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Theoretical investigation on a novel CO_2 transcritical power cycle using solar energy

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Abstract

CO_2, which is a stable power cycle working fluid, is used in the power cycle system, with the advantages of nontoxic, nonflammable and cheap. A novel CO_2 transcritical power cycle was proposed, with the aim of solving the problem that CO_2 is hard to condense in the conventional CO_2 transcritical power cycle using traditional cooling water. The theoretical analysis method was used to study the variations of performance parameters of the new cycle, with solar energy as heat source. The results showed that the mass flow rate in internal inverse cycle increases slightly with the increase of the final cooled temperature and decreases with the increase of the cooled pressure, which is contrary to the variation trend of that in internal normal cycle. The outlet temperature of the cooling water increases with the increase of the final cooled temperature and the cooled pressure. The net power output decreases with the increase of the final cooled temperature and the cooled pressure. The cycle thermal efficiency decreases with the increase of the final cooled temperature and increases with the increase of the cooled pressure, the cycle thermal efficiency reaches 0.3028 under the cooled pressure of 9.0 MPa and the final cooled temperature of 30.5°C.

Keywords: solar energy; CO_2; transcritical power cycle; cycle performance

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Nomenclature

t	temperature (°C)
p	pressure (MPa)
$\dot{P}$	power (kW)
$\dot{Q}$	heat transfer (kW)
η	efficiency
$\dot{m}$	mass flow rate of the working fluid ($kg \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
C	specific heat ($J \cdot kg^{-1} \cdot °C^{-1}$)
subscript	
b	boiling
c	criticial
tur	turbine
pum	pump
exp	expander
com	compressor
ther	thermal
1, 2, 2a, 2b, 3, 4, 4a, 4b, 5, a, b	the state points of the CO_2 transcritical power cycle
superscript	
$'$	inlet
$''$	outlet

1 Introduction

Solar energy is an important renewable and clean energy. It is of great significance to effectively exploit and utilize solar energy as a supplement of fossil resource. CO_2 is used in the power cycle system for non-toxic, nonflammable and cheap. It is an environment friendly fluid which isn't harmful to ozone layer. The global warming potential is even equal to 1.0. However, it is difficult to be condensed by the traditional cooling water in the conventional CO_2 transcritical power cycle.

In order to improve the operational performance, reduce energy consumption and satisfy the requirement, some studies have been carried out on CO_2 transcritical power cycle and solar thermal power generation. Efficiency is usually specified as the most important parameter in the optimization of the system. Chen et al. [1] aimed at low temperature thermal energy, compared the performances of the two transcritical power cycles using CO_2 and HFC32, respectively. Garg et al. [2] studied the flammable characteristics of the mixtures of CO_2 and hydrocarbons. Pan et al. [3-4] studied the theoretical cycle performance of the CO_2 transcritical power cycle by the means of theoretical and experimental methods, and proposed a novel CO_2 transcritical power cycle to solve the cooling problem in the conventional CO_2 transcritical power cycle. Zhang et al. [5-7] researched the efficiency of the CO_2 transcritical power cycle in their experimental study, with a throttle valve as the expansion component. Kim et al. [8] carried out the studies on the CO_2 transcritical and supercritical cycle using low temperature and high temperature thermal energy. The supercritical CO_2 Brayton Cycle has attracted the attention of many researchers, too. Garg et al. [9] compared the performance of the CO_2 transcritical power cycle and the steam transcritical power cycle. Mounir et al. [10] proposed a design scheme for CO_2 supercritical power cycle for the coal power generation, achieving a higher thermal efficiency in their theoretical analysis. Ma et al. [11] and Xie et al. [12] studied on the supercritical CO_2 power cycle using solar energy.

Focus on the problem of the CO_2 cooling, this study conducted theoretical investigation on a novel CO_2 transcritical power cycle using solar energy. In the new cycle, the cooling problem is avoid perfectly. It has a certain significance to provide a new perspective and a supplement for the research of CO_2 transcritical power cycle.

2 Theoretical method

Thermal oil is a traditional heat transfer medium which is usually used in the low temperature system. The molten salt can be used for the high temperature heat source. In the theoretical analysis, the following parameters are specified: the mass flow rate of molten salt is 10 kg/s and the temperature inlet is 600°C; the supercritical heating pressure is 25.0 MPa; the inlet temperature of the turbine is 550°C; the isentropic efficiency of the working fluid pump, turbine, compressor and the expander is 0.80, 0.88, 0.80 and 0.75, respectively; the temperature difference of the pinch point of the cooler and the regenerator is 5°C and 10°C, respectively; the temperature of the cooling water is 25°C. The considered cooled pressures are 7.5 MPa, 8.0 MPa, 8.5 MPa, and 9.0 MPa, respectively, while the final cooled temperature is from 30.5 °C to 35 °C. In addition, the density and the specific heat of the molten salt are calculated according to the equation (1) and equation (2) [12]. For equation (2), when the temperature exceeds the limits, the density and the specific heat are obtained by the epitaxial method.

$$\rho = 2430.2 - 0.4347T \tag{1}$$

$$C_p = 347.08 + 2.6T \qquad [286.85\text{-}430.25°\mathrm{C}] \tag{2a}$$

$$C_p = -3324.59 + 7.8T \qquad [430.25\text{-}746.85°\mathrm{C}] \tag{2b}$$

The system is mainly composed of heater, turbine, cooler, expander, gas-liquid separator, compressor, pump and regenerator. Because of the high temperature at the turbine exit, a large regenerator is also necessary. Fig. 1a shows the schematic diagram of the novel CO_2 transcritical power cycle and the fig. 1b is the flow chart. The basic cycle process is as follow: the supercritical CO_2 is heated to the state point 1 in the supercritical heater; the CO_2 enters the turbine and expands to the state point 2a; two flows of CO_2 (2a and 2b) mixed together (2); the CO_2 at the state point 2 enters the regenerator and is cooled to the state a; then the CO_2 is cooled by the cooling water to the state point 3 in the cooler; the colder supercritical CO_2 at the state point 3 enters the expander and expands to the state point 4; CO_2 at the state point 4 is separated into saturated liquid (4a) and saturated gas (4b) in the gas-liquid separator; saturated gas is pressurized from the state point 4b to state point 2b; the saturated liquid is pressurized by the working fluid pump from the state point 4a to the state point 5; then the CO_2 enters the regenerator and the heater to absorb remained energy from the turbine exhaust CO_2 and the solar energy, respectively. The whole cycle consists of two internal cycles, namely, the internal normal cycle (1-2a-2-2b-3-4-4a-5-1) and the internal reverse cycle (4b-2b-3-4-4b).

The internal normal cycle is the main cycle. As shown in Fig. 1b, the turbine outputs shaft power, while the pump consumes some shaft power. The internal reverse cycle is an auxiliary cycle which provides liquid CO_2 for the internal normal cycle. Much shaft power is also can be recovered by the expander, while the compressor consumes more shaft power than recovered. The system can be simplified by replacing the expander with throttle valve, but it will lose the expansion energy in this process.

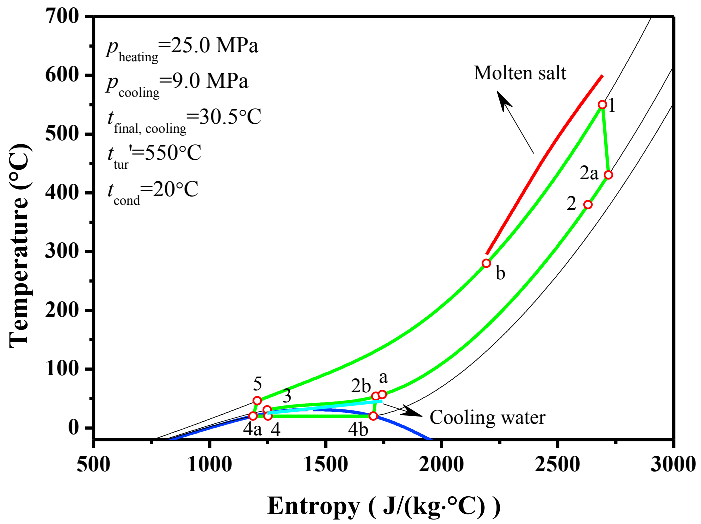

Fig. 1a Schematic diagram of the novel CO_2 transcritical power cycle.

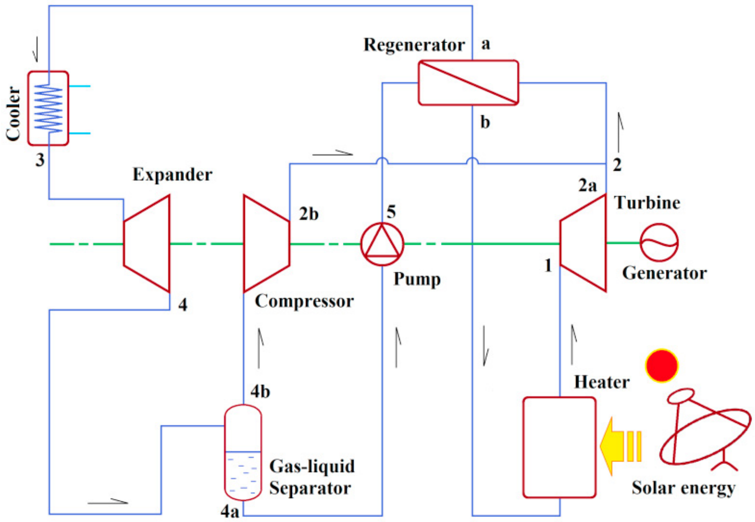

Fig. 1b Flow chart of the novel CO_2 transcritical power cycle.

The net power output and the cycle thermal efficiency are calculated by the formula (1) and (2). REFPROP 9.0 [13] provided the theoretical properties of the working fluid in the theoretical calculation.

$$\dot{P}_{\text{net}} = \left(\dot{P}_{\text{tur}} - \dot{P}_{\text{pum}}\right) - \left(\dot{P}_{\text{com}} - \dot{P}_{\text{exp}}\right) \tag{3}$$

$$\eta = \frac{\dot{P}_{\text{net}}}{\dot{Q}_{\text{heating}}} \tag{4}$$

3 Results and discussion

In this paper, the variations of the parameters (the mass flow rate of CO_2, the temperature output of the cooling water, power and thermal efficiency) with the working conditions were studied by theoretical analysis.

As shown in Fig. 2, the mass flow rate in internal reverse cycle increases slightly with the increase of the final cooled temperature and decreases with the increase of the cooled pressure, contrary to the changing trends of that in internal normal cycle. The proportion of saturated gas in the gas-liquid separator increases with the increase of the final cooled temperature. The mass flow rate of the saturated gas in the internal reverse cycle increases with the final cooled temperature while the mass flow rate of the saturated liquid in the internal normal cycle decreases. At the same final cooled temperature, the higher the cooled pressure is, the lower the dryness is after the expansion, which causes that the mass flow rate in the internal reverse cycle gets lower.

Under the cooling pressure of 7.5 MPa, when the final cooled temperature exceeds 31.5°C, the dryness after the expansion is very high because of the low cooling pressure, which causes excessive mass flow rate in the internal reverse cycle and compressor power consumption in the internal reverse cycle. Meanwhile, the net power output of the entire cycle also decreases. Therefore, these meaningless conditions are omitted.

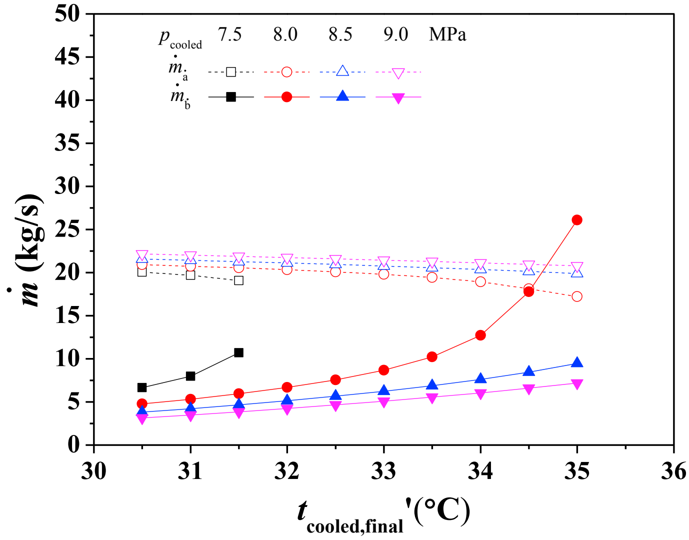

Fig. 2 Variation of the mass flow rate of the working fluid in the novel CO_2 transcritical power cycle.

As shown in Fig. 3, the outlet temperature of the cooling water increases with the increase of the final cooled temperature and the cooled pressure. The temperature difference at the pinch point in the cooler is constant, while the position of the pinch point rises with the increase of the final cooled temperature and the cooled pressure. That is the reason for the trend of the outlet temperature of the cooling water.

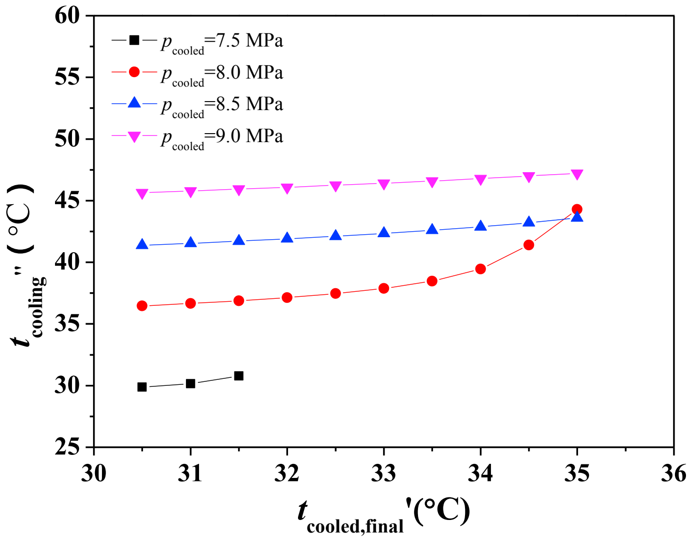

Fig. 3 Variation of the outlet temperature of cooling water in the novel CO_2 transcritical power cycle.

As shown in Fig. 4, the turbine power output decreases with the increase of final cooled temperature. The turbine power output is related to the enthalpy drop in the turbine and the mass flow rate of the working fluid. When the cooled pressure keeps constant, the mass flow rate in the internal normal power cycle of CO_2 plays a major role. As the final cooled temperature increases, the proportion of saturated liquid in the gas-liquid separator decreases, which causes the turbine power output decreases. On the other hand, when the final cooled temperature keeps constant, the enthalpy drop in the turbine plays a major role. As the cooled pressure increases, the temperature and pressure at the exit of the turbine increase, which increases the specific enthalpy of the turbine exhaust and decreases the enthalpy difference of the turbine.

The power input to pump increases with the decrease of the final cooled temperature and the increase of the cooled pressure. The power input is related to the enthalpy rise of the pump and the mass flow rate of CO_2. The mass flow rate in the normal power cycle plays a major role. As the final cooled temperature increases, the proportion of saturated gas in the gas-liquid separator increases and the mass flow rate in the internal normal cycle decreases, causing that the power input to the pump decreases with the increase of the final cooled temperature. The higher the cooled pressure is, the wetter of the working fluid is. The higher the mass flow rate in the internal normal power cycle is, and the higher the power input to the pump is.

The power output of the expander increases with the increase of the final cooled temperature and the cooled pressure. It is related to the enthalpy drop and the mass flow rate of CO_2 in the expander. Compared with the enthalpy drop, the mass flow rate of CO_2 is a more important factor in determining the power output of the expander. Therefore, the changing trend of the power output of the expander is similar to that of the CO_2 mass flow rate.

The power input to compressor power increases with the increase of final cooled temperature and the decrease of the cooled pressure. The compressor power is related to the enthalpy rise in the compressor and the mass flow rate of CO_2. The mass flow rate in the reverse power cycle plays a major role. The mass flow rate of the reverse power cycle increases with the increase of the final cooled temperature and the decrease of the cooled pressure, which results in the increase of the power input to compressor.

The net power output decreases with the increase of final cooled temperature and the cooled pressure in the considered conditions. The net power output is related to the power output of the turbine and the expander, as well as the power input to the pump and the compressor. The power output of the turbine plays a major role, which causes that the changing trend of the net power output is similar to that of the power output of the turbine.

It is worth noting that, with the cooled pressure of 7.5 Mpa and 8.0 Mpa, the higher the final cooled temperature is, the larger the mass flow rate of the internal reverse cycle. It leads to the rapid increase of the power output of the expander and the power consumption of the compressor. On the other hand, it causes the rapid decrease of the turbine power output, the power consumption of the pump and the net power output.

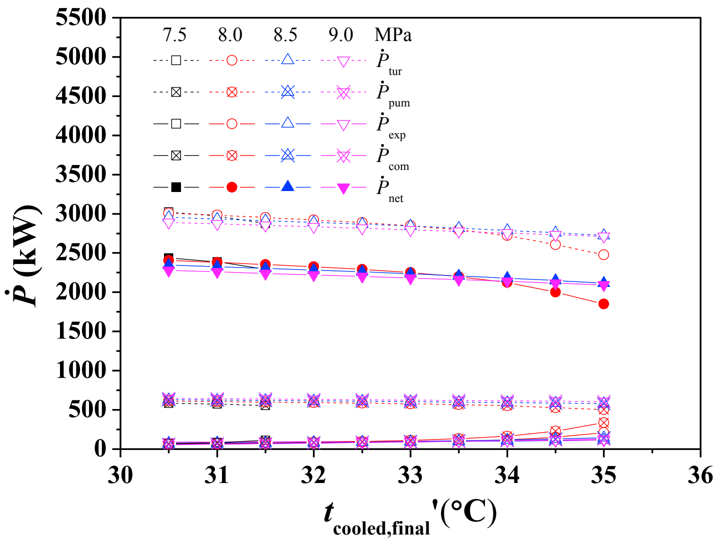

Fig. 4 Variation of power with the cooled pressure under different final cooled temperatures.

As shown in Fig. 5, the thermal efficiency of the cycle decreases with the increase of the final cooled temperature, and increases with the increase of the cooled pressure. The cycle thermal efficiency of the CO_2 transcritical power cycle is mainly related to the average temperature of the CO_2 as absorbing and releasing heat energy. As absorbing heat energy, the lower the final cooled temperature is, the lower the average temperature is, and the higher the efficiency will be.

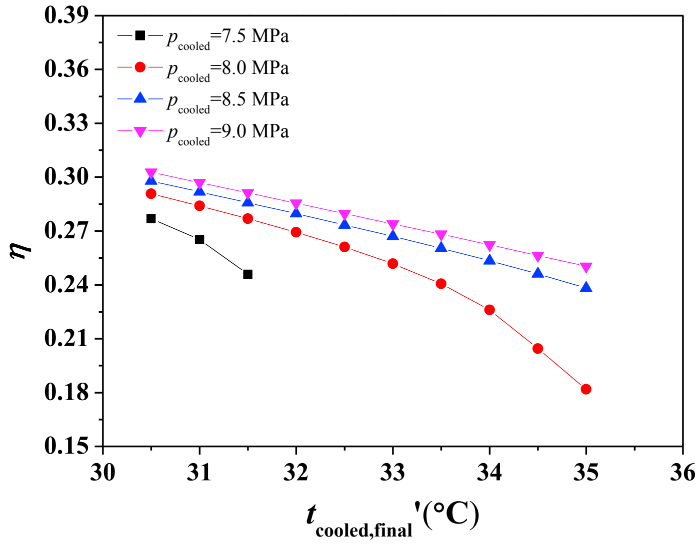

Fig. 5 Variation of the cycle thermal efficiency of the novel CO_2 transcritical power cycle.

4 Conclusions

Focus on the problem that the subcritical CO_2 is difficult to be condensed by traditional cooling water, a novel CO_2 transcritical power cycle is taken as the subject, and a theoretical method is used to investigate the variations of the parameters. The following conclusions are given:

[1] The mass flow rate in internal inverse cycle increases slightly with the increase of the final cooled temperature and decreases with the increase of the cooled pressure. These changing trends are contrary to those in internal normal cycle.

[2] The temperature outlet of the cooling water increases with the increase of final cooled temperature and the cooled pressure.

[3] The thermal efficiency of the cycle decreases with the increase of the final cooled temperature and increases with the increase of the cooled pressure.

[4] The lower the cooled pressure is, the higher the net power output and the lower cycle thermal efficiency are. Under the considered conditions, the maximum cycle thermal efficiency is required. With the final cooled temperature of 30.5°C and the cooled pressure of 9.0 MPa, the cycle thermal efficiency reached the maximum of 0.3028. Under that condition, the mass flow rate in the normal power cycle was 22.17 kg/s, the mass flow rate in the reverse power cycle was 3.15 kg/s, the outlet temperature of the cooling water was 45.64°C, the turbine power output was 2891.91 kW, the power input to pump was 646.70 kW, the output power of the expander was 88.18 kW, the power input to compressor was 55.63 kW, and the net power output was 2277.76 kW.

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