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The influence of different water-injection methods on water vapor high temperature heat pump

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Abstract

To yield higher temperature output and better performance, a high temperature heat pump with water refrigerant is developed and the corresponding prototype is established. Water-injection is adopted to reduce the discharge superheat. The theoretical results show that compared with HFO and HC refrigerants and traditional HFC refrigerant, water has better performance when the condensation temperature is above 100°C. With the increase of the condensation temperature, the simulation performance of water vapor heat pump is better, which means water is more suitable for higher temperature application fields. Based on the experimental investigation, the system performance with different injection lines and ports are compared. Its start-up and dynamic performance present that this heat pump reaches steady-state in 10 minutes and water-injection can effectively decrease the discharge temperature. The internal injection line can realize the self-adjustment of injected-water and discharge temperature. The coefficient of performance of this heat pump with internal water-injection is better than that of external.

Keywords: Water refrigerant; High temperature heat pump; COP; Internal water-injection;

1. Introduction

Global warming has always been a major environmental issue of concern to the whole world, which has brought a huge and disastrous impact on global biodiversity and the stability of the ecological environment. In order to curb global warming, effective methods must be adopted to reduce the consumption of fossil fuels and the emission of greenhouse gases. Heat pumps are an energy-saving technology with significant potential for industrial applications. Especially, vapor compression heat pumps are the most widely used and are available in a wide variety of sizes for different applications [1].

As shown in Fig. 1, the heat pumps can be classified as low-temperature heat pumps (LTHPs), medium-temperature heat pumps (MTHPs), high-temperature heat pumps (HTHPs), and ultra-high-temperature heat pumps (UHTHPs). In this classification, the different kinds of heat pumps are strictly defined by the output temperature and loosely defined by the heat source temperature. Based on the above classification, the vapor compression heat pump with output temperature ranging from 100℃ to 160℃ is regarded as the HTHP. Many researchers are studying the HTHP with different working fluids, including natural refrigerants [2, 3], HCs [4, 5] and HFOs [6, 7]. Bamigbetan O et al. [8, 9] experimentally investigated an R600 HTHP with a prototype compressor for industrial waste heat recovery from 50℃ to heat delivery at 115℃. Kondou C et al. [10] designed different cycle configurations with R1234ze(Z) refrigerant to supply the output temperature of 160℃ as the waste heat was 80℃. Arpagaus C et al. [11] examined the experimental performance of R1336mzz(Z) in a laboratory single-stage HTHP with 5~10 kW heating capacity using a variable speed piston compressor. When the heat source is 60℃ and output is 110℃, the coefficient of performance (COP) of this R1336mzz(Z) heat pump with an internal heat exchanger is 3.0 with a 24% increment compared with

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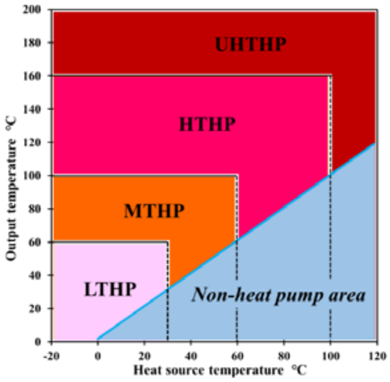

Fig. 1. The classification of vapor compression heat pump

it. By comparing with other HFO and HCFO refrigerants theoretically, they also found that R1336mzz(Z) achieves the highest COP in the temperature range from 120°C to 10°C [12]. Wu D et al. [13, 14] presented a novel water vapor HTHP system with 80~90°C waste heat recovery and above 100°C hot water supply. When the evaporation temperature was 85°C, the COP decreased from 6.10 to 1.96 with condensation temperature increasing from 110°C to 150°C.

In this work, based on the existing experimental investigation on water vapor HTHP, preliminary experimental investigation of the water vapor HTHP system performance with different injection lines and injection ports is carried out to find the effect of different injection methods on the heat pump performance.

2. Working fluid

Nowadays, the selection principle of refrigerant takes ozone depletion potential (ODP) and global warming potential (GWP) into consideration and considers them as the main indexes on environmental protection, which limits that ODP is 0 and GWP is below 150 [15]. In Table.1, five kinds of refrigerants (GWP<150)-R718, R600, R601, R1234ze(Z) and R1336mzz(Z)-are chosen to be used in HTHP systems as working fluids. A high GWP HFC refrigerant, R245fa, is added as the representative of traditional HTHP refrigerants.

Table.1 The properties of HTHP refrigerants [1, 16]

Refrigerant	Chemical formula	T_{crit} /°C	P_{crit} /bar	ODP	GWP	SG	NBP/°C
R718	H_2O	373.9	220.6	0	0	A1	100.0
R600	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	20	A3	-0.5
R601	$CH_3CH_2CH_2CH_2CH_3$	196.6	33.7	0	20	A3	36.1
R1234ze(Z)	$CHF{=}CHCF_3$	150.1	35.3	0	1	A2	9.8
R1336mzz(Z)	$CF_3CH{=}CHCF_3$	171.3	29.0	0	2	A1	33.4
R245fa	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	14.9

The theoretical performance of HTHPs with these selected refrigerants are calculated in an idealized single-stage heat pump cycle with the following assumptions: (1). the condensation and evaporation processes are isobaric; (2). the expansion process is isenthalpic; (3). the suction temperature of the compressor has 20°C superheat for R601 and R1336mzz(Z) and has 5°C superheat for the left refrigerants; (4). compression process with a constant isentropic efficiency of 0.7; (5). the condensation temperature increases from 100°C to the critical temperature with a constant 40°C temperature lift.

The calculation results and comparison at 40°C temperature differences are illustrated in the following pictures, including the COP (Fig. 2), the compression ratio (Fig. 3) and the volumetric heating capacity (Fig. 4).

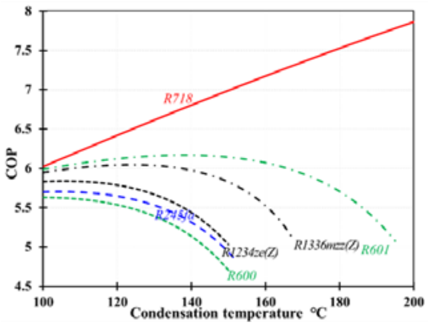

Fig. 2. The COP of the HTHPs with selected refrigerants

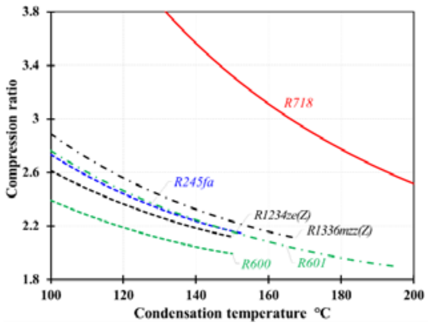

Fig. 3. The compression ratio of the HTHPs with selected refrigerants

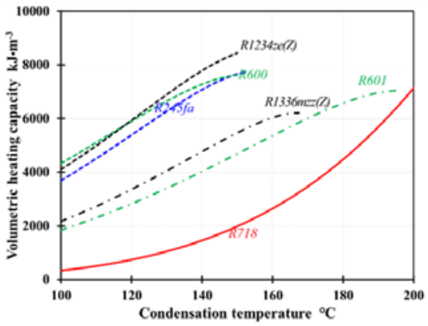

Fig. 4. The volumetric heating capacity of the HTHPs with selected refrigerants

Based on the above table and calculation results, compared with the other five refrigerants, water has many advantages in HTHP applications, especially in ultra-high-temperature output fields. Water has the highest critical temperature, the best environmental protection performance, and the safest property. The calculation COP, shown in Fig.2, also presented that water has the best theoretical performance when the condensation temperature is above 100℃. However, Fig.3 and 4 also illustrated the disadvantages of water refrigerant in heat pump systems. Compared with the other kind of refrigerants, water has the biggest compression ratio and the smallest volumetric heating capacity in the simulation conditions. So the application of water in the HTHP field needs an appropriate compressor with a bigger compression ratio to satisfy high temperature lift and a bigger volume flow rate to overcome its small volumetric heating capacity.

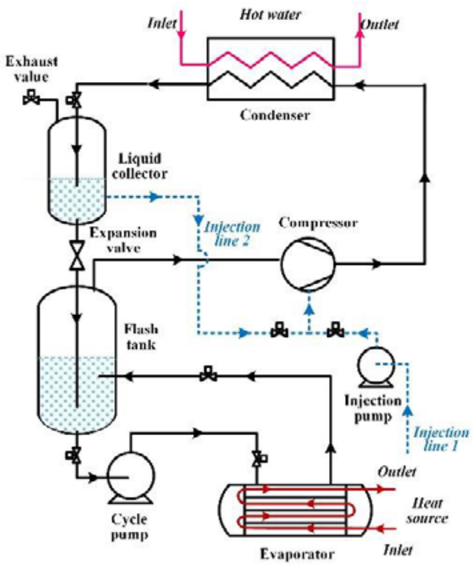

Fig. 5. The schematic diagram of the R718 HTHP with two injection lines

Furthermore, the big compression ratio of water will also lead greatly high discharge superheat and temperature in the heat pump system. So the discharge superheat and temperature must be lowed to promise the safety application of water in HTHP systems. What's more, with the increasing of the condensation temperature, the simulation COP and volumetric heating capacity of water vapor HTHP increases and the compression ratio of the heat pump decreases, which means water vapor HTHP has better performance in higher temperature application fields.

3. Water vapor HTHP

As shown in Fig.5, the schematic diagram of the water vapor HTHP has two different injection lines: external injection line (injection line 1) and the internal injection line (injection line 2). The external injection line is used to inject water from the outside with constant pressure and low temperature, and the internal injection line is used to inject condensed water from the liquid collector with various pressure and high temperature. There are also two injection ports in the water vapor HTHP prototype: the suction side injection port and the compression chamber injection port. These different injection lines and ports may have different effects on the performance of the water vapor HTHP.

4. Experimental results

Based on the schematic diagram of the water vapor HTHP, a prototype of this heat pump with two different injection lines and two different injection ports were set up. Experimental investigations were carried out to study the performance of the water vapor HTHP, including the start-up and dynamic performance, the influence of different injection ports and the injection lines.

4.1. Start-up and dynamic performance

As shown in Fig. 6(a), (b), and (c), the start-up and dynamic performance of the water vapor HTHP is presented with internal water injection in the compression chamber. With the rotate speed increasing from 0 to 5000 rpm in 8 minutes, the system reached steady-state in 10 minutes as the evaporation pressure was uncharged near 0.4 bar and other working properties were steady. In the start-up process, with the increase of the rotate speed, more water vapor was suctioned from the evaporator and the evaporation pressure decreased directly. At first, the condensation pressure increased and then decreased with the increase of the rotate speed, which is mainly due to the accumulation of the discharge steam and the flow rate of the condensation water. With the increase of the rotate speed, the discharge temperature and superheat temperature increased rapidly as the rotate speed was above 2400 rpm. In order to control the discharge temperature in the start-up process, the injected-water was injected into the compressor with a much higher flow rate when the rotate speed was 2400 rpm. After the rotate speed reaching the highest value, 5000 rpm, the flow rate of the injected-water was adjusted to control the discharge temperature near the saturation temperature.

After the start-up process, by adjusting the opening of the expansion valve to control the condensation temperature, the dynamic performance of the water vapor HTHP was illustrated as the rotate speed and the evaporation pressure were invariant. With the increase of the condensation temperature, more power consumption was demanded to protect the larger compression ratio and enthalpy lift in the compression process. Larger compression ratio and enthalpy lift mean higher discharge temperature and more injected-water, so the flow rate of the injected-water also increased. However, the flow rate of the injected-water is not only controlled by the opening of the injection valve but also adjusted by the pressure of liquid collector. As shown in Fig. 6(c), when the opening of the injection valve is fixed, with the increasing of the condensation pressure, the flow rate of injected-water also increased to control the discharge temperature. When the pressure adjustment of the injected-water was failure and the discharge temperature was higher than the saturation temperature, the opening of injection valve will permit more injected-water to control the discharge temperature.

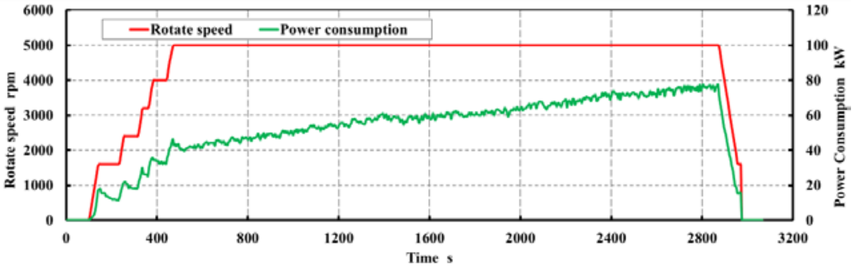

Fig. 6(a). The start-up and dynamic performance of rotate speed and power consumption

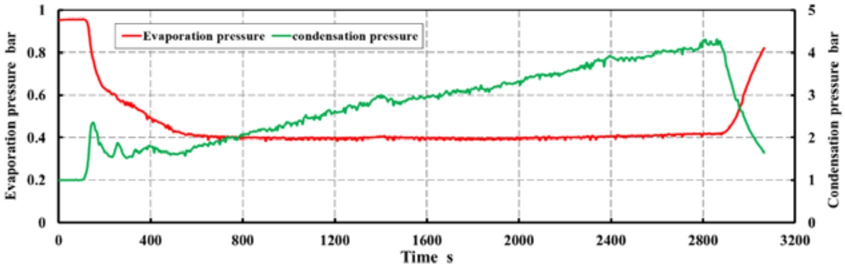

Fig. 6(b). The start-up and dynamic performance of evaporation and condensation pressure

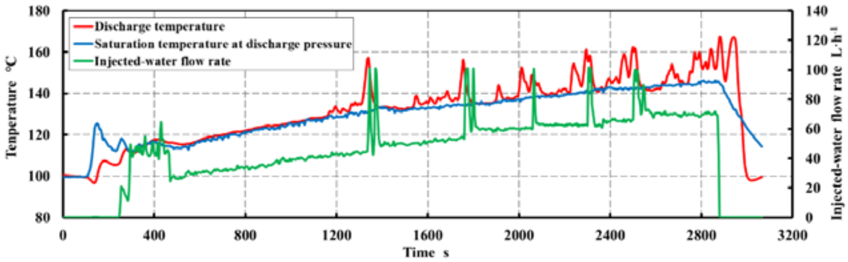

Fig. 6(c). The start-up and dynamic performance of discharge temperature and injected-water flow rate

4.2. The influence of injection ports

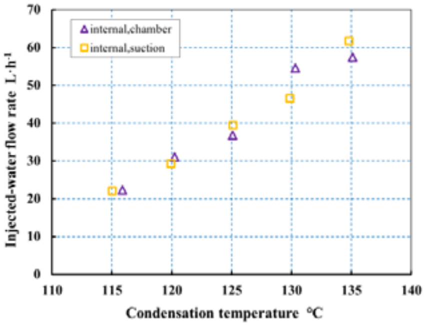

Fig. 7(a) Injected-water flow rate comparison

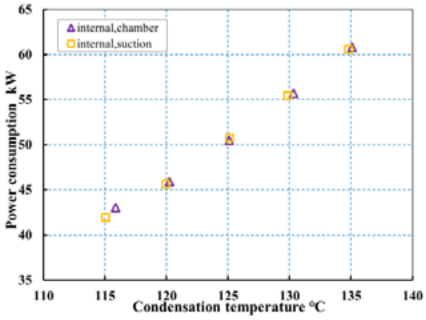

Fig. 7(b) Power consumption comparison

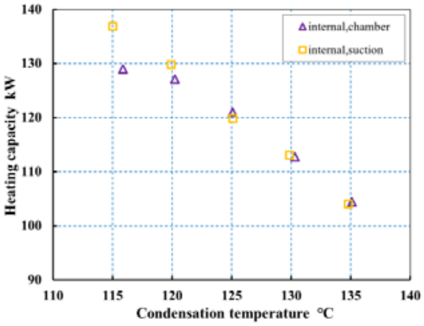

Fig. 7(c) Heating capacity comparison

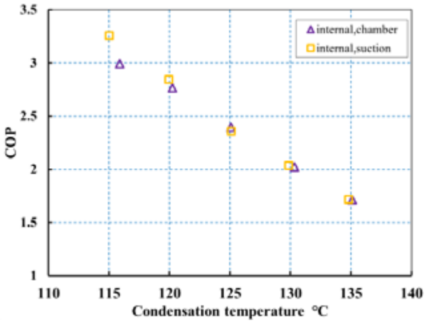

Fig. 7(d) COP comparison

Fig. 7. The performance comparison of the water vapor HTHP with different injection ports

There are two different injection ports designed in the water vapor HTHP. One is in the compressor chamber with water directly injected into the compression process to lower the discharge temperature. The other is in the suction side with water injected into the suction side of the compressor and then mixed with water vapor and suctioned into the compression chamber. When the water is injected into the system, different injection ports may have different effects on the system performance, especially on the control of the discharge temperature. When the water is injected into the compressor chamber, it can directly absorb the superheat of the compressed water vapor and lower the temperature timely. However, when the water is injected into the suction side, it can separate and mix uniformly with the water vapor, which is better for absorbing heat in the compression process. The control of the discharge temperature has a delay as the water is injected into the suction side.

To compare the influence of different injection ports, an experimental investigation is carried out with internal water injection at 73°C evaporation temperature. The result comparison is shown in Fig. 7(a) to (d), including the injected-water flow rate, power consumption, heating capacity, and COP. The result presented that the difference in system performance with different injection ports is not obvious and the injection ports have little influence on the system performance. This may due to that the compression process is faster than the heat transfer in the compression chamber, and most of the injected-water has not evaporated into steam when it was discharged from the compressor. So the separate and fogging degree of the injected-water has little influence, and the flow rate of the injected-water plays the most important role. However, more experimental investigations are needed to prove the results.

4.3. The influence of injection channels

To provide the steady of the injected water and keep the mass conversation of the water in the system, two injection lines are designed in the water vapor HTHP, external water injection from the outside and internal water injection from the liquid collector. When the injected-water is from the outside, the temperature, pressure

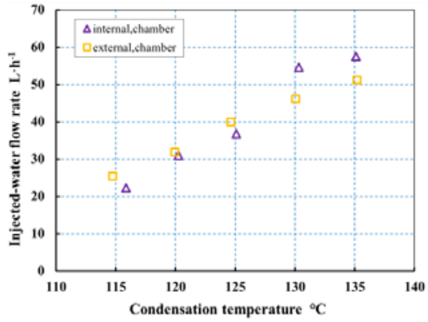

Fig. 8(a) Injected-water flow rate comparison

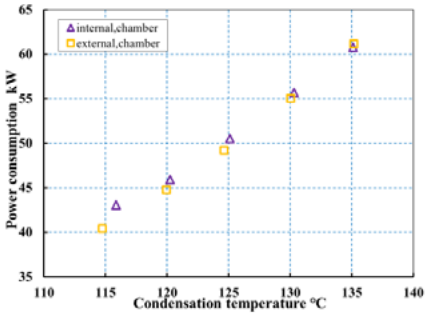

Fig. 8(b) Power consumption comparison

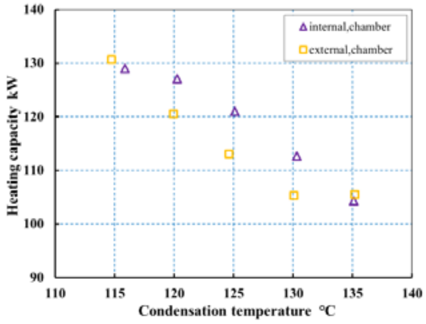

Fig. 8(c) Heating capacity comparison

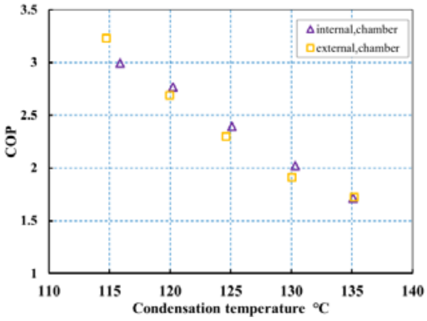

Fig. 8(d) COP comparison

Fig. 8. The performance comparison of the water vapor HTHP with different injection channels

and flow rate of the injected-water are controlled easily, which is good for the steady operation of the heat pump. However, external water injection will lead to an increase in the working fluid in the system, and destroy the balance of long-time operation. In this experimental investigation, to keep the balance of the water refrigerant in the system with the external water injection, some water will be discharged from the liquid collector. When the injected-water is from the liquid collector, the system working fluid is conversation and the flow rate of injected-water will increase simultaneously with the increase of the condensation temperature. It can realize the self-adjustment of injected-water and discharge temperature of the system. However, the temperature and pressure of the injected-water are changed with the condensation temperature.

The experimental investigation is carried out with different injection channel at 73℃ evaporation temperature. The result comparison is shown in Fig. 8(a) to (d), including the injected-water flow rate, power consumption, heating capacity, and COP. The result presented that the difference of injected-water flow rate and power consumption with different injection lines is not obvious. However, the heating capacity and COP of the two injection line systems are different. The internal injection system has better heating capacity and COP, which may due to the higher temperature of the injected-water.

5. Conclusions

Water vapor HTHP is a significant vapor compression heat pump with a high output temperature. The theoretical simulation results show that compared with new HFO and HC refrigerant and traditional HFC refrigerant, R718 has better performance when the condensation temperature is above 100oC. What's more, with the increasing of the condensation temperature, the simulation COP and volumetric heating capacity of water vapor HTHP increases and the compression ratio of the heat pump decreases, which means water vapor HTHP is more suitable for higher temperature application fields. Its start-up and dynamic performance present that this heat pump can reach steady-state in 10 minutes and water injection can effectively decrease the discharge temperature. The internal injection line can realize the self-adjustment of injected-water and discharge temperature. When the opening of the injection valve is fixed, with the increasing of the condensation pressure, the flow rate of injected-water also increased to control the discharge temperature. When the pressure adjustment of the injected-water was failure and the discharge temperature was higher than the saturation temperature, the opening of the injection valve will permit more injected-water to control the discharge temperature. Different injection ports have little influence on heat pump performance. However, the different injection channels have influence on the heat pump performance, especially on the heating capacity. So it is very significant to design a suitable water vapor heat pump cycle with the best injection method.

6. Copyright

Acknowledgments

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