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ABSTRACT

As an promising heating application of environmental conservation and energy conservation, air-source heat pump systems has been spreading. However, in cold regions of China, conventional heat pump systems have problems remaining, such as inadequate heating capacity and reduced performance under low environmental temperature condition. To solve these problems, we developed a two-stage rotary compressor for household R32 air-source heat pump system. We analyzed the thermodynamic characteristics of two-stage rotary compressor with refrigerant injection used in heat pump system with economizer. It is found that the two-stage rotary compressor can enhance heating capacity and performance of R32 heat pump under cold climate markedly.

1. INTRODUCTION

Small air-source heat pump system has been widely used in different places, such as residence, marketplace, workshop, etc., because of its advantages of efficient energy saving, environmental protection, convenient installation and so on(Hua Zhang et al.,2008, and Zhang Xinyu et al.,2015). In recent years, the small air source heat pump replaces heating by coal, Which has become an important way of energy saving and emission reduction in cold regions of China. However, from the thermodynamic principle of vapor compression refrigeration cycle, the air source heat pump is gonging to replace the northern coal heating under low temperature conditions, which has the following disadvantages(YAN Lihong et al.,2016, and Zhang Xingxing et al.,2015): 1) huge diminution of heating capacity; 2) reduction of the heating efficiency; 3) high discharge temperature of the compressor, which result in low reliability of the compressor or even damage it.

In order to promote small low temperature small air source heat pump (SLTHP for short) in cold regions of China, there are three different advanced techniques : Firstly, double scroll compressors form a two-stage compression system, which can greatly enhance the low-temperature heating capacity and heating efficiency, but, it increases the installation space and cost, and it is also difficult for the oil to return back to the compressors in series; Secondly, the scroll compressor with gas-injection can raise the heating under low temperature conditions to a certain extent, but, because it is quasi two-stage compression, the reduction rate of heating capacity is still relatively fast, and it cannot fully meet the heating demand in cold regions of China. And thirdly, variable-volume rotary compressor technology has increased efficiency under low frequency by variable-volume, but the density of suction gas has dropped sharply under the low temperature conditions.

Above all, among the existing technologies, it is difficult to control the oil, the cost is high, or the heating capacity is insufficient, and the range of work temperature is narrow. Based on the two-stage throttling intermediate cooling cycle, a two-stage compression cycle with two-stage rotary compressor technology improves the adaptability of small air source heat pumps to low temperature ambient, which can obviously improve the heating capacity and energy efficiency of heat pumps.

2. THE TECHNICAL PRINCIPLE OF TWO-STAGE ROTARY COMPRESSOR WITH REFRIGERANT INJECTION

2.1 The Principle of Two-stage Compression with Refrigerant Injection

Figure 1 shows the structure of two-stage rotary compressor with refrigerant injection (TSRC for short). TSRC has a 1st-stage cylinder, and a 2nd-stage cylinder in series. The 1st-stage compression mechanism in the 1st-stage cylinder compresses refrigerant from suction pressure to intermediate pressure and discharges it into the intermediate chamber mixing with refrigerant injection under intermediate pressure. The 2nd-stage compression mechanism in the 2nd-stage cylinder compresses refrigerant from intermediate pressure to discharge pressure, discharges it into the shell.

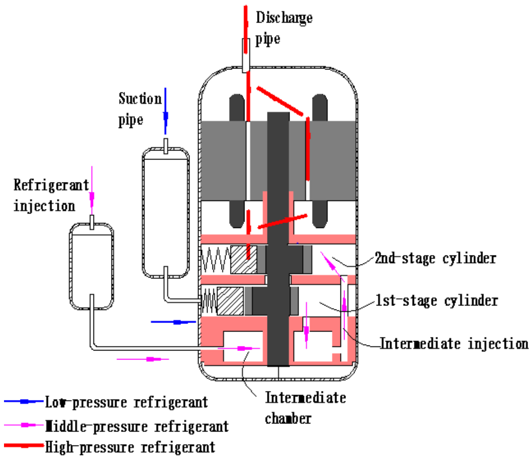

Figure 1: Schematic diagram of TSRC

From the needs of higher efficiency of SLTHP and its structure characteristics, two-stage compression system is mainly composed of TSRC, condenser, evaporator, flash vaporizer, a 1st-throttling device and a 2nd-throttling device, which is showed in figure 2. TSRC decomposes the compression process from one compression 1-4' to two stages compression 1-2 and 3-4, which can reduce the difference of suction pressure and exhaust pressure of a single cylinder, thereby reducing the leakage of a single cylinder, which improve the volume efficiency of the compressor.
Compared with the single stage compression system, the TSRC system increases a throttle and a flash vaporizer. The refrigerant from 1st-stage throttling device flow into the flash vaporizer, which separates medium pressure saturated refrigerant gas from the liquid. Then, the gas injects into intermediate chamber of TSRC, which decrease 2nd-stage suction temperature, consequently improve the 2nd-stage compression process 3-4, reduce the quality of compressor power input, exhaust temperature reduced from T4' to T4. The liquid from flash vaporizer flows to the 2nd-stage throttling, then flows into the evaporator, which leads to the enthalpy difference of the refrigerant increases, thus improving the unit mass flow.
Therefore, the two-stage compression cycle system has the obvious advantages of high capacity, high energy efficiency and high reliability compared with the single stage compression cycle system.

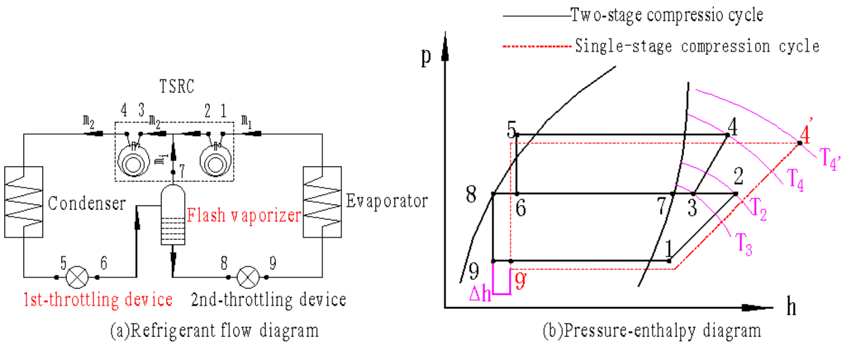

Figure 2: Two-stage compression cycle with a flash vaporizer

2.2 Optimum Volume Ratio

The volume ratio is the ratio of the working volume of the 2nd-stage and 1st-stage cylinders of TSRC. The calculation formula is as follows:

$$\xi = \frac{V_{high}}{V_{low}} \tag{1}$$

Hereinto, V_{high} is the working volume of 2nd-stage cylinder, V_{low} is the working volume of 1st-stage cylinder

The volume ratio has a great influence on the performance of TSRC(Huifang Luo et al.,2014), so it is an important parameter for the design of TSRC. The theoretical cycle of TSRC with different volume ratio is different under fixed working conditions. As shown in Fig. 3, the intermediate pressure of two-stage compression cycle with different volume ratio is different, that is, there are different Cycle States, and there is a significant difference in theoretical Coefficient of performance(hereinafter referred to as COP).

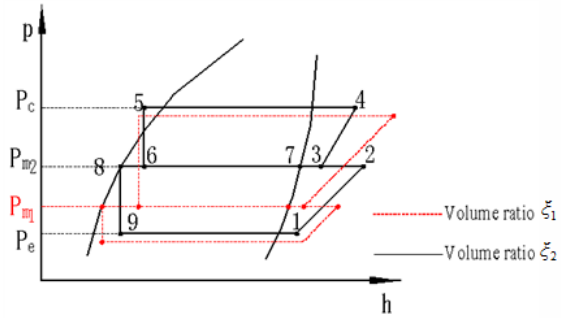

Figure 3: Theoretical cycle enthalpy diagram of TSRC with different volume ratio

In the two-stage compression cycle, we do not consider the heat loss in the flash process and the mixing process. According to The first law of thermodynamics, combined with the thermodynamic calculation method of vapor compression refrigeration theory, we can get the formula of two-stage compression type with unique theoretical COP.

$$COP = \frac{Q_{heat}}{W}$$

$$= \frac{(h_1 - h_8) \bullet m_{low}}{(h_2 - h_1) \bullet m_{low} + (h_4 - h_3) \bullet (1 + x\ ) \bullet m_{low}} + 1$$

$$= \frac{(h_1 - h_8) \bullet (h_7 - h_6)}{(h_2 - h_1) \bullet (h_7 - h_6) + (h_4 - h_3) \bullet (h_7 - h_8)} + 1$$

$$= \frac{(h_1 - h_8) \bullet (h_7 - h_6)}{(h_2 - h_1) \bullet (h_7 - h_6) + (h(s(h_3, P_m), P_c) - h_3) \bullet (h_7 - h_8)} + 1$$

$$= f_1(P_m, P_e, T_1, P_c, T_5)$$

$$= f_2(\xi, P_e, T_1, P_c, T_5) \tag{2}$$

Hereinto, Q_{heat} is the heat production in the theoretical cycle, W is the power of the theoretical cycle, h_{i} is the enthalpy of the i point in Figure3, i value 1 to 9, T_{i} is the absolute temperature of the i point in Figure 3, i value 1 to 9, x is the dryness of refrigerant after primary throttling, m_{low} is the mass flow per unit time flowing through the evaporator.

According to this, the calculate conditions include the APF conditions, which are shown in table 1, and the refrigerant is R32. In each case, the theoretical COP increases with the increase of volume ratio. The theoretical COP firstly increases and then decreases, and there is a maximum value. The volume ratio of the maximum theoretical COP corresponds to the optimal volume ratio under this condition. The theoretical COP ratio is the ratio of the theoretical COP with the optimum volume ratio and the theoretical COP with the different volume ratio in the same working condition. As shown in Figure 4, the optimum volume ratio is different with the different working conditions. In order to make the COP of the 4 working groups better, the volume ratio is 0.77-0.8, which can ensure that the theoretical COP ratio of the above 4 APF conditions is more than 99%.

Table 1: Working condition parameter

Test Conditions	Evaporating Temperature	Condensation Temperature	Suction Temperature	Degree of Subcooling	Ambient Temperature
	℃	℃	℃	℃	℃
Rating Cooling	15	44	23.1	5.1	35
Middle Cooling	20	40	28.1	5.1	35
Rating Heating	2	42	8.1	15.1	7
Low temp. Heating	-7	45	1	5.1	2

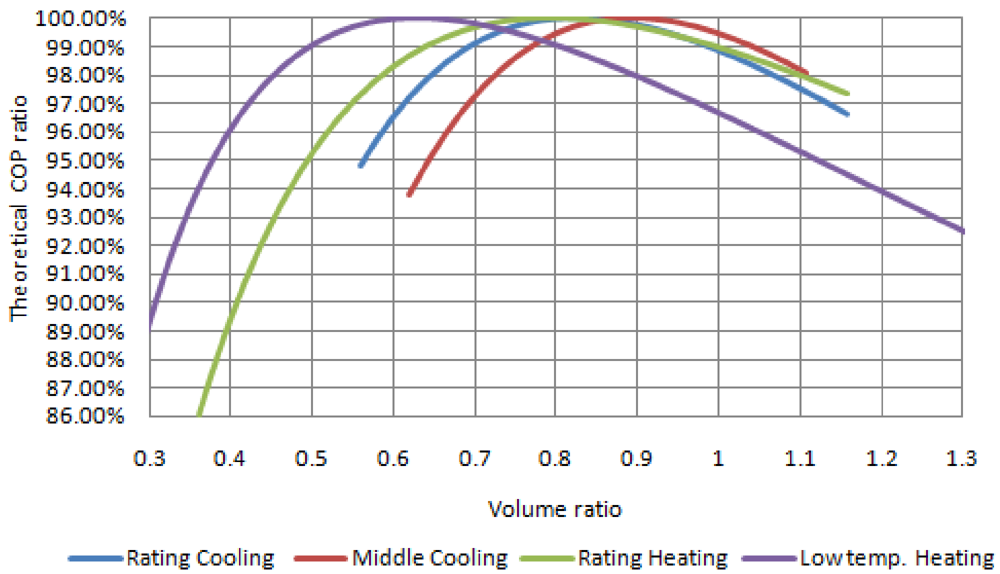

Figure 4: the variation of theoretical COP ratio with the volume ratio under different working conditions

3. APPLICATION EFFECT OF TWO-STAGE ROTARY COMPRESSOR WITH REFRIGERANT INJECTION

According to above analysis, the prototype TSRC is assembled, whose volume ratio is 0.8 and 1st-stage displacement is 9.6cc. The TSRC and its SLTHP are showed in figure 5. Firstly, the compressor performance was tested and compared with the performance of single stage rotary compressor with the same displacement under the test conditions, which are shown in Table 1. The test results are shown in figure 6. The results shows that compared to single stage rotary compressor, capacity and COP of the TSRC has significant advantages.

Figure 5: TSRC and its SLTHP

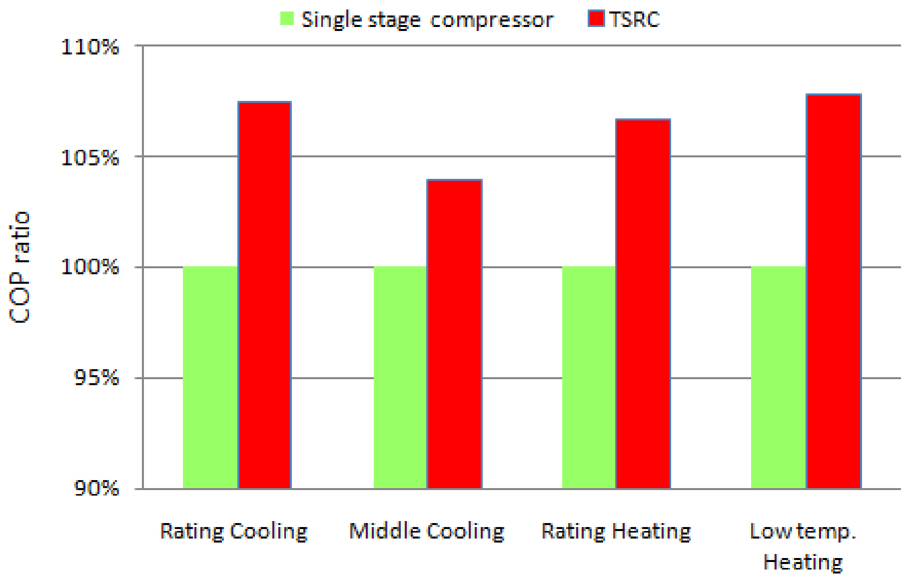

Figure 6: COP of compressor comparison

Then, we matched TSRC and the normal single stage compressor on the same SLTHP system. The test conditions include the APF conditions and some super low temperature heating condition, which are shown in Table 2. The comparison test of TSRC and the same displacement single stage compression is carried out.

Table 2: SLTHP testing conditions

Test Conditions	Indoor		Outdoor	
	Dry Temp.	Wet Temp.	Dry Temp.	Wet Temp.
-20℃Heating	20	＜15	-20	-
-15℃Heating	20	＜15	-15	75%RH
2℃ Heating	20℃	＜15℃	2℃	1℃
7℃ Heating	20℃	＜15℃	7℃	6℃
35℃ Cooling	27℃	19℃	35℃	24℃

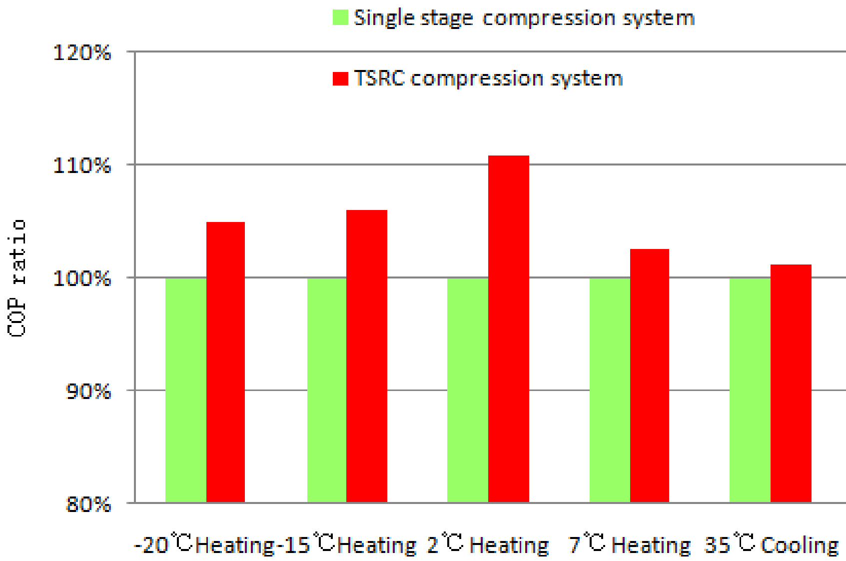

Figure 7: COP of compression system comparison

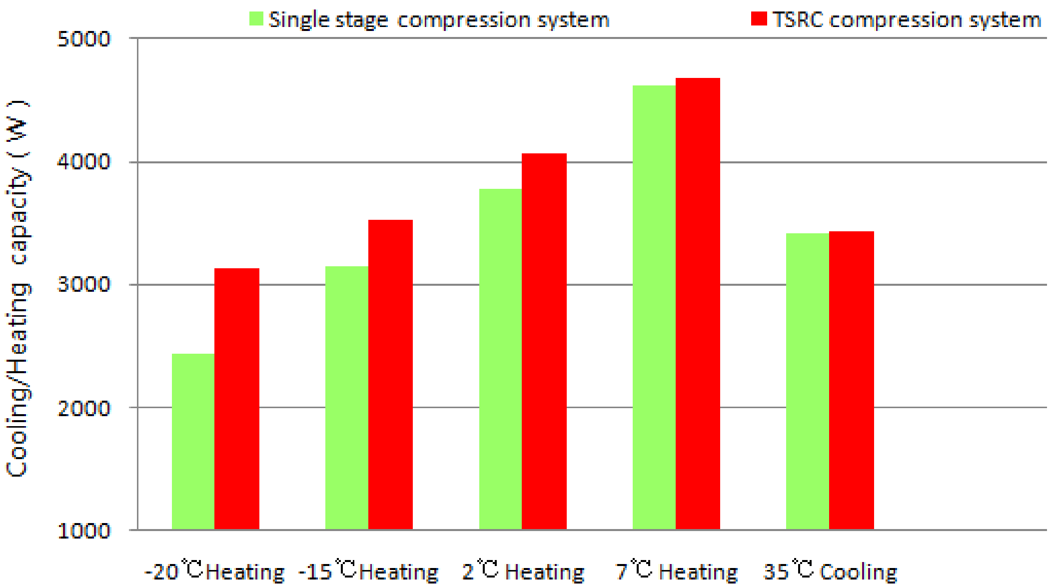

Figure 8: Capacity of compression system comparison

The test results are shown in Figures 7 and 8. Compared with the single stage rotary compression system, the capacity and COP of the TSRC compression system have significant advantages. Under the test condition of -20℃ heating, the COP is about 5% higher than the base, and the heating capacity is about 29% higher than the base.

4. CONCLUSIONS

The system modeling reveals that application of the TSRC to a small air-source heat pump can improve obviously the performances of SLTHP, including enough heating capacity and high energy efficiency in northern China, where temperatures fall into the negative double digits centigrade. The products using TSRC can work properly at the temperatures from -30℃ to 54 ℃. The SLTHP with TSRC provided up 129% heating capacity and up to 105%

higher efficiency than the baseline single-stage heat pump at -20℃ ambient and 20℃ indoor air temperature.

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