EXPERIMENTAL STUDY ON HEAT PUMP CYCLE OF FLASH-TANK ECONOMIZER WITH SCROLL COMPRESSOR

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ABSTRACT

The heat pump system with flash-tank coupled with scroll compressor is presented, and is compared with the system with sub-cooler in component and characteristic. The heat pump prototype has comprehensively experimented and its behavior has analyzed by the measured data. It is found that the heating capacity of the prototype decreases when the evaporation temperature becomes low, but the decrement is much slower than that of conventional air-source heat pump, and that the power input varies slightly with the evaporation temperature. The heat pump system with flash-tank can improve its performances more efficiently than the system with sub-cooler can under the conditions of low ambient temperature, so it has broad prospects to be used in air-source heat pump with small capacity.

Key words: *heat pump, economizer, scroll compressor, flash-tank.*

1 INTRODUCTION

With development of national economics and improvement of living level, people have an urgent requirement in heating comfort, which stimulates the development in new types of heat pump for air conditioning. Compared with other types, air-source heat pump (ASHP), which absorbs heat from its surrounding atmosphere, is very convenient to use, so it is widely running for heating rooms(Wang F, Fan X 2002). However，for a long time, the application area of ASHP has been limited in temperate zone, such as Yangtze River basin and southern China. At present, the lower limit of ambient design temperature looked up in Chinese air conditioning handbooks is -3℃(Shen M, Song Z 2002). Consequently，conventional air-source heat pump without improvement cannot operate efficiently and steadily during winter in cold regions such as Yellow River basin and northern China as its heating capacity decreases sharply and the discharging temperature of the compressor increases continually.

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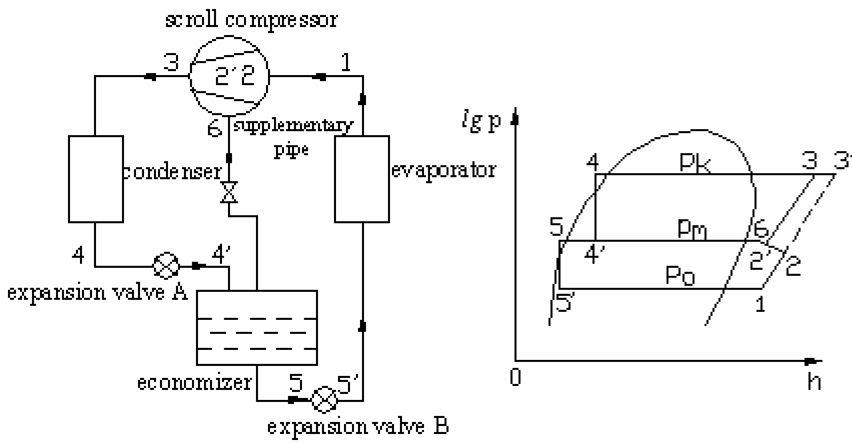
To enlarge the application area of ASHP, many efforts to improve ASHP has been made in the world recent years, for example, two stages with two compressors, vapor injection with an economizer, vapor injection with an economizer and a suction gas super-heater, and a separate heat pump loop for the sub-cooling of the condensate. The criteria of the improving projects are: (1) the heat pump system is uncomplicated in component and easy to realize; (2) the system should work reliably in lower ambient temperature, and the heating capacity can satisfy the heat requirement; (3) the system has a higher coefficient of performance in higher ambient temperature. Therefore, the heat pump system with flash-tank coupled with scroll compressor is an economical and effective project according to the above criteria (Zogg M 2002 and Ma G 2001).

The heat pump system with economizer has two basic types, namely sub-cooler and flash-tank. The heat pump system with sub-cooler coupled with scroll compressor was studied in detail(Ma G et al 2001,2002, 2003, 2004 and Chai et al 2002, 2003), and the prototype for heating in cold regions was developed. The outcomes showed that the prototype can smoothly work and produce sufficient heat to satisfy heating requirement when ambient temperature is even as low as -15^{o}C (Ma G, Chai Q, Jiang Y 2003). As the heat pump system with sub-cooler has one compressor and one-stage throttling, it is difficult to assure that the vapor into the supplementary inlets of the compressor is in saturation state. However, the heat pump system with flash-tank has one compressor and two-stage throttling, so it is simpler in component than the system with sub-cooler, and the vapor into the supplementary inlets of the compressor is very close to saturation state. In this paper, the heat pump system with flash-tank coupled with scroll compressor is comprehensively analyzed, and the experimental investigation for the prototype is presented. By the comparison of their performances, it is found that the heat pump system with flash-tank can improve heating capacity more efficiently than the system with sub-cooler under conditions of low ambient temperature.

2 HEAT PUMP SYSTEM WITH ECONOMIZER

2.1 System with Flash-Tank

The flow chart of the heat pump system with flash-tank is shown in Fig. 1a. The scroll compressor with supplementary inlets is used in the system. The superheated refrigerant with high temperature and pressure is discharged by a scroll compressor (state 3) and flows through the condenser, in which the refrigerant can transfer its heat to cooling medium and then becomes sub-cooled liquid (state 4). The heated cooling medium can be used for heating or other purpose. The liquid refrigerant from the condenser flows through the expansion A, in which the pressure of the refrigerant can be dropped to certain pressure (state 4’) between the suction and discharge pressures of the compressor (also called intermediate pressure or economizer pressure). It then flows into flash-tank, namely economizer, in which the refrigerant mixture from the expansion A separates the vapor in the top and the liquid at the bottom. The vapor in the top is partly sucked into the compressor through the supplementary inlets (state 6), and the sub-cooled liquid at the bottom (state 5) flows through expansion the valve B in which the refrigerant pressure is dropped to evaporation pressure (state 5’). The refrigerant mixture flows into the evaporator in which the refrigerant absorbs heat from the surrounding atmosphere and then becomes vapor with low pressure. The vapor from the evaporator is sucked into the compressor through its suction port (state 1) and compressed to intermediate pressure (state 2). When the supplementary pipe is turned on, the vapor in state 2 is mixed with the vapor from the supplementary inlets (state 6) until the compression chamber is cut off with the inlets (state 2’) and then compressed continually to condensation pressure(state 3). The vapor from the compressor flows into the condenser and the cycle is completed.



(a) Flow Chart **(b) the Cycle in p-h Diagram**

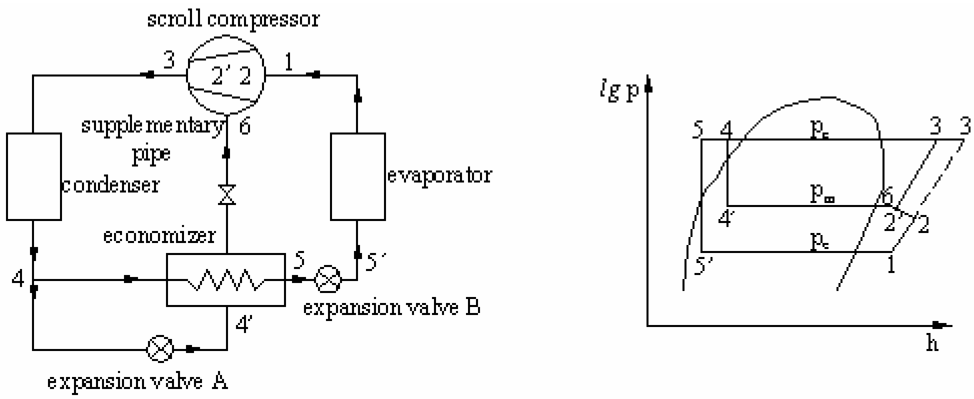
Fig. 1 Principle of the Heat Pump System with Flash-Tank

2.2 System with Sub-Cooler

The flow chart of the heat pump system with sub-cooler is shown in Fig. 2 a. Its flowing circuit are different that of the system with flash-tank. The sub-cooled refrigerant liquid from the condenser is divided into two parts. One part (state 4) flows directly into sub-cooler, and the other part flows through the expansion B in which the pressure of the refrigerant is dropped to intermediate pressure (state 4’). The refrigerant from the expansion B then flows into the sub-cooler, and there is a heat transfer process between the two parts of refrigerant in the sub-cooler. The part of refrigerant from the expansion B is vaporized and sucked into the compressor through the supplementary pipe, and the other part of refrigerant is sub-cooled (state 5) and then flows through the expansion A (state 5’) into the evaporator in which the refrigerant is vaporized. The mixed and compressed processes of the refrigerant in the compressor are same as those existing in the system with flash-tank.

2.3 Comparison of the Systems

According to the above analysis, there is a two-stage throttling process in the heat pump system with flash-tank, and the two parts of the refrigerant are separately throttled in the system with sub-cooler. So the system with flash-tank is closer to the two-stage system and moreover is simpler in component. On the other hand, the superheating degree of the refrigerant into the supplementary inlets of compressor in the system with flash-tank is lower than that in the system with sub-cooler as the sub-cooler is a wall type heat exchanger and the heat exchange is weaken the wall. Therefore, the heat pump system with flash-tank can get a greater improvement in performance and reliability than the system with sub-cooler, which is crucial to an efficient and steady operation of air-source heat pump under conditions of low temperature.



(a) Flow Chart **(b) the Cycle in p-h Diagram**

Fig. 2 Principle of the Heat Pump System with Sub-Cooler

3 ANALYSIS OF THE CYCLE WITH FLASH-TANK

3.1 Analysis of Thermodynamic Cycle

Assuming that the mixing process in the working chamber of the compressor is the process in which the two parts of the refrigerant is mixed isasterically and then compressed adiabatically. The empiric formula of the dimensionless flow rate through supplementary circuit, a , can be expressed as:

$$a = \frac{q_{mb}}{q_{mk}} = \frac{q_{mk} - q_{mo}}{q_{mk}} = \frac{v_2}{RkT_6}(p_6 - p_2) \qquad (1)$$

where

q_{mb} —mass flow rate of refrigerant in the supplementary circuit (kg/s)

q_{mo} —mass flow rate of refrigerant in the evaporator (kg/s)

q_{mk} —mass flow rate of refrigerant in the condenser (kg/s)

v_2 —specific volume of refrigerant in state 2 (m^3/kg)

R —gas constant for refrigerant，[$\mathrm{k}J/(\mathrm{kg}\cdot\mathrm{k})$]

k —adiabatic index for refrigerant

T_6 —refrigerant temperature in state 6 (K)

p_2、p_6 —pressure of refrigerant in state 2、6 (kPa)

Assuming that compressing process 1-2 is isentropic, the refrigerant enthalpy in state 2 is:

$$h_2 = h_1 + w_{1-2} \tag{2}$$

where, w_{1-2}—isentropic compressing work of process 1-2（kJ/kg）

Supposing the supplementary suction process is adiabatic, the refrigerant enthalpy in state 2’ is approximately:

$$h_{2'} = ah_6 + (1-a)h_2 \tag{3}$$

Assuming the compressing process 2’-3 is also isentropic, the refrigerant enthalpy in state 3 is:

$$h_3 = h_{2'} + w_{2'-3} \tag{4}$$

where, $w_{2'-3}$—isentropic compressing work of process 2’-3（kJ/kg）

Based on the energy conservation equation of the flash-tank, the refrigerant enthalpy in state 5 is

$$h_5 = \frac{h_4 - ah_6}{1-a} \tag{5}$$

3.2 Performances of the Cycle

heating capacity $$Q_{\mathrm{k}} = q_{mk}(h_3 - h_4) \tag{6}$$

cooling capacity $$Q_{\mathrm{o}} = q_{mo}(h_1 - h_5) \tag{7}$$

compressing work $$W = q_{mk}(h_3 - h_{2'}) + q_{mo}(h_2 - h_1) \tag{8}$$

COP for heating $$COP_h = Q_K / W \tag{9}$$

4 EXPERIMENTAL APPARATUS

The flow chart of the experimental apparatus for testing the dynamic performance of the prototype heat pump with flash-tank is shown Fig. 3 R22 was used as the refrigerant in the prototype, and glycol-water solution as chilling substance for the evaporator. The electric heater in glycol-water tank is adjustable so that the temperature of the solution is kept constant in measurement. Water was used as coolant for the condenser, and its temperature was controlled by the air flow rate through the fan-coil unit (Ma G, Chai Q, Jiang Y 2003).

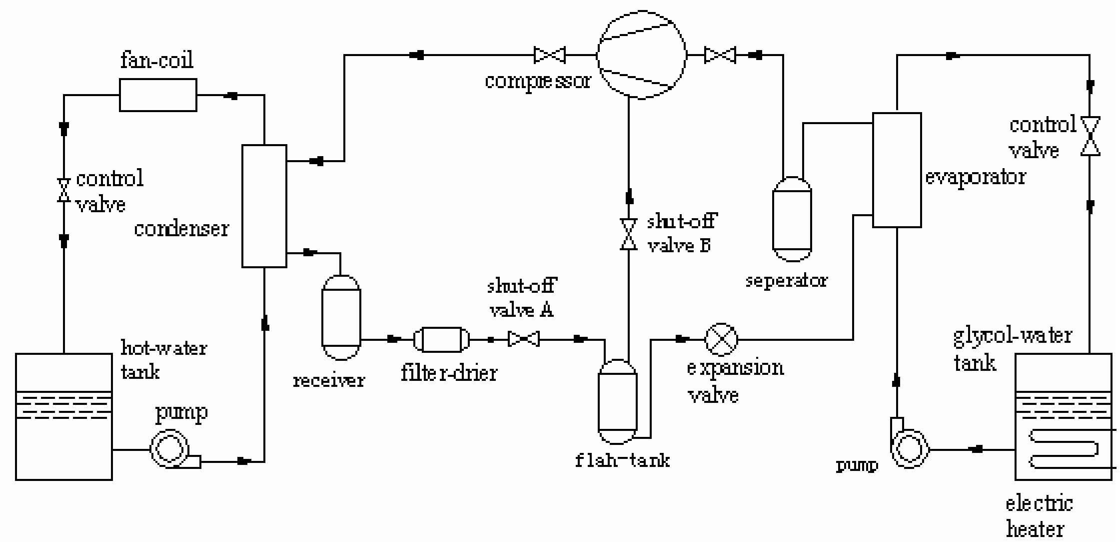


Fig. 3 Flow Chart of the Prototype with Flash-tank

5 RESULTS AND DISCUSSIONS

The dynamic performances of the prototype are plotted as the curves shown in Fig. 4 to Fig. 8 when the condensation temperatures are 42°C and 45°C, respectively. For comparison, the performances of the prototype with sub-cooler (Chai Q, Ma G, Jiang Y 2003) are adopted here

5.1 Heating Capacity

The variations of heating capacity with the evaporation temperature are shown in Fig. 4 when the condensation temperatures are 42°C and 45°C, respectively. The heating capacity at the condensation temperature of 45°C is slightly more than the one at 42°C. When the condensation temperature is kept constant, the heating capacity varies linearly with the evaporation temperature, but the varying rate is much smaller than that of conventional heat pump system. The heating capacity of the prototype is approximately 8.15 kW when the evaporation temperature is -25°C and the condensation temperature is 45°C, and this amount of heating capacity can satisfy the requirement for heating rooms in frozen weather in cold regions. From Fig. 4, it was also observed that the heating capacity of the system with flash-tank is larger than that of the system with sub-cooler under the measured operation conditions. For the condition of the evaporation temperature of -25°C and condensation temperature of 45°C, the heating capacity of the system with flash-tank 10.5% larger than that of the system with sub-cooler.

5.2 Power Input

The variations of power input with the evaporation temperature are shown in Fig. 5 when the condensation temperatures are 42°C and 45°C, respectively. For the system with flash-tank, the power input increases slightly with decrease of the evaporation temperature, which is different from conventional heat pump system and the system with sub-cooler. The power input of the conventional system varies linearly with evaporation temperature, but the one of the system with sub-cooler decreases slightly with decrease of the evaporation temperature. This is because the power input of heat pump depends mainly on the pressure ratio and the mass flow rate of the compressor. For conventional system, the pressure ratio of the compressor becomes high and the mass flow rate decreased remarkably in result when the condensation temperature kept constant and the evaporation temperature is decreased. For the system with flash-tank, though the flow rate through the suction port of the compressor decreases with decrease of the evaporation temperature, the flow rate through the supplementary inlets increases simultaneously. For example, the flow rate through the supplementary inlets contributes approximately 36.6% to the total flow rate of the compressor under the condition of the evaporation temperature of -25°C and the condensation temperature of 45°C. Thus, the total mass flow rate of the compressor varies slowly with the evaporation temperature, and that leads a slow increase of the power input with decrease of the evaporation temperature.

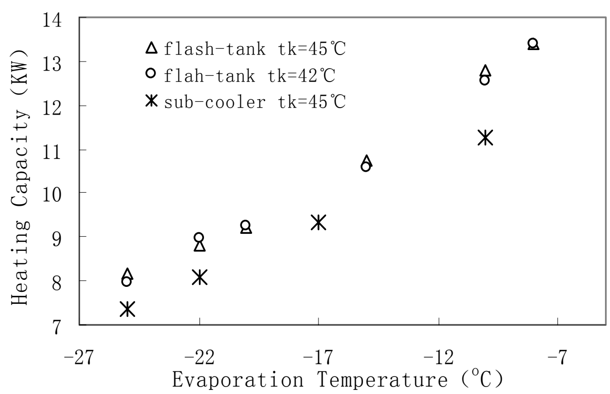


Fig. 4 Heating Capacity

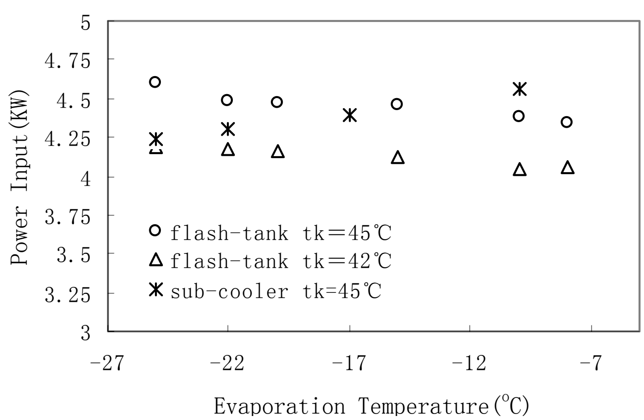


Fig. 5 Power Input

5.3 COP for Heating

The variations of coefficient of performance (COP) for heating with the evaporation temperature are shown in Fig. 6 when the condensation temperatures are 42°C and 45°C, respectively. The COP becomes high with increase of the evaporation temperature and becomes small with increase of the condensation temperature. From Fig. 6, it is observed that the COP of the system with flash-tank is higher than that of the system with sub-cooler under the measured conditions. For example, the COP of the system with flash-tank is 4.3% higher than that of the system with sub-cooler under the condition of the evaporation temperature of -25°C and condensation temperature of 45°C. This is mainly because the superheat degree of the refrigerant into the supplementary inlets of the compressor in the system with flash-tank is much less than that in the system with sub-cooler as the sub-cooler is a wall heat exchanger. So the system with flash-tank is helpful to improve the compression process and attain high a COP in result.

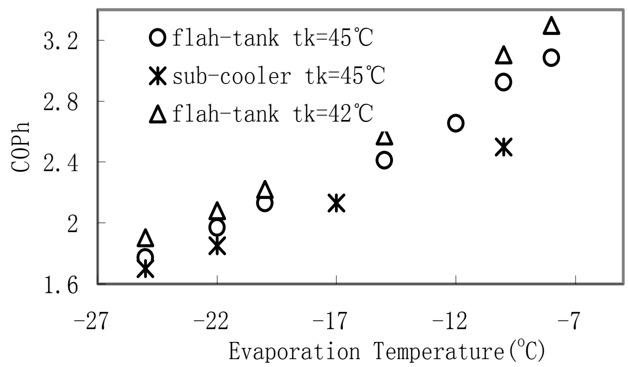


Fig. 6 COP for Heating

5.4 Discharging Temperature

The variations of the discharging temperature of the compressor with the evaporation temperature are shown in Fig. 7 when the condensation temperatures are 42°C and 45°C, respectively. It is clearly observed that the discharging temperature increases when the evaporation temperature decreases and/or the condensation temperature increases. This seems to be similar to the trend of the discharging temperature in conventional heat pump system. However, the discharging temperature of the compressor in the system with flash-tank is much less than that in conventional system and keeps the value under 130°C all the time. The discharging temperature in conventional system increased continually under the conditions of the evaporation temperature of -15°C and the condensation temperature of 45°C. If it worked for long time, the compressor would be broken down. Therefore, the heat pump system with flash-tank could effectively reduce the discharging temperature of the compressor and enlarge its working life in turn.

5.5 Intermediate Pressure

The variations of the intermediate pressure with the evaporation temperature are shown in Fig. 8 when the condensation temperatures are 42°C and 45°C, respectively. The intermediate pressure almost keeps constant with the evaporation temperature and increases when the condensation temperature becomes high.

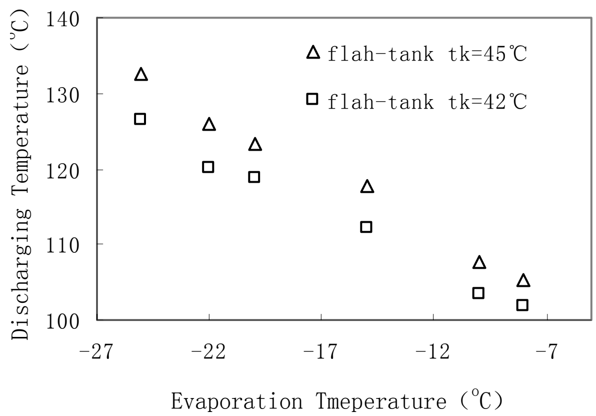


Fig. 7 Discharging Temperature

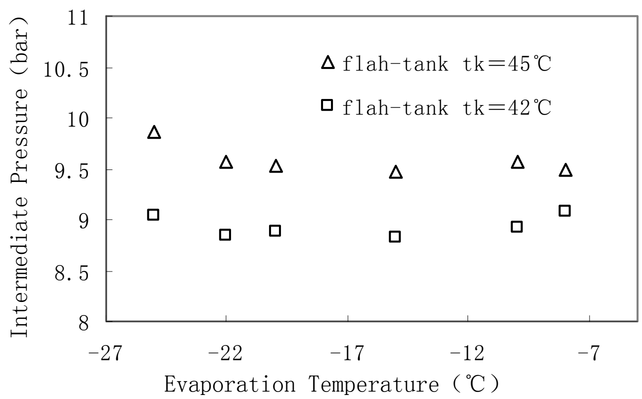


Fig. 8 Intermediate Pressure

6 CONCLUSIONS

Based on the above analysis, it is conclude that

(1) For the heat pump system with flash-tank, the heating capacity decreases with decrease of the evaporation temperature, but the decrement is much smaller than that of conventional heat pump system. The heating capacity of the prototype is approximately 8.15 kW when the condensation temperature is 45^0C and the evaporation temperature is -25^0C, and this amount can satisfy the requirement for heating in severe weather in cold regions. The electric power input varies slightly with the evaporation temperature as the flow rate of the refrigerant through the supplementary inlets of the compressor increases with decrease of the evaporation temperature.

(2) Under the operation conditions of low ambient temperature, the heat pump system with flash-tank can improve the heating performances more efficiently than the system with sub-cooler. Moreover, the system with flash-tank is uncomplicated in component and easy to construct, so it is suitable to the application in air-source heat pump with small size.

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ACKNOWLEDGEMENTS

We are very grateful to the support of Beijing Natural Science Foundation No. 3042004, and express our heartfelt thanks to Mr. Wu Xue-zhi, Prof. Wu Li-zhi, Miss Zhang Jing and Mr. Wu Xiao-hua for their effective help in the development and experiment of the prototype.