (2) On the Pareto frontiers of thermal efficiency and LEC, the compressor inlet temperature drops by 5 °C, the thermal efficiency

increases by 2 %, and the LEC decreases by 0.00176 \$/kWh on average when another fitness function remains the same. As the design compressor inlet temperature increases, the minimum cycle pressure of optimal points increases, and the reheating pressure increases in a certain range. (3) On the Pareto frontiers of thermal efficiency and economic performance with the different ambient temperature, the S-CO₂ Brayton cycle LEC increases as the ambient temperature increases.

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