Experimental study on characteristics of transcritical heat pump water heater using refrigerant HFC125

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Abstract: To evaluate the performance of heat pumps using refrigerant HFC125, an experimental rig of a DC-inverter heat pump water heater is designed and set up, and the research on the transcritical heat pump water heater is carried out experimentally. It is found that there is a top value of the coefficient of performance(COP) when the system runs at 95 Hz of frequency. The relationships between the COP and compressor frequency, condensation pressure, evaporation pressure, condensation water temperature rise, and discharge temperature are discussed and analyzed at 95 Hz. And the COP of the HFC125 transcritical cycle is also compared with that of a R410 subcritical heat pump under the same conditions. The results indicate that there exists an optimum frequency for a better COP, and the system COP shows an increasing tendency with the decrease in condensation pressure and compressor ratio while the evaporation pressure remains invariant, and the COP decreases rapidly when cooling water temperature rises over 47.5 ℃. Compared with the R410A subcritical cycle, the COP of HFC125 transcritical cycle significantly increases by 12% on average.

Key words: HFC125; transcritical cycle; heat pump water heater; coefficient of performance(COP)

The heat pump has attracted more and more attention due to its unique advantages in energy saving and environmental protection, which can provide more energy than the driven power. Based on the primary energy consumption and economic analysis, the heat pump system, when its COP is up to 2.0 to 2.5, has almost the same energy efficiency and economy as that of the oil-fired boiler heating system[1]. Therefore, it is of considerable significance for research and development of high efficiency heat pump systems.

Currently, there are many problems with heat pump applications of which the most important one is the narrow temperature range for conventional single stage heat pumps. Therefore, a two or a multistage compressor is necessary to realize a heating supply with a large temperature difference, which will lead to a complex system and the inconvenience in operation and regulation[2]. The transcritical cycle is proposed by choosing CO_2 as a natural refrigerant for its good characteristics. Many researches have focused on a CO_2 transcritical cycle, which is mainly applied to automobile air conditioning and heat pump water heaters[3-4]. It is observed that the temperature variations in condensation can well match those of a water heating process from the experimental study of the CO_2 transcritical cycle, and the experimental results demonstrate that it has a high COP used as a heat pump refrigerant and can work within a large temperature range[5]. As a natural refrigerant, CO_2 has good environmental characteristics. However, due to its high critical pressure and low critical temperature, its thermal performance is not favourable, and its application on heat pumps is restricted for its working pressure over 10 MPa. Up till now, no open literature on other refrigerants except for CO_2 working in a transcritical cycle have been published. It is found that HFC125 seems to be promising in a heat pump cycle through theoretical analysis and experimental study by our team[6-8]. So, this paper focuses on the HFC125 transcritical cycle combined with DC-inverter compressor technology, and gives some recommendations about the characteristics of the critical cycle heat pump water heater, which are of significance for the application of the cycle used in the heat pump system.

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1 Theoretical Analysis

At present, the technology of a subcritical cycle heat pump has been well developed. Generally, a common cycle operates far below a critical point to avoid large throttling loss. For heat pump systems, they have a higher COP when the temperature rise of cooling water is less than 60 ℃. If it is higher than 60 ℃, the COP will decrease. In addition, too large a temperature glide will result in a higher compression ratio, therefore, lower volumetric efficiency, and even more it will do harm to the stability of the refrigerant[9]. In this cycle, there is great irreversible loss in condensation[5].

Compared with the conventional heat pump system, the critical cycle heat pump has little difference except for a high working pressure and counter flow heat transfer in condensation; otherwise, its thermal performance is poorer than that of the traditional one. In theory, the irreversible loss in condensation can be overcome(see Fig. 1). The temperature glide property can be utilized to heat the cooling water to a high temperature. The most important characteristic of the cycle is its evaporation and condensation carried out in subcritical and transcritical areas, respectively. In a critical area, there is a large temperature glide in condensation with the increase in refrigerant density, which can better match a variable temperature heat source. The cycle is considered as a special Lonrenz cycle. At the same time, the smoothly ascending temperature curve on the water side can better match the counter flow in the condenser, which decreases the irreversible loss due to large temperature differences. It is especially suitable for the heating system in which a large temperature rise is demanded.

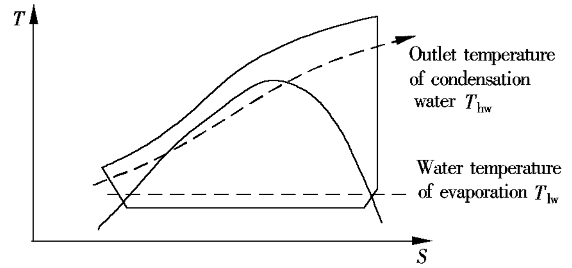

Fig. 1 Scheme of heat pump critical cycle

The present study focuses on the HFC125 transcritical heat pump cycle, which takes advantage of the sensible heat, carried from the exhaust refrigerant of a compressor to saturation point of condensation to achieve a large temperature rise.

2 Experimental Setup

2.1 Test rig

The heat pump works on the principle of the vapour compression cycle. The main components are the DC-inverter compressor, two expansion valves(double-throttling), and two heat exchangers referred to as evaporator and condenser, as well as a reservoir and an inverter. The components are connected to form a closed circuit, as shown in Fig. 2.

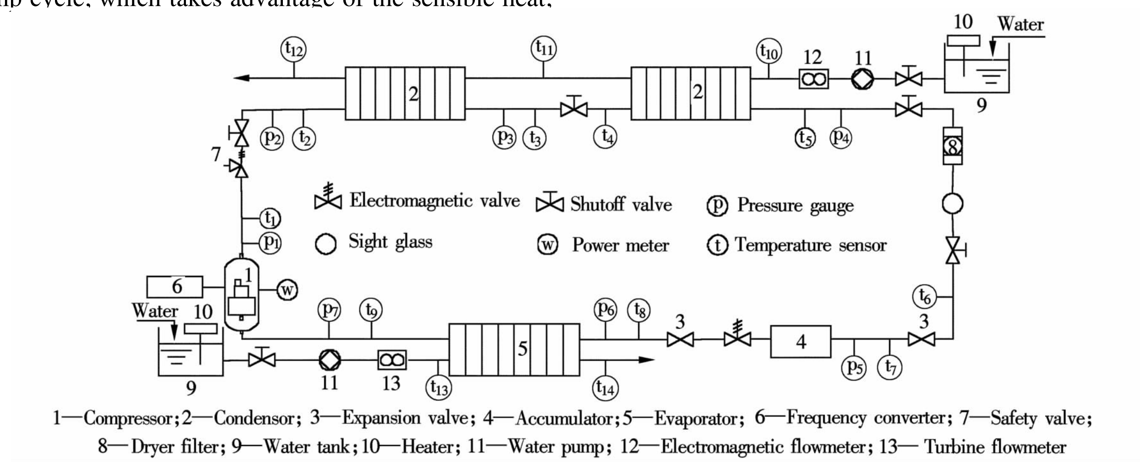

Fig. 2 Schematic diagram of heat pump experimental system

When the system works, after absorbing heat from water and evaporating it in the evaporator, HFC125 is compressed into high pressure and temperature vapour in the compressor, and then flows into the condenser, where HFC125 vapour turns into liquid by cooling water. By two expansion valves, the liquid HFC125 becomes low temperature and pressure liquid-gas mixture, and then, re-enters into the evaporator. Between the two expansion valves, a 5 L high pressure reservoir is installed to guarantee the system's operation under different conditions. In this study, the compressor is a hermetic pendulum DC-inverter compressor for R410A and the condenser is a tube-in-tube counter-flow heat exchanger with four coaxial nested copper tubes and two groups of cascades while the evaporator is a plate heat exchanger. The HFC125 flows inside the inner tube and cooling water flows through the annular space in a counter current. The inner tube is a smooth copper tube with ID 4. 35 mm and OD 6. 35 mm, and the heat transfer length of a single tube is 3 000 mm.

The experimental system is designed for a multi-function heat pump unit. An electric heating water tank is used to simulate bath water for the heat consumer, which is connected with an electromagnetic flow-meter, a pump and valves. Another water tank is applied to simulate chilled water for air conditioning, piping with a turbine flow-meter, a pump and valves. This study is just restricted to heat exchange in a condenser without considering the heat exchange in an evaporator.

To evaluate the performance of the system, the following parameters need to be measured, such as refrigerant temperature and pressure, water temperature, compressor frequency and power input. According to the above requirements, seven test points are set for pressure measurements along the refrigerant flow at the inlet(outlet compressor), middle and outlet of the condenser, the inlet and outlet of the evaporator, the front and back of the two expansion valves. At the same time, nine test points are arranged for temperature along the refrigerant flowing direction at the outlet of the compressor, the inlet, middle and outlet of the second condenser, the outlet of the dryer filter, the outlet of the evaporator and the back of the two expansion valves. Along the water flowing direction, three testing points for temperature are arranged at the inlet, middle and outlet of the second condenser, respectively. At the inlet of the evaporator on the water side, a testing point for the water flow rate is laid at the inlet of the evaporator and two measuring points for temperature are arranged at the inlet and outlet of the evaporator. The determination of the water flow rate is calibrated on an electronic scale. All the testing data are collected by an Angilent data acquisition system. The measurement instruments are given in Tab. 1.

2.2 Experimental methods and procedures

First, with a good seal, the refrigerant HFC125 is filled into the system after vacuum pumping. Then the water level of the water tank is examined. Under the condition of suitable water capacity, the water pump is started and the valve opening is adjusted to make the water flow in the condensers and the evaporator at the setting position. In order to simulate the actual application of a heat pump water heater, the water flow on the evaporator side is kept stable, and that in the condensers side is set to a proper value. It is difficult to control the high side pressure by using a thermostatic expansion valve. To ensure the safe operation of the system, the transcritical cycle can be realized by adjusting the

Tab. 1 Instruments for measurement

Measurement value	Measurement range	Instrument	Specification and type	Instrument accuracy
Pressure/Pa	0 to 6.0×10^6	SETRA pressure sensor	P71200BGB6001A3UAX	0.25%
Temperature/℃	−100 to 200	Resistance temperature sensor	Pt100	0.1 ℃
Volume flowrate of water/($m^3\cdot h^{-1}$)	0.063 6 to 9.54	Electromagnetic flowmeter	JXLDBE-15L-M2F120-2	0.01 m^3/h
Volume flowrate of water/($m^3\cdot h^{-1}$)	0.6 to 4	Turbine flowmeter	LWGY	0.5%
Mass flowrate of water/kg	0 to 100	Electronic scale	TCS-100	10 g
Frequency/Hz	0.1 to 440	Frequency converter	VT230SE-11ha	0.1 Hz
Power/kW	0 to 5	Active power transducer	XPW	0.5%

compressor frequency and the water flow rate, and the maximum pressure is 4.20 MPa. Before the system runs, a certain frequency of the compressor is set and the water flow rate into the condenser is also set. At the same time, the condensation pressure remains stable between 3.62 and 4.20 MPa. When the outlet water temperature is stable, the system is continually tested for 30 min, and the rate of data acquisition is 6 times/min. When a set of experimental results is obtained, another test at different frequencies are carried out by changing the compressor frequency (90, 95, 100, 105, 110, 115 Hz). When six sets of different frequency tests are completed, a new test is carried out by adjusting the water flow into the condenser; at the same time, the water flow on the evaporator side remains constant. Thus, the experiments have been conducted according to the above experimental procedure.

3 Results and Discussion

The data are obtained by testing and calculating under the same inlet water temperature of cooling water (23.2 ℃) and a similar air temperature (the temperature difference is less than 1 ℃). When the compressor runs at high frequency under the low water flow rate, the condensation pressure is too high. For this reason, some test points about low water flow rate do not involve data at high frequency.

Fig. 3 shows the relationship between the COP and compressor frequency at different water flow rates. It can be seen that the system COP has an increasing tendency with the decrease in frequency, and near frequency 95 Hz, there is a peak value. After that, it decreases when the compressor frequency decreases. At the same frequency, the system COP illustrates an increasing trend with the increase in the water flow rate. As is well known, both refrigerant velocity and flow rate increase with compressor frequency. The increase in the flow rate can improve the heat capacity of the system, but the velocity rise will reduce the heat-exchange time between the refrigerant and the cooling water. Then the heat exchange is not enough and the temperature difference is large. For the frequency below 95 Hz, since the positive influences resulting from the refrigerant flow rate increase exceed the negative influences resulting from the refrigerant velocity increase, the COP shows an increasing tendency, and a maximum COP will be obtained at about 95 Hz. But when the frequency is greater than 95 Hz, the condensing pressure obviously decreases with the further increase in frequency, and the compressor power consumption used to overcome friction and the compressor heat loss resulting from exhaust temperature rise will increase greatly. Therefore, the COP decreases. At the same frequency, the condensing pressure of the refrigerant will decrease with the cooling water flow rate, which will lead to a decrease in compressor output, and as a result, the system COP shows a tendency to increase.

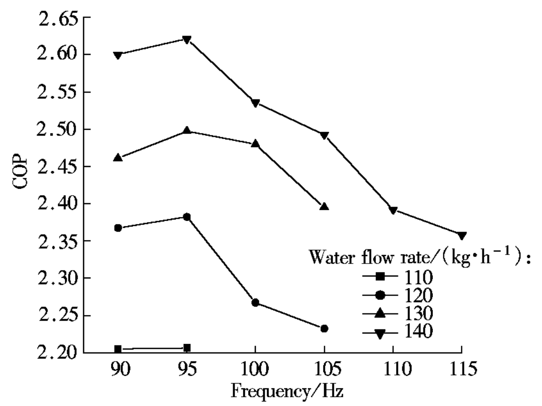

Fig. 3 Relationships between COP and compression frequency

Fig. 4 shows the relationships between the system COP and condensation pressure, evaporation pressure and compression ratio. It can be seen that the system COP has a decreasing tendency with the increase in condensation. When

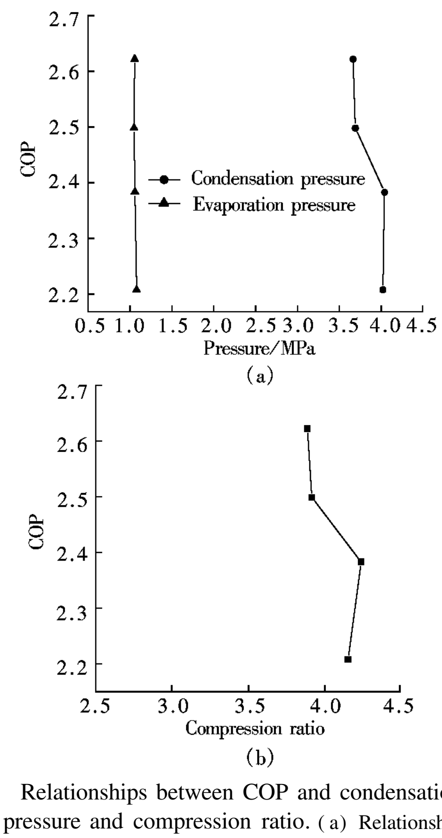

Fig. 4 Relationships between COP and condensation/evaporation pressure and compression ratio. (a) Relationship between COP and condensation/evaporation pressure; (b) Relationship between COP and compression ratio

condensation pressure increases over 4. 02 MPa, minor variations of pressure will affect the COP significantly. The relationship between the COP and compression ratios is the same as that between the COP and condensation pressure under the constant evaporation pressure. At the same time, it is observed that the condensation pressure varies significantly with the flow rate of cooling water when the system runs at some frequency under the transcritical condition, and even more, the condensation pressure is beyond the designed safe pressure, which makes it impossible to carry out the experiments at some frequencies (such as 100, 105, 110, 115 Hz at a water flow rate of 110 kg/h). Meanwhile, the evaporation pressure varies slightly.

Fig. 5 shows the relationship between the system COP and the discharge temperature for compressor and the temperature rise of cooling water. It can be seen that the COP varying with the two parameters is almost the same; i. e. , the COP increases when the discharge temperature and the temperature rise of cooling water decrease. It can be explained that the heat transfer temperature difference between refrigerant and water decreases with the decrease in the discharge temperature and the temperature rise of the cooling water. The loss owing to the temperature differences decreases correspondingly, and at the same time, the decrease in the discharge temperature will reduce the system heat loss. So the system COP generally shows an increasing tendency. From Fig. 5, it can also be observed that the descending rate of the COP with the increase in condensation water temperature is different. Between temperatures 40. 9 and 42. 8 ℃, the COP decreases by 0. 07 when the cooling water temperature increases by 1 ℃. Between 42. 8 and 47. 5 ℃, the value is 0. 02, and between 47. 5 and 48. 6 ℃, the value is up to 0. 16. From the above, it can be deduced that there exists an optimum temperature rise of cooling water which is near 47. 5 ℃ for this study. It is observed that the discharge temperature is less than 90 ℃, and the temperature difference between refrigerant and water is about 14 ℃, which shows a better matching of heat transfer.

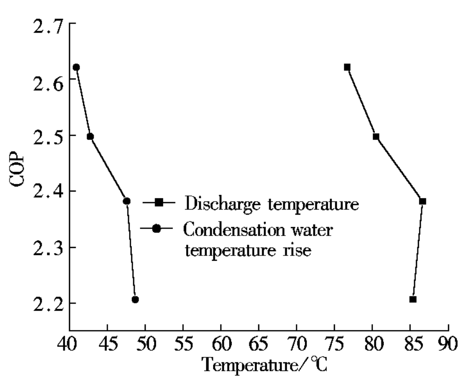

Fig. 5 Relationship between COP and discharge temperature and condensation water temperature rise

Under the same condition, a 140 kg/h flow rate of cooling water and the same heat source at the evaporation side, the system COP of the HFC125 transcritical cycle in comparison with the R410A subcritical cycle is shown in Fig. 6. It can be observed that the system COP tendencies of the two refrigerants with the compressor frequency almost show the same characteristics under the same conditions. However, compared with that of the R410A subcritical cycle, the COP of the HFC125 transcritical cycle significantly increases by an average of 12%, the maximum COP is up to 2. 62. It is also found that the discharge temperature of the R410A subcritical cycle is more than that of the HFC125 transcritical cycle by 10 ℃, and moreover, the vibration of the former is severe in operation. From the above, it can be concluded that the transcritical cycle using HFC125 is superior to that of the R410A.

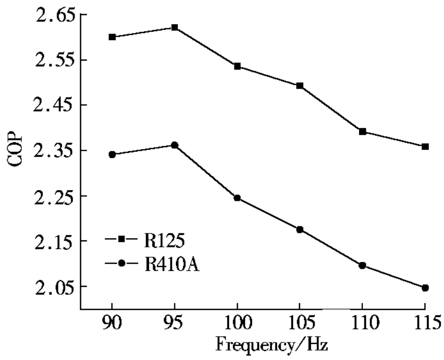

Fig. 6 Comparison of COP of HFC125 transcritical cycle with R410A subcritical cycle

4 Conclusions

In this paper, an experimental study on the characteristics of a transcritical heat pump water heater is carried out with refrigerant HFC125 to analyze the relationships between the COP and the compressor frequency, the compression ratio, the condensation pressure, the evaporation pressure and the discharge temperature. Finally, the system COP of the HFC125 transcritical cycle is compared with that of the R410A subcritical cycle, and the following conclusions can be obtained.

1) There is an optimum frequency when the compressor runs at 95 Hz.

2) It is found that there is an optimum cooling water temperature rise which is near 47. 5 ℃ in this study, and at the same time, the system shows a better match of heat transfer. When the compressor runs, the discharge temperature is less than 90 ℃, which is in a safe range.

3) Compared with the R410A subcritical cycle, the COP of the HFC125 transcritical cycle significantly increases by an average of 12%.

References

[1] Zhou Xiangjiang, Lian Zhiwei, Ye Xiangjiang, et al. Feasibility analysis of high temperature heat pump using in China [J]. *Fluid Machinery*, 2003, **31**(7): 55 − 58. (in Chinese)

[2] Khan Jameel-Ur-Rehman, Zubair Syed M. Design and rating of a two-stage vapor compression refrigeration system[J]. *Energy*, 1998, **23**(10): 867 − 878.

[3] White S D, Yarrall M G, Cleland D J, et al. Modeling the performance of a transcritical CO_2 heat pump for high temperature heating[J]. *International Journal of Refrigeration*, 2002, **25**(4): 479 − 486.

[4] Ma Y T, Wang J G, Lü C R, et al. Characteristic study of supercritical fluids and supercritical cycles[J]. *HV&AC*, 2002, **32**(1): 101 − 104. (in Chinese)

[5] Nekså P, Rekstad H, Zakeri G R, et al. CO_2-heat pump water heater: characteristics, system design and experimental results[J]. *International Journal of Refrigeration*, 1998, **21**(3): 172 − 179.

[6] Zhou Xiangjiang, Lian Zhiwei, Yao Ye. The optimal temperature difference of the high temperature heat pump system [J]. *Acta Energiae Solaris Sinica*, 2004, **25**(3): 394 − 398. (in Chinese)

[7] Zhou Xiangjiang, Lian Zhiwei, Yao Ye. An ideal cycle of transcritical heat pump[C]//*Proceedings of the 4th International Symposium on Heat, Ventilating and Air Conditioning*. Beijing, China, 2003: 905 − 909.

[8] Zhou Xiangjiang, Lian Zhiwei, Li Zhihua, et al. Experimental study on HFC125 critical heat pump[J]. *Applied Thermal Engineering*, 2007, **27**(5/6): 988 − 993.

[9] Chen D, Lü C R, Ma Y T, et al. Estimation of the basic properties of new stratospherically safe working fluids and study of geothermal heat pump fluids[J]. *Journal of Engineering Thermophysics*, 1997, **18**(4): 401 − 404. (in Chinese)

HFC125 跨临界热泵热水器性能实验研究

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摘要:为深入了解 HFC125 跨临界循环热泵热水器的运行特性,设计和建造了一个直流变频热泵热水器实验装置,对 HFC125 跨临界循环热泵热水器性能进行了实验研究,发现压缩机运行在 95 Hz 时系统存在一个 COP 峰值. 然后以 95 Hz 为例,研究了系统 COP 与压缩机频率、冷凝压力、蒸发压力、冷却水温升、压缩机排气温度等参数的关系,并与 R410A 亚临界循环系统性能进行了比较. 结果表明:系统存在一最优频率,此时系统有较好的 COP 值,系统 COP 随冷凝压力和压比的降低呈上升趋势,而蒸发压力基本恒定;当冷却水温升超过 47.5 ℃时,COP 迅速下降. 相对 R410A 亚临界循环,HFC125 跨临界循环系统 COP 显著提升,提高幅度平均在 12% 以上.

关键词:HFC125;跨临界循环;热泵热水器;COP

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