State of the Art of Air-source Heat Pump for Cold Regions

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Abstract: In this paper, research on air source heat pump systems for cold regions in recent years is first summarized and compared. These systems can be divided into three kinds: a single-stage compression heat pump, liquid/vapor injection heat pump, and a two-stage heat pump. Finally, our research with a two-stage compression variable frequency air source heat pump is presented. A two-control-model with the priority target as *COP* or heating capacity is advanced. The experimental results show that the *COP* of this heat pump system is over 2, the compressor discharge temperature under 120 , and the heating capacity can meet the heating load needed when the condensing temperature is 50 and outdoor air temperature is over -18 .

Key words: air source heat pump; cold region; review; two-stage compression; variable frequency

1. INTRODUCTION

More and more heat pump systems have been used as the cold source and heat source of air conditioning systems due to their higher efficiency, pollution-free and multi-use. Specially, air source heat pump (ASHP) is the most widely-applied equipment among all kinds of heat pump units for its low initial investment, convenient maintenance and little influence to ambient. Since 1990’s, ASHP had been successfully used in the unconventional heating region of China including the middle and lower reaches of the Yangtze River, south and southwest China since it can meet the building’s needs of cooling and heating in these regions with less energy consumption. Nowadays, the coal-fired boilers are still the main heating source in north China where are very cold in winter, however the pollution and slow development of centralized heat-supply network make people search some green and high efficiency heating system to supplement or replace the conventional one.

Much research has been made to try to use the ASHP system in cold regions. In this paper, the air source heat pump systems for cold regions are introduced and compared firstly, and then our research with a two-stage compression variable frequency air source heat pump system is presented.

2. THE PROBLEM OF COMMON ASHP FOR COLD REGIONS

There are four main problems when the common ASHP systems are used in the winter of cold region:

1) Along with the decrease of ambient temperature, heat capacity goes down obviously whereas the building heat load increases, which cannot be solved completely in common ASHP system.

2) *COP* decreases and energy consumption increases along with the decrease of ambient temperature.

3) The discharge temperature of compressor goes up so high that the ASHP system cannot operate normally when the ambient temperature is much lower.

4）When the ambient temperature drops to 5 or even lower, the frost will form on the surface of outdoor heat exchanger. The frost layer causes the increase of heat resistance and decrease the rate of air flow, which leads to the decline of the COP. In some conditions, the system even cannot work with serious blockage.

The frost formation is a general problem for all ASHP system, and what is more, less frost will form when the ambient temperature is lower than -10℃. So the frost formation would not be involved in the paper.

3. TECHNICAL REVIEW OF ASHP FOR COLD REGIONS

In the paper, the ASHP systems for cold regions are divided into three groups: single-stage compression heat pump, liquid/vapor injection heat pump, and two-stage heat pump.

3.1 Single-stage Compression Heat Pump

For single-stage compression heat pump, there are methods including increasing the fan speed of outdoor heat exchanger, heating evaporator inlet air, and changing the concentration of refrigerant mixture to improve the applicability of ASHP in cold regions.

3.1.1 Variable Speed Fan

Wang suggested the variable speed fan is used for the outdoor heat exchanger of ASHP system [1]. When ambient temperature is very low, the fan works with high rotary speed to increase the air flow rate through the heat exchanger, and to improve evaporating temperature and the refrigerant mass flow rate to compressor. But the method is appropriate for the ambient of not very low temperature and its improvement is not obvious.

3.1.2 Air Source Improvement

Yamagami used an oil heater to increase the air temperature at the outdoor heat exchanger inlet in order to improve the heating capacity of ASHP [2]. The evaporating temperature becomes higher in cold regions with a kerosene-fired burner. Furthermore, the burner also can be used as an auxiliary heat source. The method is not suitable for small system because the system is more complicated and the initial investment is much higher.

3.1.3 Varying Concentration of Refrigerant Mixture

Sami and Tulej improved the heating capacity of ASHP with a ternary refrigerant mixture for cold climates [3].

Chen analyzed the theoretical cycle performances of R32/R134a and R22 [4]. The experimental investigation on a novel ASHP with altering concentration of refrigerant mixture was carried out, and the results showed that R32/R134a has better heating capacity adjustment performance.

3.2 Liquid/vapor Injection Heat Pump

Zheng set a vapor injection inlet on one-stage screw compressor and developed a quasi two-stage heat pump system with the mode of one-stage compression and two-stage throttle device [5].

Horiuchi proposed an ASHP system with an inverter scroll compressor and liquid injection [6] (Fig.1). High pressure refrigerant liquid flows into compressor through liquid injection port to reduce the compressor discharge temperature and enhance the heating capacity under low outdoor air temperature. Also, the heating capacity can be improved by means of increasing the power frequency of compressor, but meanwhile the evaporating temperature and *COP* go down along with the increase of power frequency.

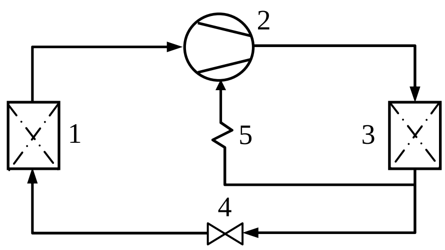

Fig. 1 Liquid injection heat pump

1. Evaporator 2.Compressor 3. Condenser 4. Expansion valve 5. Injection pipe

Ma proposed a quasi two-stage compression ASHP system with an economizer and a scroll compressor basing on the liquid injection heat pump system [7] (Fig. 2). The economizer can make the liquid refrigerant out of condenser a large subcooling degree, and enhance the heat absorbed from outdoor air for per mass refrigerant and *COP*. Also, the economizer can reduce the discharge temperature of compressor. The *COP* of system is 1.69, and discharge temperature is 121.4℃ when the condensation temperature is 45℃ and evaporating temperature is -25℃.

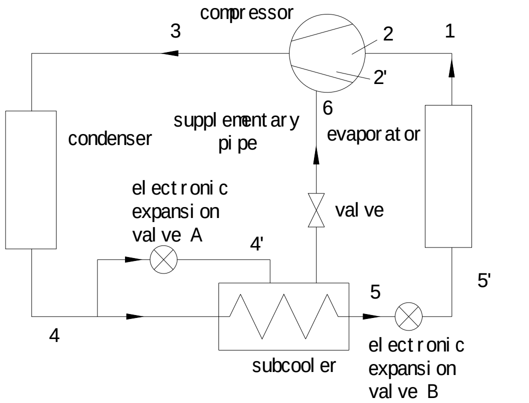

Fig. 2 Quasi two-stage compression heat pump

3.3 Two-stage Heat Pump

Ma developed a two-stage coupling heat pump system which obtains heat from cold air through low temperature heat pump loop and produces water of 10-20℃[8]. The water is used as the low grade heat source of high temperature heat pump loop to produce the hot water or hot air for building heating (Fig.3). The *COP* of the system can reach 2.48 in Beijing and the discharge temperature is no more than 60℃.

Hulten and Berntsson combined the absorption heat pump (as low temperature loop) and vapor compression heat pump (as high temperature loop), and developed an absorption/vapor-compression coupling heat as the high grade heat source, absorbs heat from pump [9]. The system, with the industrial waste heat air and produces the medium temperature (higher than ambient temperature) air, with which as low grade heat source, the compression heat pump produces the hot water. The absorption/vapor-compression coupling heat pump is effective system to improve the heating efficiency in cold regions, but it has complicated structure and needs waste heat source with a proper temperature.

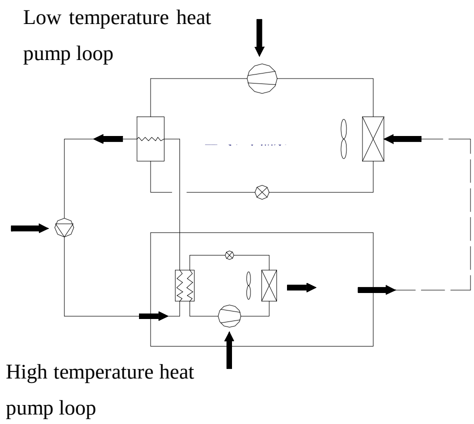

Fig. 3 Two-stage coupling heat pump

3.4 Comparison of Different ASHP for Cold Regions

The heating capacity, *COP*, discharge temperature, system complexity and applicability of the ASHPs for cold regions are compared in Tab.1. It can be seen that all methods extend the applicability of ASHP in cold regions to a certain extent.

4. TV-ASHP SYSTEM

Finally, this paper introduces our scheme for cold regions, i.e. two-stage compression variable frequency air source heat pump (TV-ASHP) system [10].

4.1 Description of TV-ASHP

The schematic diagram of TV-ASHP system is shown in Figure 4. The uncompleted intercooling two-stage compression cycle is adapted, and the system mainly includes a low pressure stage compressor, a high pressure stage compressor, an outdoor heat exchanger, an indoor heat exchanger, an intercooler, two throttling devices, a four-way valve, and a solenoid valve. Three work conditions including the single-stage compression cooling, single-stage compression heating and two-stage compression heating can be carried out by controlling four-way valve and

Tab.1 Comparison of ASHPs for cold regions

Method	Heating capacity	*COP*	Discharge temp.	Complexity	Applicability
Variable speed fan	Lower	Low	Very high	Low	Poor
Air source improvement	High	Low	Little lower	High	Good
Varying concentration	Little higher	Normal	Little lower	Little lower	Preferable
Liquid injection	Little higher	Little lower	Normal	Little higher	Preferable
Quasi two-stage	Little higher	Little higher	Normal	Little higher	Good
Two-stage	High	High	Little lower	High	Good

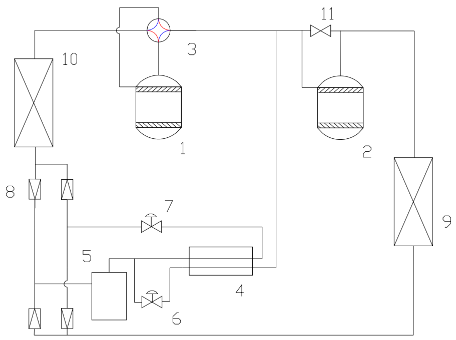

Fig. 4 Schematic of TV-ASHP system

1- low pressure stage compressor
2- high pressure stage compressor
3-four-way valve 4- intercooler 5- receiver
6-throttling device I 7- throttling device II
8- one-way valve 9-indoor heat exchanger
10-outdoor heat exchanger 11-solenoid valve

solenoid valve and changing the refrigerant flow circuit.

Two-control-mode with the priority target as *COP* or heating capacity is advanced to assure the system higher *COP* when the heating capacity can meet the heating load. That is, when the heating capacity meets the heating load, the system works in the mode of *COP* priority and is kept the optimal intermediate pressure by changing the power frequency of low pressure stage compressor. But if the heating capacity is insufficient for demand, the control mode of heating capacity priority has to be chosen and the power frequency should be adjusted to meet the heating demand. With the TV-ASHP system, the heating capacity is enhanced with two-stage compression and increase of power frequency of low pressure stage compressor together, *COP* is improved with two-stage compression and optimal intermediate pressure by power frequency adjustment of low pressure stage compressor together, and the discharge temperature of high pressure stage compressor is decreased with the two-stage compression cycle, which are used to solve the insufficient heating capacity, lower *COP*, and high compressor discharge temperature in the common ASHP systems.

4.2 Experimental Results

The test bench with a standard cooling capacity of 16 kW is built up, the *COP* and discharge temperatures of single-stage compression and two-stage compression, and heating capacity of two-stage compression are measured.

4.2.1 Comparison of *COP* in Two-stage and Single-stage Compression

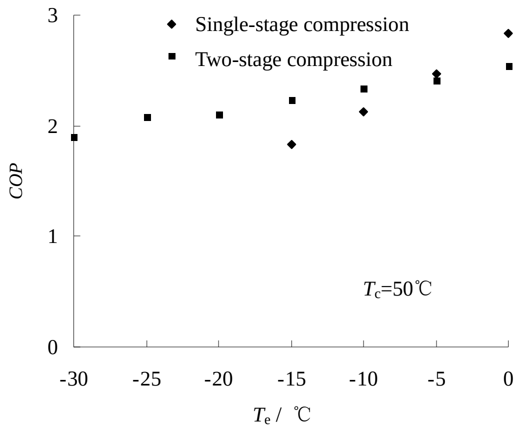

Fig. 5 Comparison of *COP*

Fig.5 shows the comparison of *COP* in

two-stage and single-stage compression heating condition when the condensing temperature (T_c) is 50ºC. The *COP* of both two-stage and single-stage compression system goes down along with the decrease of the evaporating temperature(T_e), but the decreasing rate is more less for two-stage compression system, especially when the evaporating temperature is lower. As shown in Fig.5, the *COP* of two-stage compression system is still more than 2 when the evaporating temperature is -25ºC. The *COP* of two-stage compression system exceeds the one of single-stage compression system when the evaporating temperature is below -7ºC. The results above show that the *COP* of TV-ASHP system is noticeably higher than the common single-stage compression heat pump in cold regions. The lower outdoor temperature, the more the energy saving.

4.2.2 Comparison of Discharge Temperature in Two-stage and Single-stage Compression

The variations of the discharge temperature of compressor, T_d, along with the evaporating temperature in two-stage and single-stage compression system are shown in Fig.6 when the condensing temperature is 50ºC. The discharge temperature in single-stage compression system increases dramatically when the evaporating temperature goes down. When the evaporating temperature is -15ºC, the discharge temperature rises to 130ºC, which is harmful to the compressor. In the case of two-stage compression system, the increasing rate of discharge temperature is less. When the evaporating temperature is down to -25ºC, the measured discharge temperature of high pressure stage compressor is below 120ºC, with which the compressor can still run reliably and safely.

Fig. 7 shows the variations of the heating capacity, Q_c, along with the evaporating temperature when TV-ASHP system is operating at the optimal intermediate pressure. The heating capacity goes down along with the decrease of the evaporating temperature, and is only 9kW when the evaporating temperature is -25^{o}C (outdoor temperature is about -18^{o}C) though it has been greatly improved.

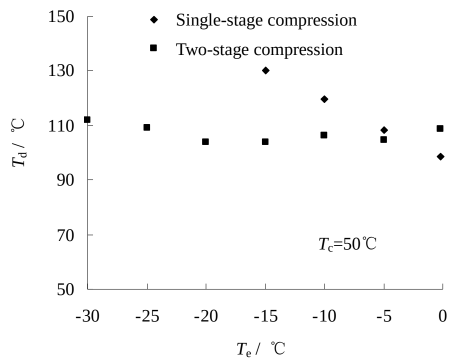

Fig. 6 Comparison of discharge temperature

4.2.3 Heating Capacity of TV-ASHP

For the heat pump unit with the standard cooling capacity of 16kW, the minimal heating capacity must be higher than 12kW in order to meet the heating demand. That means only the two-stage compression in optimal condition alone cannot satisfy the heating requirement when the outdoor temperature is very low. So the system should adjust the power frequency of low pressure stage compressor by the control mode of heating capacity priority. stage compressor, f_1, when the condensing temperature is about 50^{o}C and the evaporating stage compressor, f_1, when the condensing temperature is about 50^{o}C and the evaporating temperature is -25℃. The heating capacity rises along with the increase of the power frequency of low pressure stage compressor and the heating capacity reaches 12.6 kW when f_1=80Hz. Basing on the improvement of two-stage compression in optimal condition, increase of power frequency can enhance the heating capacity further, which can meet the heating demand without auxiliary heat source in cold regions.

Fig. 8 shows the variations of the heating capacity with the power frequency of low pressure

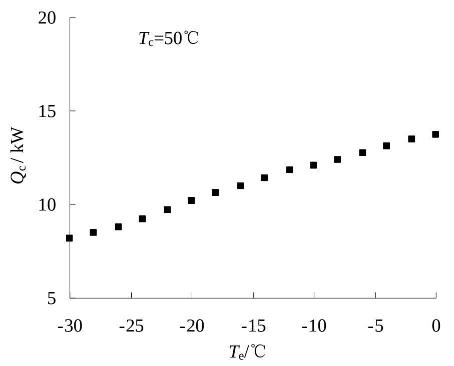

Fig. 7 Heating capacity vs. evaporating temperature

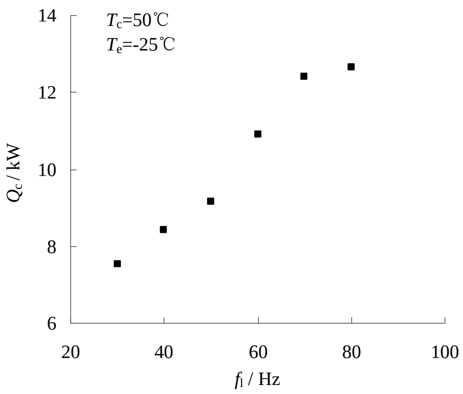

Fig. 8 Heating capacity vs. power frequency

5. CONCLUSIONS

In this paper, the researches on air source heat pump systems for cold regions in recent years are summarized and compared firstly. These systems can be divided into three kinds: single-stage compression heat pump, liquid/vapor injection heat pump, and two-stage heat pump. And then, our scheme for cold regions, i.e. two-stage compression variable frequency air source heat pump is introduced. The *COP* of this system is over 2, the compressor discharge temperature under 120 ℃, and the heating capacity can meet the heating load needed when the condensing temperature is 50 ℃, which can be used in the cold regions where outdoor temperature is over -18℃.

REFERENCES

[1] WANG H. Discussion of heat pumps in low temperature environment [J]. Journal of HV&AC, 1998, 28(6): 34-37 (in Chinese).

[2] YAMAGAMI M. Development of burners for room air conditioners. Technical Review – Mitsubishi Heavy Industries, 1998, 35 (2) (in Japanese).

[3] SAMI S M, TULEJ P J. A new design for an air source heat pump using a ternary mixture for cold climates. Heat Recovery Systems & Chp, 2001, 15(6):521-529.

[4] CHEN G, ZHANG L, CHEN B. Study of air heat pump with altering concentration of mixture refrigerant. Fluid Machinery, 2005, 33(supplement): 168-171 (in Chinese).

[5] ZHENG Z, JIN L, QIAN R. The research on air source heat pump system. Chemical Engineering & Machinery, 1994, 21(5): 292-294 (in Chinese).

[6] HORIUCHI N. Development of package air conditioner for cold regions. Refrigeration, 1997, 72(7): 837 (in Japanese).

[7] MA G, CHAI Q, JIANG Y. Experimental investigation of air-source heat pump for cold regions. International Journal of Refrigeration, 2003, 26: 12-18.

[8] MA Z, YANG Z, YAO Y. Analysis of using air-source heat pump water chiller-heater units in the cold regions. AV&AC，2001,31(3):17-21 (in Chinese).

[9] HULTEN M, BERNTSSON T. The Compression/Absorption Heat Pump Cycle-Conceptual Design Improvements and Comparisons with the Compression Cycle. International Journal of Refrigeration, 2002, 25(4): 487-497.

[10] TIAN C, SHI W, WANG S. Research on two-stage compression variable frequency air source heat pump in cold regions. ACTA ENERGIAE SOLARIS SINICA, 2004, 25(3): 388-393 (in Chinese).