PERFORMANCE COMPARISON OF TRANSCRITICAL CO_2 POWER CYCLE, ORGANIC RANKINE CYCLE AND KALINA CYCLE FOR LOW TEMPERATURE GEOTHERMAL SOURCE

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ABSTRACT

The wide utilization of renewable energy can relieve the energy crisis effectively. As a type of the renewable energy, geothermal energy is sustainable, abundant, environmentally-friendly, independent of various weather conditions and easily coupled with the conventional system. Among the low-temperature recovery technologies, the basic transcritical CO_2 Rankine cycle (B-TCRC), and organic Rankine cycle (ORC) and Kalina cycle have their own characteristics. This paper explored the thermodynamic performance of B-TCRC with the various turbine inlet pressure and temperature, and determines the optimal design operating condition for the 120 ℃ geothermal heat source at first. Then, a comparative analysis of the thermodynamic performance of B-TCRC, ORC and Kalina cycle was presented under the optimal design operating condition. Results show that the net power output of B-TCRC is the largest while the ORC has advantages in term of thermal efficiency, whose value is 12.28%. However, the net power of ORC is the lowest, whose value is only 1556 kW. The thermal efficiency and net power of Kalina cycle are 9.78% and 2705 kW, respectively. The Kalina cycle has the maximum exergy efficiency.

1. INTRODUCTION

The global climate change has become an important issue. A comprehensive, high-efficient, and clean utilization of energy is critical for a sustainable development. Meanwhile, there are a lot of primary and secondary low-grade heat energy that need to be utilized. CO2 power cycle can be used for high and low temperature sources (Sarker,2015; Ahn et al.,2015; Shu et al., 2018). With the progress of technology, the maximum operation pressure of the closed-loop power cycle becomes higher and higher, which makes it possible for the employment of the supercritical or transcritical CO2 power cycle. Compared with water or organic working fluids, CO2 has some advantages and attracts people' s attentions from all over the world recently (Song et al.,2018; Olumayegun et al.,2019; Manjunath et al., 2018; Wu et al.,2018). Many investigations have been performed to CO2 power cycle in terms of system topology design, performance characteristics analysis, and operation parameters optimization. In this paper, the performances of the basic transcritical CO2 Rankine cycle with the different turbine inlet pressure and temperature is analyzed. Then, the optimal operating working conditions are determined to compared with the performance of the Kalina cycle and the ORC for a low-temperature geothermal heat source. In addition, the heat addition process and the advantage of the position of

PPTD in evaporator of the different working fluids are also discussed to clarify the potential of TCRC in recovering low-temperature geothermal energy.

2. SYSTEM DESCRIPTION

The basic transcritical CO_2 Rankine cycle (B-TCRC) is selected for this study. Figure 1 shows the structure of B-TCRC and the relative T-s diagram is shown in Figure 2. The B-TCRC mainly consists of a pump, an evaporator, a turbine and a condenser. The working process of the B-TCRC is the simplest. First, the CO_2 is compressed to a supercritical state by the pump. Then, the CO_2 is delivered to the evaporator, where it absorbs heat from the low-temperature geothermal source. Afterwards, the supercitical CO_2 with a high temperature and pressure expands in the turbine. Finally, the CO_2 exhausted from the turbine is cooled and condensed in the condenser. The detailed working conditions for this model are listed in Table 1.

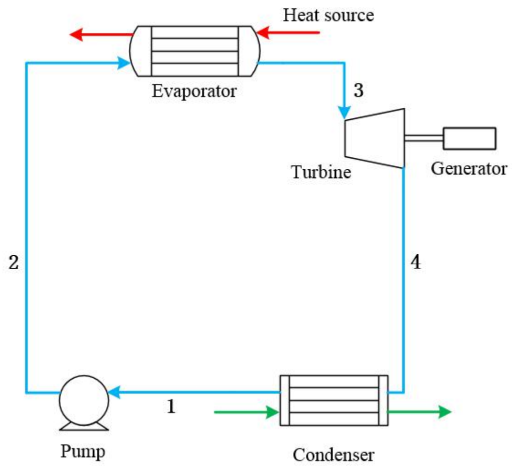

Figure1: The structure of B-TCRC

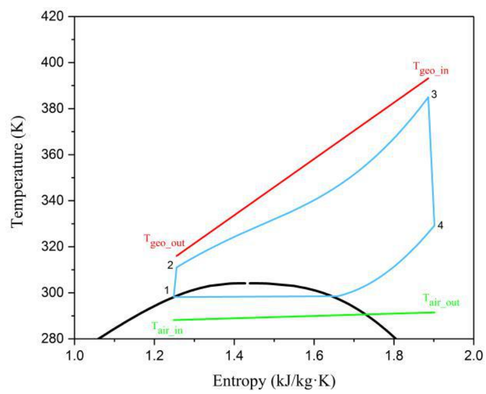

Figure 2: The T-s diagram of B-TCRC

Table 1: Working conditions of B-TCRC

Parameter	Value	Unit
Ambient temperature	283.15	K
Ambient pressure	101.1	kPa
Condenser temperature	298.15	K
Isentropic efficiency of the pump	0.8	/
Isentropic efficiency of the turbine	0.85	/
PPTD of the evaporator	5	K
Temperature of geothermal water	393.15	K
Mass flow rate of geothermal water	141.8	kg/s

3. DISCUSSION AND RESULTS

3.1 Thermodynamic performance of B-TCRC

3.1.1 Net power

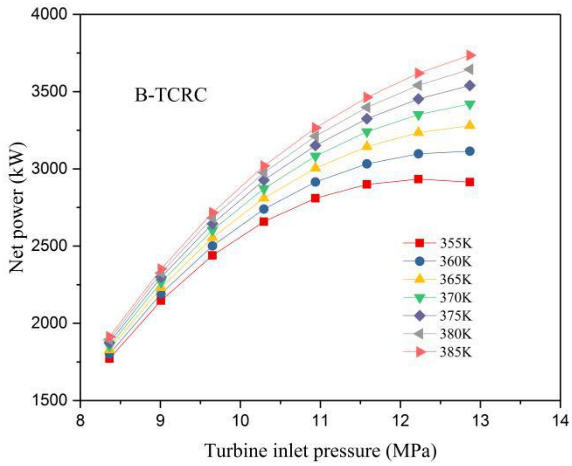

Figure 3 : Net power of B-TCRC as a function of turbine inlet pressure and temperature

The net power of the B-TCRC is displayed in Figure 3, which increases as the turbine inlet pressure rises if the turbine inlet temperature is fixed. The net power output under a high turbine inlet temperature is greater than that with a low one. When the turbine inlet pressure is low, the differences of the net power among various turbine inlet temperatures are small. However, when the turbine inlet pressure is high, the influence of the turbine inlet temperature is increased. Therefore, the net power reaches a maximum of 3736 kW when the turbine inlet pressure and temperature are 12.86 MPa and 385 K, respectively.

3.1.2 Thermal efficiency

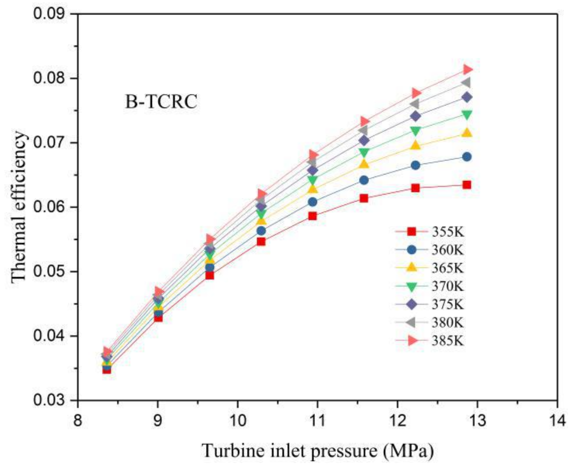

Figure 4 : Thermal efficiency of B-TCRC as a function of turbine inlet pressure and temperature

Results for the thermal efficiency of B-TCRC are shown in Figure 4. Because the temperature at the outlet of the condenser is fixed in this study, the temperature of the geothermal water at the outlet of the evaporator keeps slightly higher than that of the CO_2 for all the cases owing to the position limitation of PPTD. Therefore, the heat transfer between the geothermal water and the CO_2 is almost constant for all the cases with a fixed turbine inlet pressure. As a result, the variation trend of the thermal efficiency is similar with that of the net power output. Therefore, the maximum thermal efficiency is 8.14% when the turbine inlet pressure and temperature are 12.86 MPa and 385 K, respectively.

3.1.3 Exergy efficiency

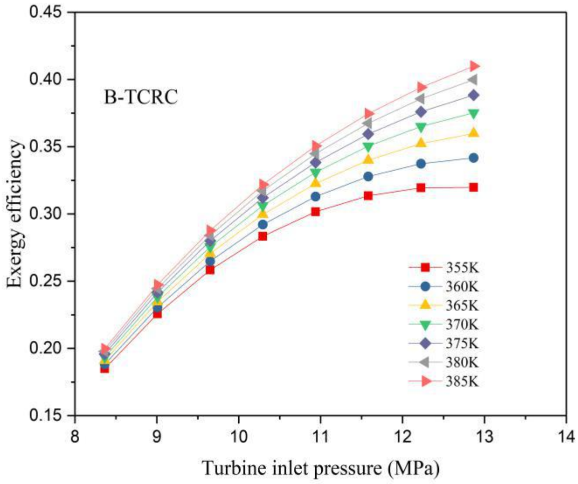

Figure 5 : Exergy efficiency of B-TCRC as a function of turbine inlet pressure and temperature

Figure 5 shows the exergy efficiency of B-TCRC with the turbine inlet pressure and temperature. The exergy efficiency increases with the increase of turbine inlet pressure and temperature. The the exergy efficiency has a small change with the increase of turbine inlet temperature under the low turbine inlet pressure. However, with the increase of turbine inlet pressure, the exergy efficiency changes obviously with the increase of turbine inlet temperature. This is mainly because exergy efficiency is the net output power of the system divided by the difference between exergy of the heat source at the inlet and outlet of the evaporator. With the increase of turbine inlet pressure, the difference of geothermal water exergy in the inlet and outlet of evaporator decreases gradually. However, the turbine inlet pressure has little influence on the difference of the exergy of geothermal water at the inlet of the evaporator, so the variation trend of exergy efficiency is mainly affected by the net output power. The maximum exergy efficiency of TCRC is 40.99% when the turbine inlet pressure and temperature are 12.86 MPa and 385 K, respectively.
Based on the above analysis of thermodynamic performance of B-TCRC, the study found the optimal operating condition used for recovery the 120 °C geothermal source. However, the Kalina cycle and the ORC are also suitable for low-temperature heat source utilization. Therefore, performances of the B-TCRC, the Kalina cycle, and the ORC are analyzed and compared. The Kalina cycle is the same with that in (Wang et al.,2017a) and the mass fraction of the ammonia is 0.748. The ORC has a simple architecture and similar with that in (Wang et al.,2017b). The zeotropic mixture of R134a/R245fa is used as the working fluid and the mass fraction of R134a is 0.187. The heat source is also a geothermal water with a temperature of 120 °C and a mass flow rate of 141.8 kg/s.

3.2 Comparison with Kalina cycle and ORC

3.2.1 Thermal efficiency

Results for the thermal efficiency of the B-TCRC, the Kalina cycle, and the ORC are shown in the Figure 6. Both the thermal efficiencies of the ORC and the Kalina cycle are significantly higher than that of the B-TCRC. The ORC has the highest thermal efficiency as 12.28%. The thermal efficiency of the Kalina cycle is 9.78%. The reason for such a low thermal efficiency of the B-TCRC is mainly owing to the high power consumption of the pump. Under the optimal operating condition of the B-TCRC, the power consumption of the pump accounts for nearly 38.2% of the power output of the turbine. However, this proportion is only 3.4% and 5.4% for the Kalina cycle and the ORC, respectively. Therefore, the power consumption of the pump for the B-TCRC seriously affects the improvement of the thermal efficiency, and special attentions should be paid to maintain a high efficiency of the pump in practice.

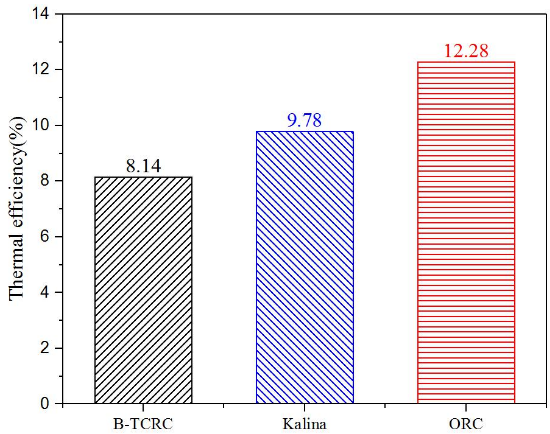

Figure 6 : Thermal efficiency of B-TCRC、Kalina cycle and ORC

3.2.2 Net power

Figure 7 shows the results for the net power output of the three cycles. Although the ORC has the highest thermal efficiency shown as Figure 6, the net power output is the lowest as 1556 kW. In contrast, the net power of the B-TCRC is the highest as 3736 kW, even higher than that of the Kalina cycle as 2705 kW. This is mainly owing to the difference of position of PPTD in the evaporators. Figure 8 shows the positions of PPTD in the evaporator for the B-TCRC, the Kalina cycle, and the ORC, respectively. For the B-TCRC, the pinch-point position is located at the inlet of the evaporator, maximizing the utilization of the heat from the geothermal source. Because the glide temperature of the zeotropic mixture R134a/R245fa is small, the outlet temperature of the geothermal water is very high, leading to a limited utilization of the heat source. Even if the ORC has the highest thermal efficiency, the heat addition in the evaporator is constrained. Therefore, the net power output of the ORC is the lowest. For the Kalina cycle, the pinch point position is very close to the inlet of the evaporator, which allows more heat absorbed than that of the ORC and ultimately results in a higher net power output than that of the ORC.

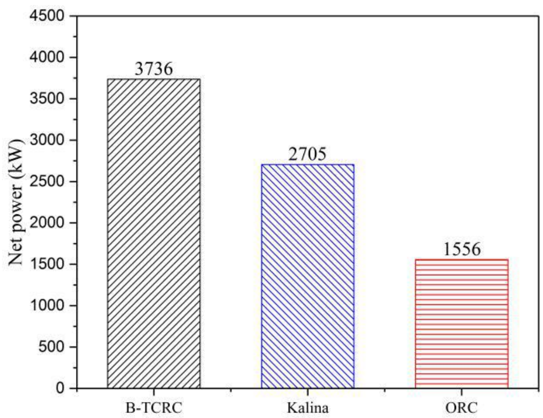

Figure 7 : Net power of B-TCRC、Kalina cycle and ORC

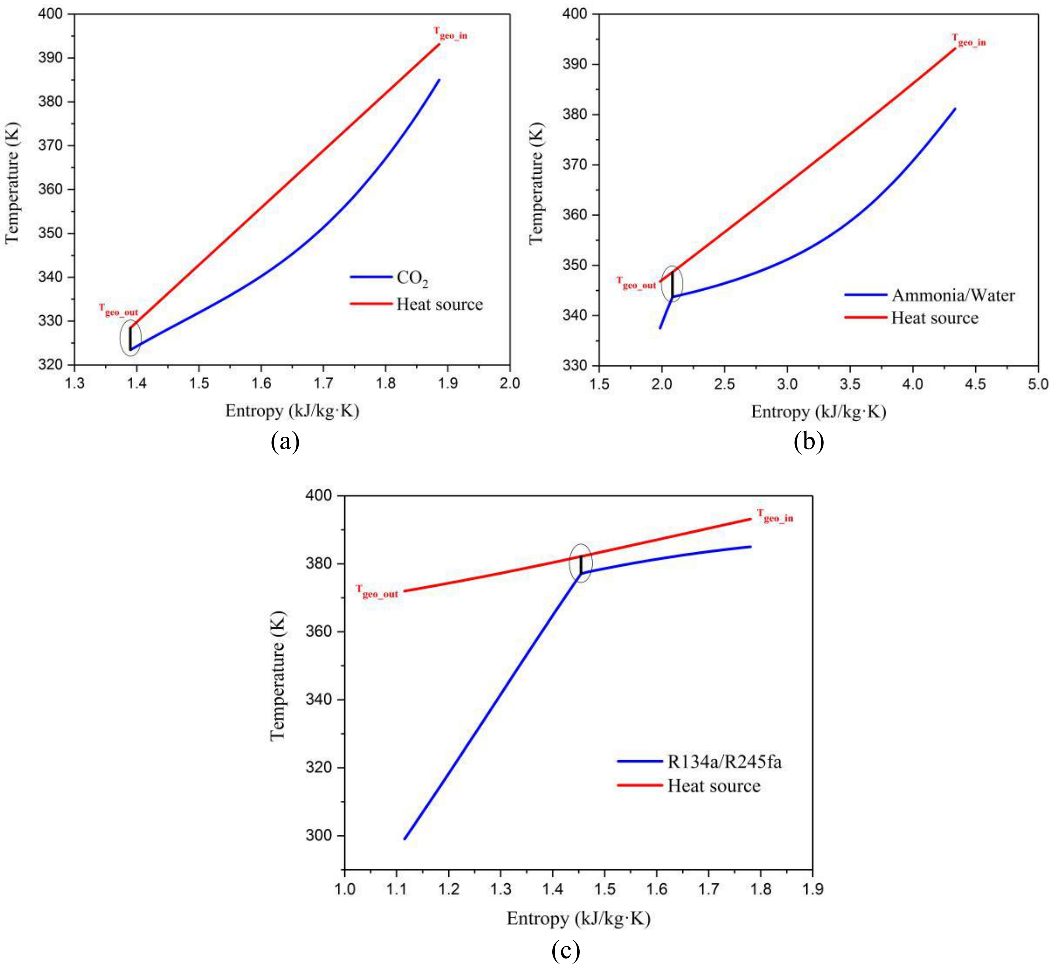

Figure 8 : Results for the pinch-point position in the evaporator: (a) B-TCRC; (b) Kalina cycle; (c) ORC.

3.2.3 Exergy efficiency

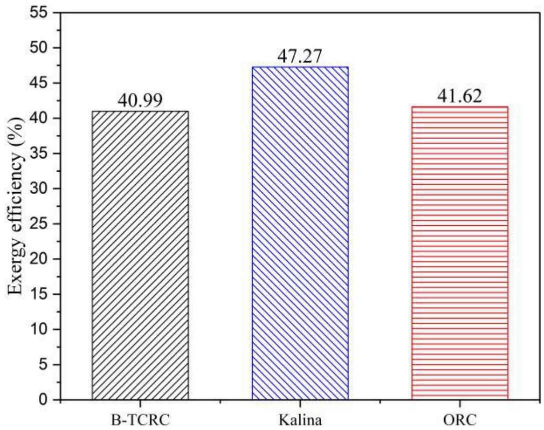

Figure : 9 Exergy efficiency of B-TCRC, Kalina and ORC

As we can see from the figure 9, the exergy efficiency of the Kalina cycle is the largest as 47.27% followed by the ORC (41.62%) and the B-TCRC (40.99%). In this study, the exergy efficiency is determined by the net power output and the exergy difference of the heat source between the inlet and the outlet of the cycle. The net exergy addition of the B-TCRC is the largest, resulting in a lower exergy efficiency. However, the working fluid temperature at the outlet of the evaporator for the ORC is the highest. Therefore, the net exergy transferred into the ORC system is the smallest. However, as the net power of ORC is the lowest, the exergy efficiency is lower than that of kalina cycle.

4. CONCLUSIONS

- The thermal efficiency and net power of B-TCRC are increased with the increase of turbine inlet pressure and temperature. The maximum thermal efficiency and net power are 8.14% and 3736 kW, respectively.
- Based on the same low-temperature geothermal heat source, the thermal efficiency of the B-TCRC is the smallest, but the net power output of the B-TCRC is significantly higher than that of the Kalina cycle and the ORC. The thermal efficiency of ORC is the highest, and the net power of ORC is the lowest. The Kalina cycle has the maximum exergy efficiency. The transcritical CO_2 Rankine cycle has a great potential for low-temperature heat source utilization.

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