EFFECTS OF EJECTOR ON PERFORMANCES OF QUASI TWO-STAGE COMPRESSION HEAT PUMP SYSTEM COUPLED WITH EJECTOR

Pang Zong-zhan, Graduate Student
College of Environmental and Energy Engineering
Beijing University of Technology, Beijing 100022, China

MA Guo-yuan, Professor
College of Environmental and Energy Engineering
Beijing University of Technology, Beijing 100022, China

Abstract: To improve the performance and enlarge the operation conditions of air-source heat pump, a quasi two-stage compression heat pump system coupled with ejector was designed. The prototype of the heat pump system coupled with ejector was experimented comprehensively when condensation temperature keeps at 45ºC and evaporation temperature varies from -8ºC to -25ºC and the effects of the ejectors on the performances of the heat pump was discussed. The results demonstrate that the heat pump coupled with the ejector with optimized construction has higher coefficient of performance in a wide range of operation conditions and achieve its better performances while the ejection coefficient (u) is 0.1.

Key Words: ***heat pump; ejector; experimental study***

1 INTRODUCTION

Comparing with conventional air-source heat pump system, quasi two-stage compression (QTSC) heat pump system can increase heating capacity, EER and operation reliability. So it has becoming an effective technology to enlarge the application of air-source heat pump in cold regions [1-3]. The throttling process is irreversible and the enthalpy at the beginning and end of the process keeps constant, no matter in conventional single-stage compression heat pump system cycle or in QTSC heat pump cycle. The throttling process will cause a great irreversible loss, and the EER of the cycle will be decreased. Although many researchers tried to use reciprocating, rotary or turbine expander to replace throttling valve, these equipments have a high cost in investment, operation and maintenance, and will be easily destroyed in the process with two-phase working fluid. So it is very difficult to use the expander in practical heap pump with medium or small capacity. As ejector has advantages such as simple construction, low cost, no moving parts, safe for two-phase working fluid and so on, it can be used to replace throttling valve to save the energy consumed in throttling process. It has been proved that the performance of the refrigeration cycle with ejector to replace the throttling element has been remarkably improved and the application effect was great [4-7]. In order to improve the performance of air-source heat pump, the ejector was used to replace the throttling element in the supplementary loop of QTSC heat pump system and the combined heat pump system with ejector was developed [8]. In this paper, the experimental results of the prototype will be presented, and the effects of ejector on the performances of the combined system will be analyzed.

2 QUASI TWO-STAGE COMPRESSION HEAT PUMP SYSTEM WITH EJECTOR

The principle of QTSC heat pump system coupled with ejector (coupled heat pump system) is shown in Figure 1. The heat pump system coupled with ejector is comprised of compressor, condenser, flash-tank, expansion valve, evaporator, ejector and other apparatus. The compressor, condenser, flash-tank, expansion valve and evaporator are connected together to form the main circuit, and the circuit is same as conventional single-stage compression heat pump system. The compressor has supplementary inlets, the ejector is connected between flash-tank and supplementary inlets of compressor, those equipments form supplementary circuit. The flashed vapor at the top of the flash-tank as a working fluid flows through the ejector, and entrained a part of the refrigerant vapor from the evaporator, which is called entrained fluid. The working fluid and entrained fluid are mixed in ejector, and the pressure of the mixed fluid then rises to the intermediate pressure at the exit of the ejector. This part of refrigerant is sucked into compressor through supplementary inlets.

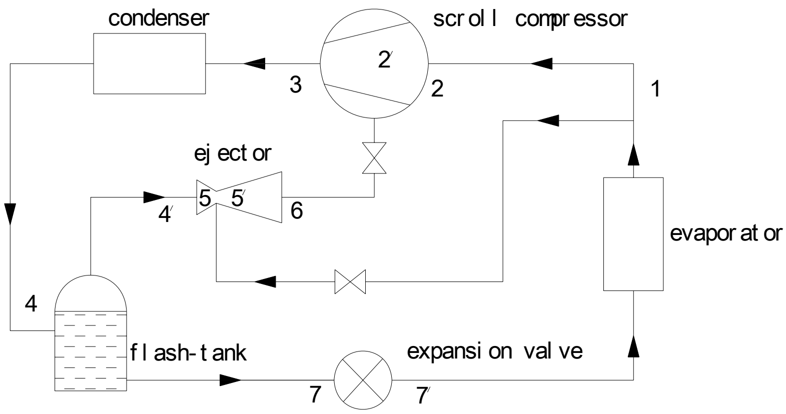

Figure 1: Principle of quasi two-stage compression heat pump system coupled with ejector

Compared with QTSC heat pump system, the coupled system uses ejector to replace the throttling valve in the supplementary circuit. The ejector is able to increase the pressure of the entrained fluid without mechanical energy consumption, and using it in the coupled system can reduce the loss of effective energy. As ejector has advantages such as simple structure, low cost, no moving parts, safety for two-phase working fluid and so on, the coupled system not only be simply composed, conveniently installed, but also has a high efficiency and a wide range of operation condition.

The principle and structure of the ejector is shown in Figure 2. The ejection coefficient (u) of the ejector, which is defined as the mass of the entrained fluid sucked by unitary mass of working fluid that flow through the ejector, is one of important indexes to reflect the working capability of the ejector.

The designing conditions of the ejector include the pressure of working fluid and the pressure of entrained fluid. In the coupled system, the saturation temperature corresponding to the pressure of working fluid is the condensation temperature, tk. The saturation temperature corresponding to the pressure of entrained fluid is the evaporation temperature, to. So the condensation temperature (tk) and the evaporation temperature (to) are used to denote the designing conditions of the ejector.

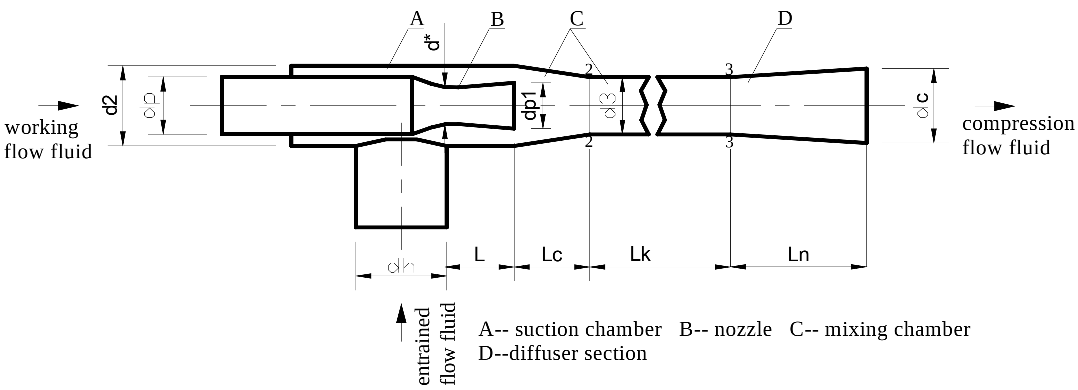

Figure 2: Principle and structure of the ejector

The performance of the ejector is simulated and analyzed, which is proved that the intermediate pressure at the exit of the ejector will reduce with the increase of the ejection coefficient [9]. The variation of heating COP of the coupled system by simulating and analyzing with coefficient of ejector is shown in Figure 3. It is seen that the heating COP of the coupled system increase with the increase of the ejection coefficient. It is mainly because the intermediate pressure will reduce with the increase of the ejection coefficient. As the flow rate through the supplementary inlets of the compressor decreases while the intermediate pressure becomes low, therefore the heating capacity and input power of the system decreases, but the decrement of the input power is higher than that of the heating capacity. The discharge temperature of the compressor increases with the increase of the ejection coefficient as the flow rate through the supplementary inlets of the compressor decreases. To ensure the discharge temperature is not too high and safe for steady operation of the heat pump, too great value of ejection coefficient does not mean more benefit for the coupled system and there is optimum value for the ejection coefficient. So it is necessary to find the excellent coefficient of ejector for working stability of the system.

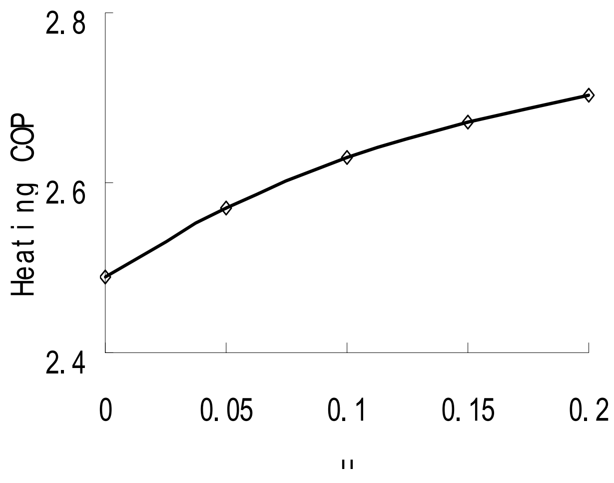

Figure 3: Variation of heating COP with ejection coefficient

To find out real effects of the ejection coefficient on performances of QTSC heat pump system with ejector, the two prototypes of ejector were developed while they own same designing conditions of tk=45ºC and to=-15ºC, but different ejection coefficients of 0.1 and 0.2, respectively. Also, to understand influences of construction parameters of the ejector on the performances of the coupled system, the three prototypes of ejector were developed while they own same ejection coefficients of 0.1, but different designing conditions. Namely, ejector 1 own the designing conditions of tk=45ºC and to=-15ºC, and ejector 2 the conditions of tk=45ºC and to=-25ºC, and ejector 3 by optimized design the conditions of tk=45ºC and to=-20ºC. The experimental projects of the heat pump system coupled with the separate one of the ejectors are designed.

3 EXPERIMENTAL METHOD AND APPARATUS

To test the effects of the ejector with different construction on the performance and running situation of the prototype when it is operating under the conditions of low evaporation temperature and study the working mechanism of the ejector, the four prototypes of ejector were developed under the above designing conditions, and the separate one of the ejectors connected in the coupled system tested comprehensively. In the experiments, the condensation temperature keeps at 45ºC and the evaporation temperature varies from -8ºC to -25ºC. the refrigerant of QTSC heat pump system with ejector is R22. The experimental setup of QTSC heat pump system was explained in details [9].

Experimental method and data processing accord with the standards of GB10870-89, the methods of performance test for reciprocating and screw water-chilling units, and GB7941-87, test of refrigerating equipment, all test instruments meet the requirements in GB10870-89 and BG7941-87.

The cooling capacity is calculated by the measured values of the flow rate and the temperature difference of the glycol water solution flowing through the evaporator. The evaporation temperature varies by adjusting the input power of the electric heater immerged in the glycol water solution. The heating capacity is computed by the measured values by the flow rate and the temperature difference of the water flowing through the condenser. The temperature of the water flowing into condenser adjusts by the input power of the electric heater in the water tank. And the condensation temperature varies with the water temperature. All electric parameters are measured by ZW3433B type three-phase electric multi-meter. The relevant temperatures and the pressures in the measurements are transduced into the computer through Agilent data acquisition unit by their transducers.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Influence of ejection coefficient on performances of the coupled system

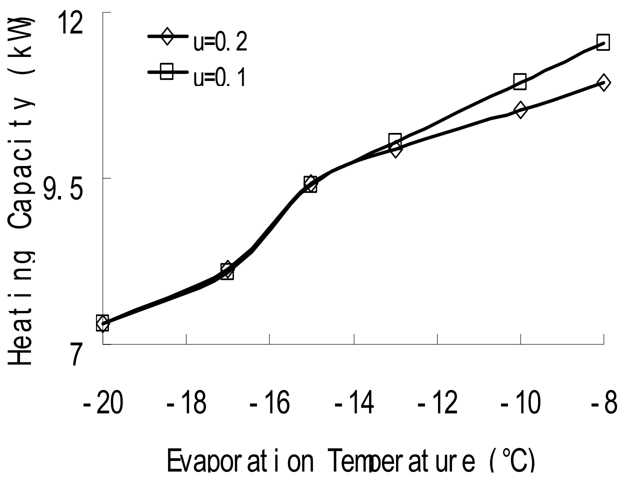

Figure4: Variation of heating capacity with evaporation temperature

The variation of heating capacity with the evaporation temperature is shown in Figure 4. It is observed that the heating capacity of the coupled system decreases with the decrease of the evaporation temperature while the ejection coefficient is 0.1 and 0.2, respectively. The heating capacity of the coupled system with the ejection coefficient of 0.1 (the coupled system 1) is larger than that of the coupled system with the ejection coefficient of 0.2 (the coupled system 2) when the evaporation temperature is more than -15ºC. The improvement of the heating capacity of the coupled system 1 increases with the increase of evaporation temperature. The heating capacity of the coupled system 1 is approximately 10.9 kW when the evaporation temperature is -10ºC and the condensation temperature is 45ºC, which is about 3.8% larger than that of the coupled system 2. It is mainly because when the ejection coefficient becomes smaller, the achievable intermediate pressure at the exit of the ejector will be higher. Higher intermediate pressure means more the flow rate of the refrigerant through the supplementary inlets entering the chambers of the compressor, and the flow rate through the condenser of the coupled system increases, too. When the evaporation temperature is less than -15ºC, the heating capacity of the coupled system is very close whether the ejection coefficient is 0.1 or 0.2. It is mainly because the efficiency of the ejector with ejection coefficient of 0.1 decreases when working off the designing conditions. So the improvement of the heating capacity of the coupled system1 is not obvious comparing with the coupled system 2.

The variation of input power with the evaporation temperature is shown in Figure 5. It is observed that the variation trend of the input power of the coupled system with the evaporation temperature is similar whether the ejection coefficient is 0.1 or 0.2. The input power of the coupled system 1 is lower than that of the coupled system 2, and the decrement is approximately 35W in average. It is mainly because the intermediate pressure at the exit of ejector will be higher when the ejection coefficient becomes smaller. The intermediate pressure is higher means the irreversible loss in the mixing process in compressor is lower. This leads to decrease of the input power of the coupled system 1.

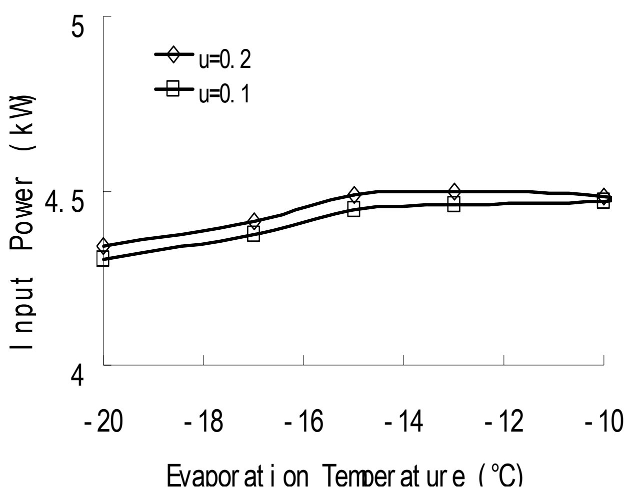

Figure5: Variation of the input power with evaporation temperature

It is also observed that the input power varies slightly though it decreases with decrease of the evaporation temperature. Therefore it is considered that the input power of the coupled system keeps nearly constant. The varying trend of heating COP with the evaporation temperature is similar to that of the heating capacity as the input power varies slightly. The heating COP of the coupled system 1 is higher than that of the coupled system 2 when the evaporation temperature is more than -15ºC. And the improvement of the heating COP of the coupled system 1 increases with the increase of evaporation temperature. The heating COP of the coupled system 1 is approximately 2.45 when the evaporation temperature is -10ºC and the condensation temperature is 45ºC, which is about 4.3% higher than that of the coupled system 2. Although the heating COP of the coupled system1 is higher, it is very close to that of the coupled system2 when the evaporation temperature is less than -15ºC. It is mainly because the input power of the coupled system 1 is slightly lower than that of the coupled system 2.

The heating COP of the coupled system 1 keeps higher than that of the coupled system 2 in a wide range of operation conditions. It is mainly because the efficiency of the ejector with the ejection coefficient of 0.2 decreases obviously off designing conditions as the coupled system with bigger ejection coefficient affects heavily its efficiency when working under the off-design conditions. Therefore, the heating COP of the coupled system is higher in a wide range of operation conditions when its ejector own optimum value of ejection coefficient. It is indicated that the ejector with ejection coefficient of 0.1 performs better from the present study.

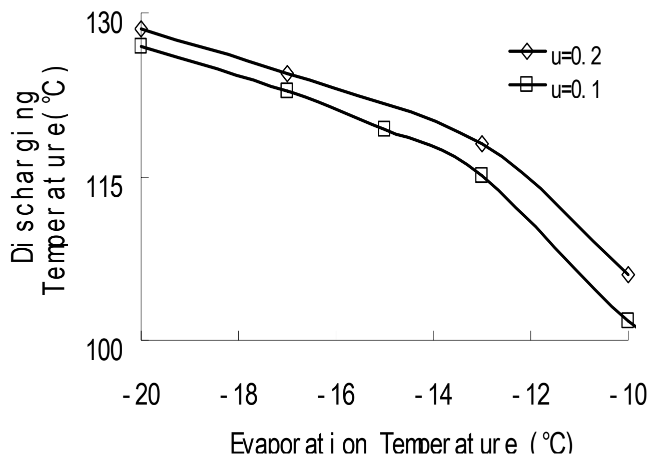

Figure6: Variation of discharge temperature with evaporation temperature

The variation of discharge temperature with the evaporation temperature is shown in Figure 6. It is seen that the discharge temperature of the coupled system increases with the decrease of the evaporation temperature and own a similar varying trend whether the ejection coefficient is 0.1 or 0.2. The discharge temperature of the coupled system 1 is slightly smaller than that of the coupled system 2. The discharge temperature of the coupled system 1 is 115ºC, and 3ºC lower than that of the coupled system 2 when the evaporation temperature is -13ºC and the condensation temperature is 45ºC. The decrement of the discharge temperature of the coupled system 1 reduces with decrease of the evaporation temperature. It is mainly because the flow rate sucked into the chambers through the supplementary inlets increases with the decrease of the ejection coefficient so that the discharge temperature of the coupled system reduces.

4.2 Influence of ejector construction on performances of the coupled system

To test the influence of ejector construction on the performances of the coupled system, three ejectors with the ejection coefficient of 0.1 were developed according to different designing conditions. As mentioned above, they are named ejector1, 2 and 3, respectively. Three experimental projects of the heat pump system coupled with separate ejector are designed. Their performances and the performances of QTSC heat pump system were compared respectively. The experimental results to analyze influence of three different constructions of ejector on performances of the coupled system are shown in Figure.7 - Figure.9, where ejector 3 owns an optimized construction.

The variation of heating capacity with the evaporation temperature is shown in Figure 7. It is seen that heating capacity of the coupled system with ejector 3 by optimized design is higher than that of the coupled systems with other two ejectors and QTSC heat pump system in a wide range of operation condition. It is about 3.3% higher than that of the coupled system with ejector 1 and is 7% higher than that of QTSC heat pump system when the evaporation temperature is -20ºC and the condensation temperature 45ºC. When the evaporation temperature is -25ºC and the condensation temperature keeps constant, it is about 13% higher than that of the coupled system with ejector 2 and 7% higher than that of QTSC heat pump system. It is mainly because the coupled system with ejector by optimized design keeps a high working efficiency in a wide range of operation conditions. Therefore, the achievable intermediate pressure and the flow rate through the supplementary inlets entering the compressor increases. The heating capacity of the coupled system with ejector 1 or 3 is higher than that of QTSC heat pump system. It is mainly because the flow rate through the supplementary inlets of the compressor in the coupled system is higher than that of QTSC heat pump system as the entrained effect of the ejector. The coupled system with ejector 2 does not perform well as its designing condition is not reasonable.

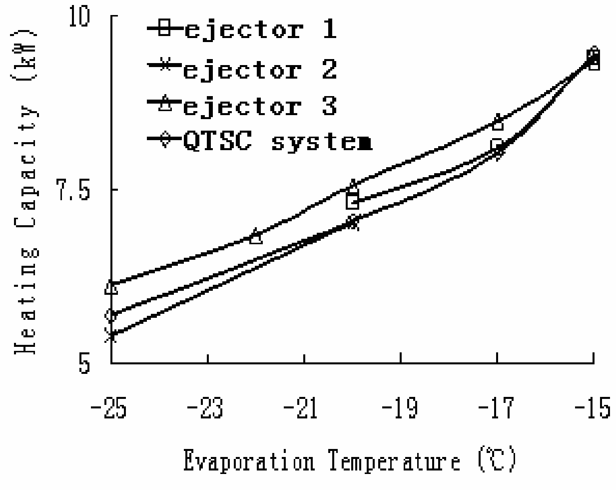

Figure7: Variation of heating capacity with evaporation temperature

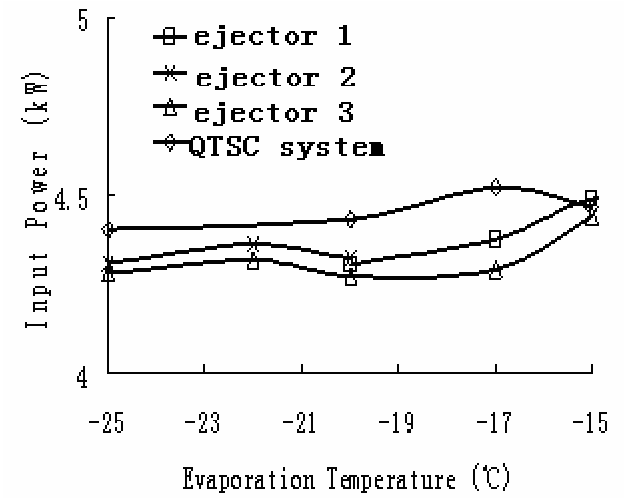

Figure8: Variation of input power with evaporation temperature

The variation of input power with the evaporation temperature is shown in Figure 8. It is seen that the input power of the coupled system is smaller than that of QTSC heat pump system. It is mainly because that the flow rate through the suction inlet of the compressor in QTSC heat pump system is more than that of the coupled system as the former system has no entrained effect of ejector. So the compression work in the first stage of compression processes in QTSC heat pump system increases, leading to the input power being higher. The input power of the coupled system with ejector 3 by optimized design is smaller than that of the system with ejector 1 or 2. When the evaporation temperature is -20ºC and the condensation temperature 45ºC, the input power of the coupled system with ejector 3 is 4.29 kW, and 2% smaller than that of the coupled system with ejector 1. When the evaporation temperature is -25ºC and the condensation temperature keeps constant, the input power of the coupled system with ejector 3 is 4.28 kW, and 1% smaller than that of the coupled system with ejector 2. It is demonstrated that the input power of the coupled system with ejector 3 is smaller than the system with ejector 1 or ejector 2. It is mainly because the ejector by optimized design can attain higher pressure at its exit, namely intermediate pressure. So the flow rate through the supplementary inlets of the compressor increases, but the flow rate through the suction inlet decreases accordingly, leading to improvement of the first-stage compression process and reduction of its energy consumption.

It is also observed that the variation rate of input power with the evaporation temperature is slight. Therefore, it is considered that the input power of the coupled system keeps constant nearly. The varying trend of heating COP with the evaporation temperature is similar to that of the heating capacity. The heating COP of the coupled system with ejector 3 is higher than that of the system with ejector 1 or 2 and QTSC heat pump system in wide range of operation conditions. It is about 4% higher than that of the coupled system with ejector 1 when the evaporation temperature is -20ºC and the condensation temperature 45ºC, and is 14% higher than that of the coupled system with ejector 2 when the evaporation temperature is -25ºC and the condensation temperature 45ºC. It is observed that the COP of the coupled system with ejector 3 still keeps high under the off-designing conditions. Therefore, the COP of the coupled system can be improved further by optimizing the construction of the ejector in wide range of operation conditions.

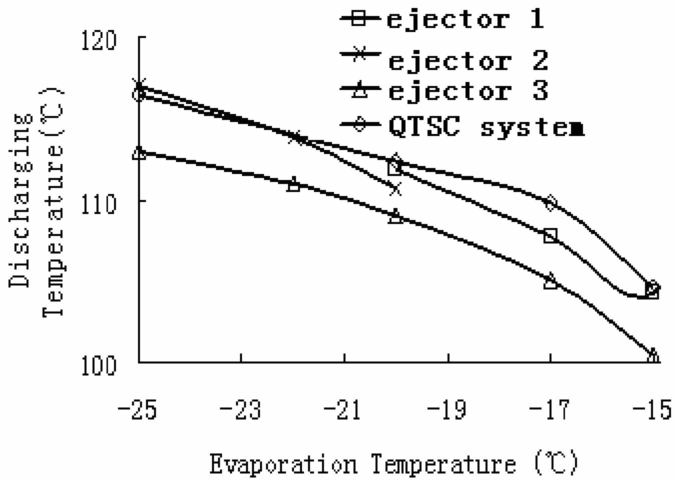

Figure9: Variation of discharge temperature with evaporation temperature

The variation of discharge temperature with the evaporation temperature is shown in Figure 9. It is seen that discharge temperature of the coupled system with ejector 3 by optimized design is lower than that of the system with ejector 1 or 2 and QTSC heat pump system in wide range of operation conditions. The discharge temperature of the coupled system with ejector 3 is 109ºC, which is 3ºC lower than that of the coupled system with ejector 1, and 3.5ºC lower than that of QTSC heat pump system, when the evaporation temperature is -20ºC and the condensation temperature 45ºC. When the evaporation temperature reduces to -25ºC, the discharge temperature of the coupled system with ejector 3 is 117ºC, which is 4ºC lower than that of the coupled system with ejector 2, and 3.3ºC lower than that of QTSC heat pump system. It is mainly because the intermediate pressure attained by the ejector by optimized design is higher and the flow rate through the supplementary inlets of the compressor increases. Therefore the second-stage compression process of the compressor is cooled well by the refrigerant through the supplementary inlets and the discharge temperature decreases accordingly. There is a greater irreversible loss in the throttling process of supplementary circuit in QTSC heat pump system, and its discharge temperature is higher.

5 CONCLUSIONS

From the above analysis for the experimental results of the coupled system with different ejector, it is concluded as follows.

1. The ejector with optimum ejection coefficient performs better in wide range of operation conditions. The heat pump system coupled with the ejector with ejection coefficient of 0.1 has a higher coefficient of performance in the experiments.
2. The heat pump system coupled with the ejector by optimized design own higher heating capacity, heating COP and lower input power, and can run steadily and efficiently in wide range of operation conditions.

ACKNOWLEDGEMENTS

We are very grateful to the support of National Natural Science Foundation No. 50776001.

6 REFERENCES

Ma G, Shao S. 2002.“Research on heat pump cycle for air conditioning in cold regions, “*Acta Energiae Solaris Sinica*, Vol.23, Part 1, pp. 17-21.

Ma G, Yan Q. 2002.”Experimental research on scroll compressor with economizer for heat pump,” *Refrigeration Journal*, Vol.23, Part 1, pp. 27-31.

Zhao H. 2005. “Theoretical analysis and experimental study on heat pump system with flash-tank coupled with scroll compressor,” Thesis of *Master Degree*, Beijing: Beijing University of Technology.

Fan x. 1997. “Study on a new kind of vapor-compression/ejection hybrid refrigeration cycle,” *Doctor dissertation*, Xi＇an: Xi＇an Jiaotong University.

Fan X,Yin J. 1995. “A kind of two-stage compression/ejection refrigeration cycle, “Journal of Zhongyuan Institute of Technology, Vol.6, Part4, pp. 10-14.

Fan X,Yin J. 1996.”Study on a new kind of vapor-compression/ejection hybrid refrigeration cycle,”Journal of Xi＇an Jiaotong University, Vol.30, Part5, pp.5-11.

Wu J, Liu ZH. 2000.”Thermodynamics analyze on a a new kind of vapor-compression/ejection hybrid refrigeration cycle,” Fluid Machinery, Vol.28, Part8, pp.47-49.

Ma G, 2005, A heat pump (refrigeration) system coupled with ejector and sub-cooled storage tank, *China Patent*, ZL 2005 1 0063463. 3.

Yu L, 2006. ”Simulation and Experiment Study on the Quasi Two-Stage Compression Heat Pump System Coupled with Ejector,” Thesis of *Master Degree*, Beijing: Beijing University of Technology.