2014

Experimental investigation on the influencing factors of a transcritical CO2 heat pump

J.L. Ma
School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China, juanli.ma@stu.xjtu.edu.cn

C.H. Liu
School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China, changhailiu@stu.xjtu.edu.cn

Y. Hou
yuhou@mail.xjtu.edu.cn

T.W. Lai
School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China, laitianwei@mail.xjtu.edu.cn

Experimental Investigation on the Performance Influencing Factors of a Transcritical CO_2 System

Ma J.L.,[1] Liu C.H.,[1] Hou Y.,[1,2,*] Lai T.W.[1]

[1] School of Energy and Power Engineering, Xi'an Jiaotong University,
Xi'an Shaanxi, China

[2] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University,Xi'an Xi'an Shaanxi, China

* Correspondence author. E-mail: yuhou@mail.xjtu.edu.cn

ABSTRACT

As one of the earliest natural refrigerants, CO_2 has a lot of unique advantages, such as zero ODP, negligible GWP, excellent heat transfer coefficient, high volumetric capacity, non-toxicity, non-flammability, and cost effectiveness. Since it was proposed to applying in the mobile air-conditioning, the transcritical CO_2 cycle has been attracting great attentions to replace CFC and HCFC refrigerants in many areas, including refrigeration, heat pump, and air-conditioning, etc.Unlike the conventional refrigerants, the heat rejection pressure and temperature of the gas-cooler in the transcritical cycle are usually decoupled in the transcritical cycle. Besides, there exists an optimal heat rejection pressure under which the maximum cycle efficiency can be achieved. The concept of “the optimal heat rejection pressure” has attracted wide attentions in the scientific community. Therefore, the interaction effect between heat rejection pressure and system performance has been studied by many researchers.The heat rejection pressure of the gas-cooler has a great impact on the COP of the transcritical CO_2 system, but the investigation on the influence factors of the heat rejection pressure is quite rare in the open literature. In this paper, the effects of the water inlet temperatures and the water flow rates on the heat rejection pressure of a water-to-water transcritical CO_2 refrigeration heat pump with single-stage expansion system have been investigated. Furthermore, the operation parameters and the performance of the system are also evaluated.

1. INTRODUCTION

As one of the earliest natural refrigerants, CO_2 has a lot of unique advantages, such as zero ODP, negligible GWP, excellent heat transfer coefficient, high volumetric capacity, non-toxicity, non-flammability, and cost effectiveness. Since it was proposed to applying in the mobile air-conditioning(Lorentzen and Pettersen, 1993), the transcritical CO_2 cycle has been attracting great attentions to replace CFC and HCFC refrigerants in many areas, including refrigeration, heat pump, and air-conditioning, etc.(Sarkar , 2010; Groll and Kim. , 2007).
Compared to conventional refrigerants, the most remarkable property of CO_2 is the low critical temperature of 31.1 ℃. Vapor compression systems with CO_2 operating at normal refrigeration, heat pump and air-conditioning temperatures will therefore work above the critical pressure of 7.38 MPa， causing the heat rejection pressure of the gas-cooler above supercritical point. Thus, unlike the conventional refrigerants, the heat rejection pressure and temperature of the gas-cooler in the transcritical cycle are usually decoupled in the transcritical cycle. Besides, there exists an optimal heat rejection pressure under which the maximum cycle efficiency can be achieved.
Since Kauf (1999) first advanced the concept of “the optimal heat rejection pressure”, which has received wide attention in the scientific community. Therefore, the interaction effect between heat rejection pressure and system performance has been studied by many researchers. Actually, almost all the investigations were performed at a constant gas-cooler outlet temperature and a constant low pressure (evaporating temperature, suction pressure or

ambient temperature). The heat rejection pressure of the gas-cooler has a great impact on the COP of the transcritical CO2 system, but the investigation on the influence factors of the rejection pressure is quite rare in the open literature. The only related work so far is reported in Ref. (Cho et al., 2005;, Baek et al. ,2013). Cho et al. (2005) investigated the effects Effects of refrigerant charge amount on the heat rejection pressure and system performance. Baek et al investigated the effects EEV opening and outdoor fan speed on the heat rejection pressure and system performance. The pressure in the high side is determined by the relationship between refrigerant charge (mass), inside volume and temperature (Kim et al., 2004). In this paper, the effects of the water inlet temperatures and the water flow rates on the rejection pressure of a water-to-water transcritical CO_2 refrigeration system with single-stage expansion system have been investigated. Furthermore, the operation parameters and the performance of the system are also evaluated.

2. TEST RIG

The test rig of the transcritical CO_2 refrigeration system presented in this paper consists of three parts, including the refrigeration cycle, the water supply system, and the data acquisition system. The schematic diagram of the transcritical CO_2 refrigeration system is shown in Fig. 1. The presented system is composed of a semi-hermetic reciprocating compressor, an evaporator, an electronic expansion valve, a receiver, a gas-cooler, and an oil separator, as shown in Fig. 2. Details about the components are listed in table 1.

Heat generated from the evaporator and the gas-cooler was controlled and regulated by two circulating water systems. The inlet temperature of the water was regulated in the range of 5 ℃ to 90 ℃ with a precision of ±0.5 ℃. And in this paper, the system performance was evaluated with the inlet temperature of the gas-cooler water and the evaporator water set to 30 ℃ and 15 ℃, respectively. The T-type thermocouples with an accuracy of 0.5 ℃ (from -10 ℃ to 150 ℃) were used to measure the temperature. The pressure sensors with an accuracy of ±2.5% (from 0 MPa to 15 MPa), were employed for pressure data acquisition. A digital power meter with accuracy of 0.15% (AC: 0.0-500.0 V, 0.030-40.00 A) was used to monitor the electrical power supply. The accuracy of the turbine flowmeter is ±0.5% (0.8 m^3 to 8.0 m^3). A data acquisition device was used for data recording.

Table 1: Main Components

Name of components	Main characteristic
Compressor	Semi-hermetic reciprocating compressor; Swept volume: 8.3 m^3/h.
Gas-cooler	Plate heat exchanger; Heat transfer area: 2.09 m^3
Evaporator	Plate heat exchanger; Heat transfer area: 1.81 m^3
Expansion valve	Electrically expansion valve and regulating valve.
Receiver	Inner volume: 4.9×10^{-3} m^3.
Oil separator	Inner volume: 11.7×10^{-3} m^3.

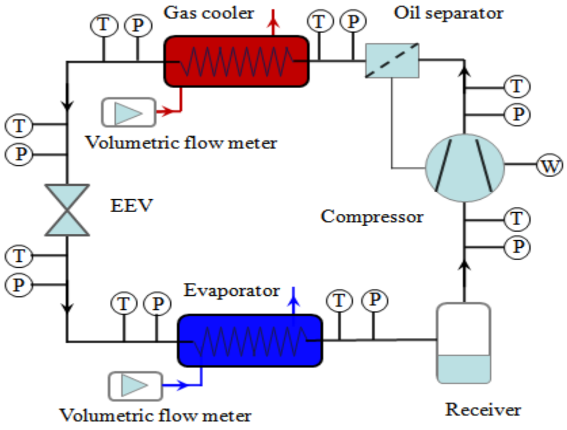

Figure 1 (a): Schematic of the transcritical CO_2 refrigeration system

Figure.1 (b): Picture of the test system

3. RESULTS AND DISCUSSION

In this section, the experimental results on the effects of the water inlet temperatures and the water flow rates are presented and discussed. The system performance was evaluated with EEV opening set to 50%.

3.1 The effects of flow rates of the gas-cooler water

The effects of flow rates of the gas-cooler water on the key pressure in transcritical CO_2 system are illustrated in Fig.2. It can be seen that within the working pressure range of 9.5 MPa to 10.0 MPa, the compressor discharge pressure increases with the flow rates of the gas-cooler water. When changed from 100% to 60%, the flow rate of the gas-cooler water has little effect on the compressor suction pressure, which varied from 3.7 MPa to 3.8 MPa. This is because the pressure and temperature of the evaporation are coupled, and the compressor suction temperature depends strongly on the heat transfer conditions in the evaporator. In our tests, the evaporator water inlet temperature and water mass flow rate remain unchanged. And when the flow rates of the gas-cooler water changed, the compressor suction pressure unchanged.

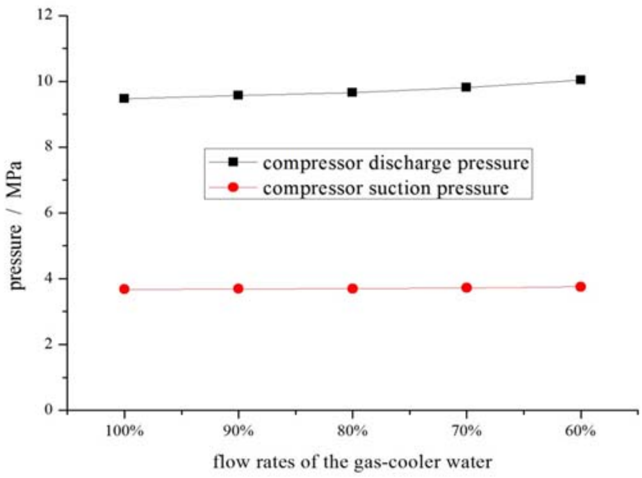

Figure 2: Variations of the pressures with flow rates of the gas-cooler water

The variations of the system key temperatures caused by the decrease of flow rates of the gas-cooler water (from 100% to 60%) are shown in Fig. 3. The decrease of flow rate of gas-cooler water leads to the increase of the discharge temperature of the compressor, the evaporating temperature and gas-cooler outlet temperature. It is clearly seen from Fig. 3, the discharge temperature of the compressor increases from 75.6℃ to 79.5 ℃ with the flow rate decreasing from 100% to 60%. In the meantime, the evaporating temperature and the gas-cooler outlet temperature increase from 6.3 ℃ to 7. 0 ℃ and from 32.7 ℃ to 35.8℃, respectively.

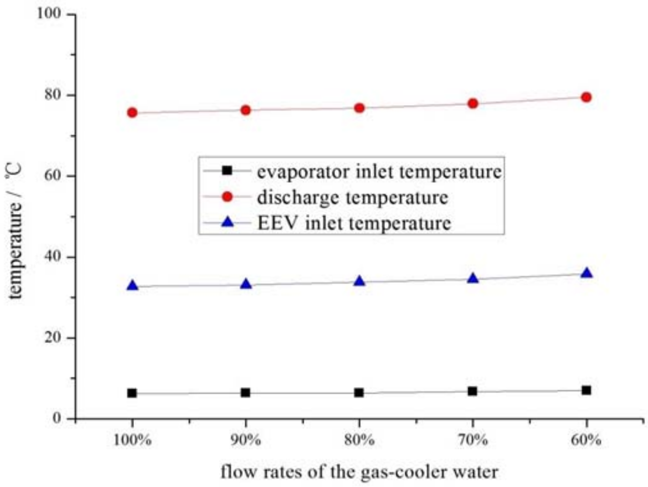

Figure 3: Variations of the temperatures with flow rates of the gas-cooler water

As shown in Fig. 4, the COP decreases dramatically from 1.6 to 1.4 as flow rates of the gas-cooler water decreases from 100% to 60%. Actually, both the compressor power and the cooling capacity decrease with the flow rates of the gas-cooler water. Due to the fact that the decrease of cooling capacity overweighs the decreasing of the compressor power, the COP decreases with the flow rates of the evaporator water.

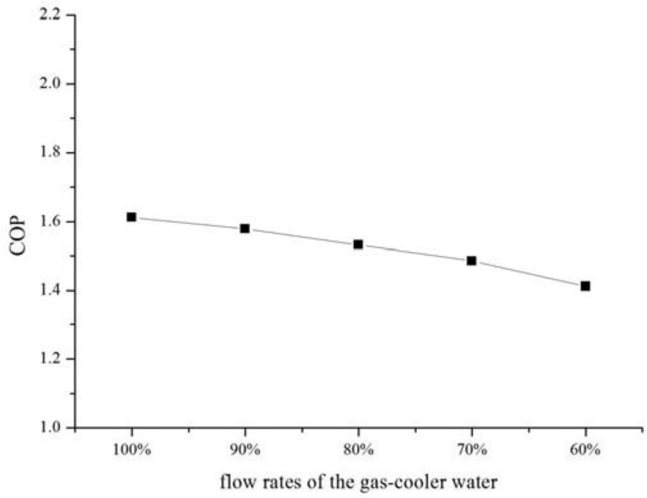

Figure 4: Variations of the COP with flow rates of the gas-cooler water

3.2 The effects of inlet temperature of the gas-cooler water

The effects of inlet temperature of the gas-cooler water on the key pressures in transcritical CO_2 system are illustrated in Fig.5. Both the compressor discharge pressure and compressor suction pressure increase with the inlet temperature of the evaporator water（from 20 ℃ to 40℃）.The compressor discharge pressure increases with the inlet temperature of the gas-cooler water from 8.2 MPa to 10.9 MPa. And the compressor suction pressure is varied from 3.5 MPa to 3.9MPa. This is because the pressure and temperature of the evaporation are coupled, and the evaporating temperature not only depends on heat transfer conditions in the evaporator but also on the heat transfer conditions in the evaporator.

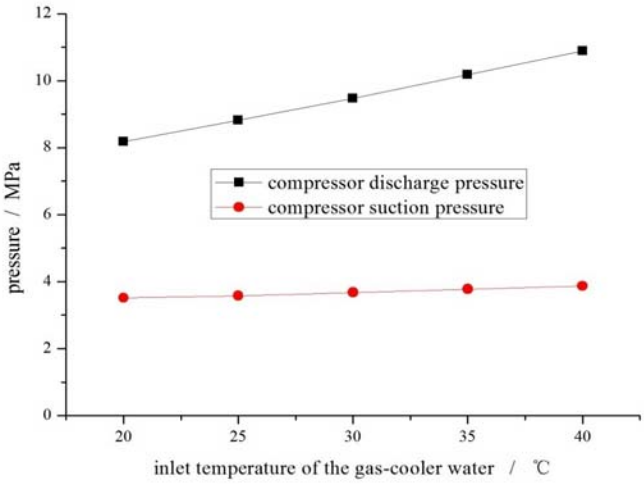

Figure 5: Variations of the pressures with inlet temperature of the gas-cooler water

The variations of the system key temperatures caused by the inlet temperature of the gas-cooler water (from 20℃ to 40℃) are shown in Fig. 6. The increase of inlet temperature of gas-cooler water leads to the increase of the discharge temperature of the compressor, the evaporating temperature and gas-cooler outlet temperature. It is clearly seen from Fig. 6, the discharge temperature of the compressor increases from 65.4 ℃ to 85.7 ℃ with the inlet temperature of the gas-cooler water increasing from 20℃ to 40℃. In the meantime, the evaporating temperature and the gas-cooler outlet temperature increase from 4.5 ℃ to 8.1 ℃ and from 25.0 ℃ to 40.5 ℃, respectively. The evaporating temperature variation imply that the evaporating temperature not only depend on heat transfer conditions in the evaporator but also on the heat transfer conditions in the gas-cooler.

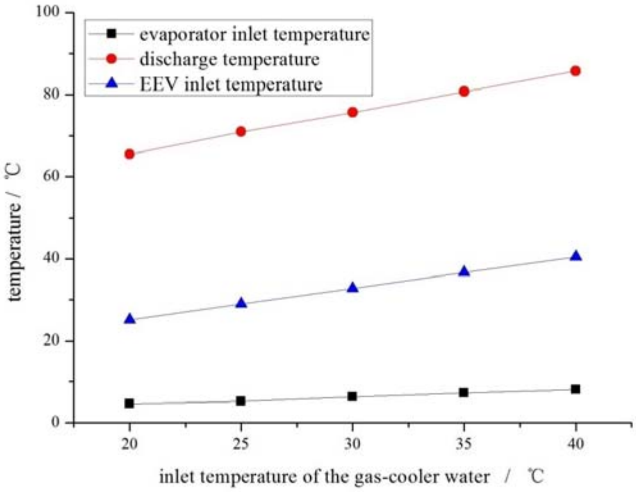

Figure 6: Variations of the temperatures with inlet temperature of the gas-cooler water

As shown in Fig. 7, the COP decreases dramatically from 2.1 to 1.1 as inlet temperature of the gas-cooler water increases from 20℃ to 40℃. This is because that the compressor power and the cooling capacity decreases with the flow rates of the gas-cooler water and the decrease of cooling capacity overweighs the decreasing of the compressor power.

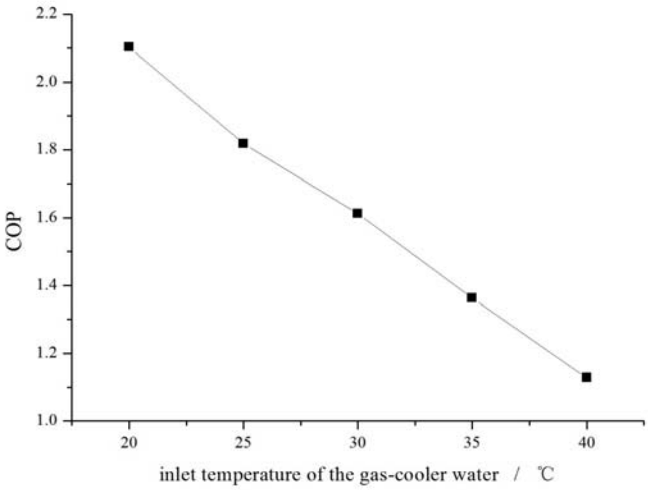

Figure 7: Variations of the pressures with inlet temperature of the gas-cooler water

3.3 The effects of flow rates of the evaporator water

The effects of flow rates of the evaporator water on the key pressures in transcritical CO_2 system are illustrated in Fig.8. Both the compressor discharge pressure and compressor suction pressure decrease with the flow rates of the evaporator water（from 100% to 50%）.Within the working pressure range of 8.9 MPa to 9.5 MPa, the compressor discharge pressure decreases with the flow rates of the evaporator water. When changed from 100% to 50%, the flow rate of the evaporator water has similar effect on the compressor suction pressure, which is varied from 3.3 MPa to 3.7MPa. This is because the pressure and temperature of the evaporation are coupled, and the compressor suction temperature depends strongly on the heat transfer conditions in the evaporator. As the flow rates of the evaporator water decrease, the temperature and the pressure in evaporator decrease. Thus, the compressor suction pressure and the compressor discharge pressure decrease.

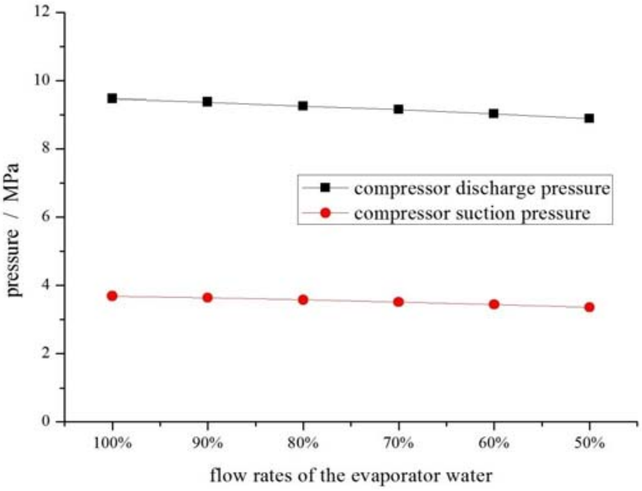

Figure 8: Variations of the pressures with flow rates of the evaporator water

The variations of the system key temperatures caused by the decrease of flow rates of the evaporator water (from 100% to 50%) are shown in Fig. 9. The decrease of flow rate of evaporator water leads to the decrease of the discharge pressure and the discharge temperature of the compressor. It is clearly seen from Fig. 9, the discharge temperature of the compressor decreases from 75.7 ℃ to 71.6 ℃ with the flow rate decreasing from 100% to 50%. In the meantime, the evaporating temperature decrease from 6.3℃ to 2.7 ℃. When changed from 100% to 50%, the flow rates of the evaporator water has little effect on the gas-cooler outlet temperature, which is varied from 32.7 ℃to 32.6 ℃ This is due to the counter flow heat exchange between water and CO_2 in gas-cooler, the CO_2 outlet temperatures are influenced by the gas-cooler water inlet temperatures and water mass flow rates. In our tests, the gas-cooler water inlet temperature and water mass flow rate remain unchanged. And when the flow rates of the evaporator water changed, the gas-cooler outlet temperature remains unchanged.

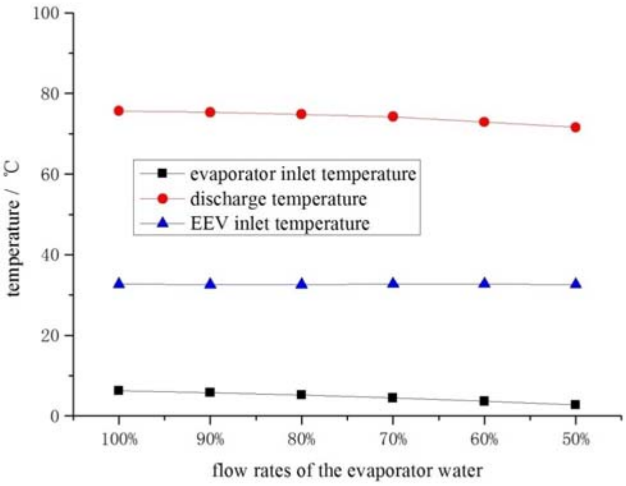

Figure 9: Variations of the temperatures with flow rates of the evaporator water

As shown in Fig. 10, the COP decreases from 1.6 to 1.4 as flow rates of the evaporator water decreases from 100% to 50%. Actually, both the compressor power and the cooling capacity decreases with the flow rates of the evaporator water. Due to the fact that the decrease of cooling capacity overweighs the decreasing of the compressor power, the COP decreases with the flow rates of the evaporator water.

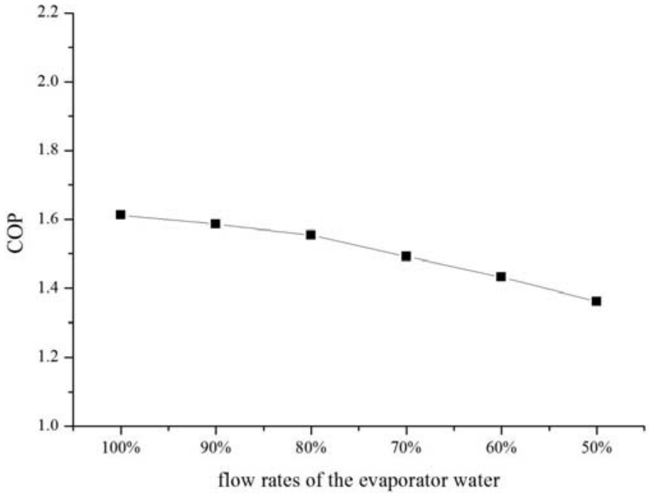

Figure 10: Variations of the COP with flow rates of the evaporator water

3.4 The effects of inlet temperature of the evaporator water

The effects of inlet temperature of the evaporator water on the key pressure in transcritical CO_2 system are illustrated in Fig.11. Both the compressor discharge pressure and compressor suction pressure increase with the inlet temperature of the evaporator water（from 9 ℃ to 24℃）.Within the working pressure range of 9.1 MPa to 10.6 MPa, the compressor discharge pressure increases with the inlet temperature of the evaporator water. When the inlet temperature of the evaporator water changed from 9℃ to 24℃, the compressor suction is varied from 3.3 MPa to 4.2 MPa. This is because the pressure and temperature of the evaporation are coupled, and the compressor suction temperature depends strongly on the heat transfer conditions in the evaporator. As the inlet temperature of the evaporator water increase, the temperature and the pressure in evaporator increase. Thus, the compressor suction pressure and the compressor discharge pressure increase.

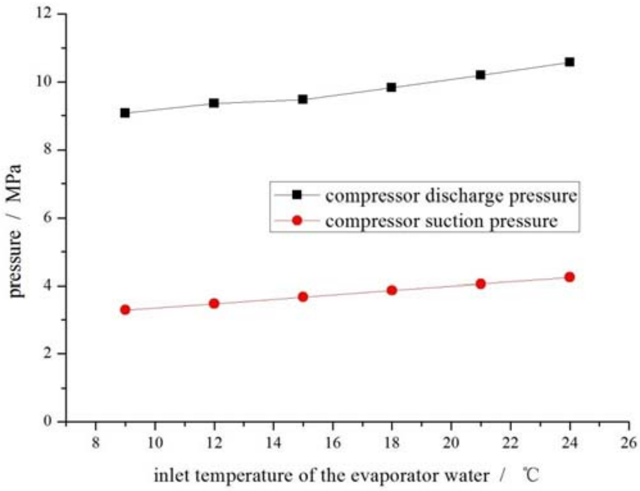

Figure 11: Variations of the pressures with inlet temperature of the evaporator water

The variations of the system key temperatures caused by the increase of inlet temperature of the evaporator water (from 9℃ to 24℃) are shown in Fig. 12. The increase of inlet temperature of evaporator water leads to the increase of the discharge pressure and the discharge temperature of the compressor. It is clearly seen from Fig. 12, the discharge temperature of the compressor increases from 76.7 ℃ to 82.0 ℃ with the inlet temperature increasing from 9℃ to 24℃. In the meantime, the evaporating temperature decrease from 2.1 ℃ to 11.9 ℃.When changed from 9℃ to 24℃, the inlet of the evaporator water has little effect on the gas-cooler outlet temperature, which is varied from 32.6℃to 32.6 ℃.This is due to the counter flow heat exchange between water and CO_2 in gas-cooler, the CO_2 outlet temperatures are influenced by the gas-cooler water inlet temperatures and water mass flow rates. In our tests, the gas-cooler water inlet temperature and water mass flow rate remain unchanged. And when the flow rates of the evaporator water changed, the gas-cooler outlet temperature remains unchanged.

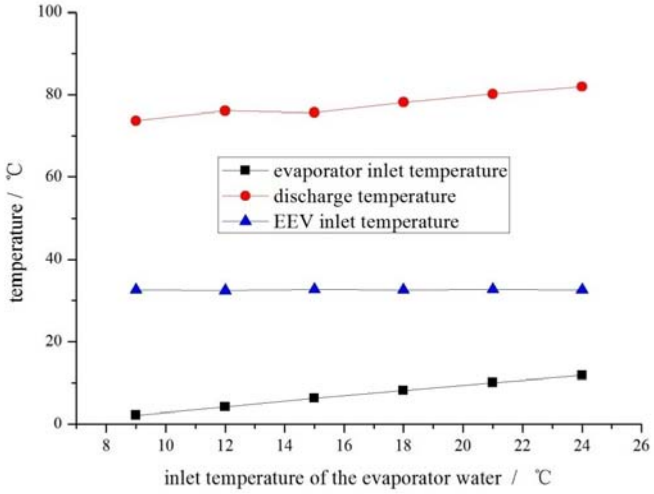

Figure 12: Variations of the temperatures with inlet temperature of the evaporator water

As shown in Fig. 13, the COP increases dramatically from 1.3 to 1.9 as inlet temperature of the evaporator water increases from 9℃ to 24℃.This is because the compressor power decreases with the inlet temperature of the evaporator water and the cooling capacity increases with the inlet temperature of the evaporator water.

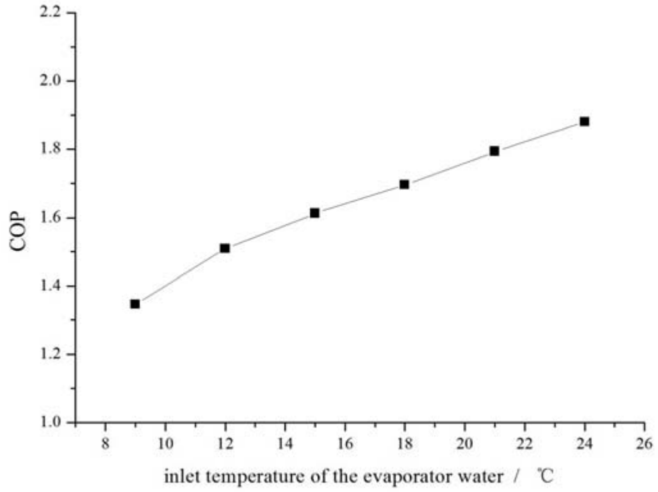

Figure 13: Variations of the COP with inlet temperature of the evaporator water

4. CONCLUSIONS

The effects of flow rates and inlet temperature of the heat exchangers water on the system characteristics of a water-to-water transcritical CO_2 refrigeration system were investigated. The main findings of this study are as follows. (1)The EEV inlet temperature is strongly dependent on the heat transfer condition of the gas-cooler. The heat transfer condition of evaporator has little effect on the EEV inlet temperature. (2)The evaporating pressure and temperature are dependent on heat transfer condition of the gas-cooler. The compressor discharge pressure and temperature relates to both the heat transfer condition of the gas-cooler and evaporator. (3) The effects inlet temperature and flow rates of heat exchangers on the system characteristics are the same as the conventional refrigerants.

REFERENCES

Baek C, Heo J, Jung J, Cho H, Kim Y,2013, Optimal control of the gas-cooler pressure of a CO_2 heat pump using EEV opening and outdoor fan speed in the cooling mode, Int. J. Refrig., vol.36: p. 1276-1284.

Cho H, Ryu C, Kim Y, Kim HY,2005, Effects of refrigerant charge amount on the performance of a transcritical CO_2 heat pump, Int. J. Refrig.,vol. 28:p.1266-1273

Groll E A.,J H Kim. , 2007, Review of recent advances toward transcritical CO_2 cycle technolog. Hvac&R Research, vol. 13(3):p. 499-520.

Kauf F., 1999, Determination of the optimum high pressure for transcritical CO_2 refrigeration cycles, Int. J. Therm. Sci., vol.38: p.325-330.

Kim M-H, Pettersen J, Bullard CW, 2004, Fundamental process and system design issues in CO_2 vapor compression systems, Progress in Energy and Combustion Science,vol. 30:p.119-174.

Lorentzen G, Pettersen J , 1993, A new efficient and environmentally benign system for car air-conditioning, Int. J. Refrig., vol. 16:p. 4–12.

Sarkar J.,2010, Review on Cycle Modifications of Transcritical CO_2 Refrigeration and Heat Pump Systems, Journal of Advanced Research in Mechanical Engineering, vol.1(1):p. 22-29.

Acknowledgement

This project was supported by the National Nature Science Foundation of China (50976082), the Specialized Research Fund for the Doctoral Program of Higher Education (20130201110038) and the Fundamental Research Funds for the Central Universities.