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## Experimental Investigation on the Two-stage Compression Heat Pump Water Heater System with Refrigerant Injection

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### ABSTRACT

Nowadays heat pump water heater becomes a very hot topic in hot water industry. However it still has many problems such as higher condensing temperature, large-scale operation conditions and lower COP in cold regions. Based on these problems, the paper presents a prototype assembled with a two-stage rotary compressor which can be used in cold regions. The working principle and the basic feature are introduced in this paper. The operation performance was measured under different ambient temperatures especially  $-7^{\circ}\text{C}$ ,  $-15^{\circ}\text{C}$ , and it is also discussed about the performance, heating capacity and parameters of the system with the vapor injection. The influence factor and the trend of optimization design are also demonstrated.

The experiments show that the prototype can provide much better energy performance than the conventional heat pump water heater especially in cold regions. The heating capacity can even increase 40% when the ambient temperature is  $-15^{\circ}\text{C}$ . The improvement rate of heating capacity varies with the water temperature, while the total heating capacity enhances obviously when the mid-pressure refrigerant injection is available. It is important to control the mid-pressure and injection refrigerant volume for the enhancement of all the heating periods.

### 1. INTRODUCTION

The heat pump water heater (HPWH) uses a vapor-compression refrigeration cycle, like a refrigerator or air conditioner, and the coefficient of performance (COP) largely compensates for primary electricity conversion loss. HPWHs are commonly installed in basements, attics, garages or utility rooms, where they take heat from the air at relatively low temperature and reject heat to the water tank. During the process, most units are also cooled and dehumidified, which can be valuable. Compared with conventional electric-resistance water heaters, HPWHs have a high initial cost. However, they can save significant amounts of energy and money, and often recover the system's extra cost within several years. Therefore, it is obvious to be energy saving, environmental friendly.

When the hot water temperature is  $55^{\circ}\text{C}$ , the condensing temperature is higher than the hot water temperature, and the condensing temperature maybe reach  $65^{\circ}\text{C}$ , which is the upper limit for the common compressor of air conditioner. Because the discharging temperature is higher than the common refrigeration system, and the system runs all the year, the compressor of HPWH must be especially taken into account. In cold regions there is even high demand on hot water supply, but owing to the technical and economical issues, air source heat pump is not considered conventionally. So the common HPWH can be only used in those areas where it is over  $0^{\circ}\text{C}$ . To overcome the above-mentioned problems, we assembled a prototype using a two-stage rotary compressor with refrigerant (R410A) injection port which can improve the performance at low ambient temperature. Based on the prototype, this study performs experimental tests under different working conditions and provides some guidance for optimum design and manufacture of air source HPWH.

### 2. DESIGN OF HPWH

As shown in Figure 1, the prototype includes outdoor unit and an adiabatic water tank. The outdoor unit consists of a two-stage rotary compressor with an injection port, evaporator, electric expansion valve, storage container, solenoid valve, four-way valve and flash tank. The corresponding refrigerant state points in pressure-enthalpy diagram are shown in Figure 2. During the operation of the vapor injection cycle, the refrigerant from the condenser at state 4 passes through the first stage expansion device. The expanded two-phase refrigerant at a medium pressure enters the flash tank, in which the vapor and the liquid components separate into two streams. The saturated vapor with relatively low temperature at state 6 is injected to the intermediate-compression chamber through the injection port, where it mixes with the higher-temperature refrigerant at state 2 compressed from state 1 by the first-stage of the vapor-injected compressor. The mixed vapor at state 2' is compressed to the discharge pressure at state 3 through the second-stage compression. The saturated liquid exiting the flash tank at state 5 is expanded to two-phase flow at state 7 by the second expansion device. The two-flow enters the evaporator, and returns to the compressor suction line at state 1 as saturated vapor. When the solenoid valve in the liquid injection circuit is cut off, the prototype operates as a conventional HPWH. When the low-temperature liquid injects compressing chamber, the compressor will cool down and work under well conditions.

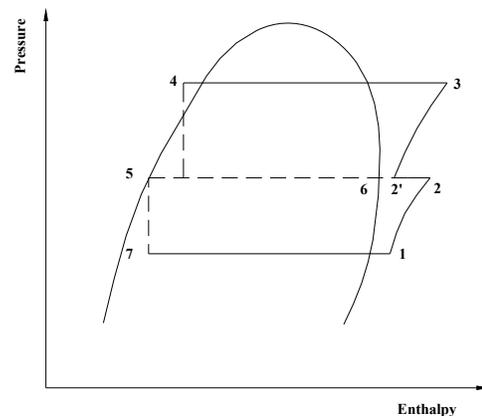
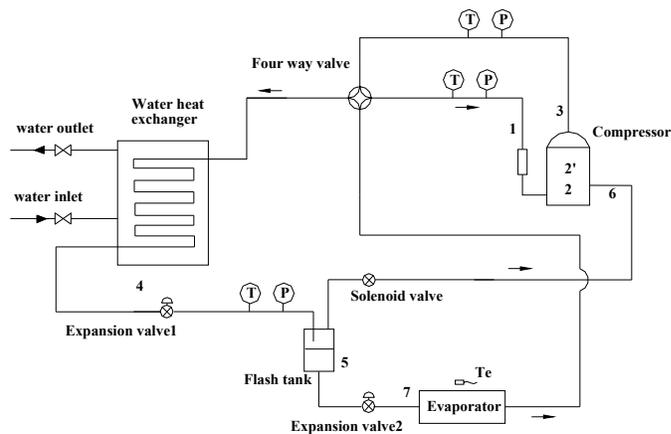


Figure 1: The flow chart of two-stage vapor-injection HPWH

Figure 2: The circle of the HPWH in P-h diagram

### 3. EXPERIMENTAL APPARATUS

The prototype was tested in the laboratory which consists of thermally-insulated wall, air and water handling equipments. The laboratory includes two chambers. In chamber one the water-handling equipment could supply water with given initial inlet temperature, and the air-handling equipment was provided in chamber two to control the dry-bulb and wet-bulb temperatures. The experimental equipments and photo of water tank are shown in figure 3.

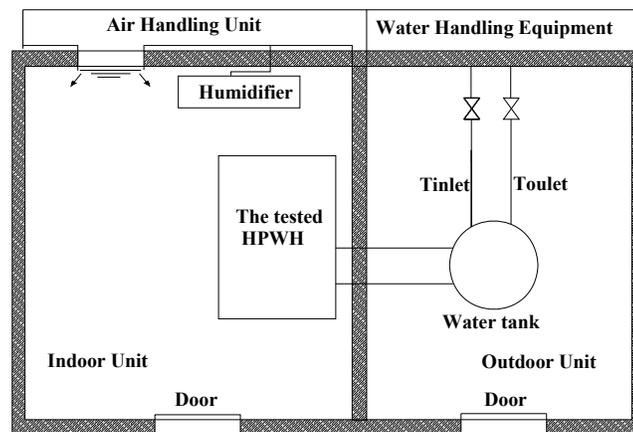


Figure 3: Experimental equipments and the tested HPWH including water tank with condenser coil inside

Because the condenser coil immerses into the tank, hot water temperature is different from the top down, and the COP of the HPWH can not be given directly by the testing system. Yet we can calculate the average COP during a period of time according to the equations (1)-(3) as follows.

The average heating power  $q$  can be given in equation (1):

$$q = Q / \Delta\tau = \rho_w c_w V_w (T_{w,2} - T_{w,1}) / \Delta\tau \quad (1)$$

Where  $Q$  is the total heating capacity in the operating period ( $\Delta\tau$ );  $\rho_w$  and  $c_w$  are density and specific heat of water, respectively;  $V_w$  is capacity of the water tank;  $T_{w,1}$ ,  $T_{w,2}$  are initial and final water temperatures in the tank. The performance of HPWH can be described as a time-average equation or a total average one. The time-average  $COP'$  can be shown as:

$$COP' = q'(\tau) / P'(\tau) \quad (2)$$

And the total average equation is

$$COP = Q / W \quad (3)$$

Where  $P'(\tau)$  and  $q'(\tau)$  are the time-average input power and heating capacity, respectively;  $W$  is the total electric energy consumption. For a whole heating cycle, the COP given as above is the average one when the initial and final water temperatures are 15°C and 55°C, respectively. The storage tank shall be mixed by an auxiliary pump that circulates water from the top to bottom of the tank at more than two tank volumes per hour. For a two-stage compression system, when the condenser and evaporation temperature are certain, it will have an optimum medium pressure in theory which can be calculated by exponential Equation  $P_m = \sqrt{P_k / P_e}$  (4)

Where  $P_m$  is the optimum medium pressure,  $P_k$  and  $P_e$  are the condensing and evaporating pressures respectively.

## 4. RESULTS

### 4.1 The Influence of Vapor Refrigerant Injection

Experimental results of Vapor-injection and conventional system are illustrated in Fig.4 and 5, which indicate the curves of heating capacity and COP at different inlet water temperature when the ambient temperature is -7°C and -15°C. As we can see, the COP is linear to reduce and the heating capacity trends to decrease rapidly according to the raise of water temperature, while for the conventional system, the heating capacity and COP decrease obviously. When ambient temperature is -7°C, the heating capacity changes from 3.3kW to 3.0kW for vapor-injection system, however, for the conventional system the heating capacity sharply decreases from 2.9kW to 2.2kW, and the difference is obvious with the inlet water temperature.

The condensing temperature rises with the increase of water temperature. As shown in Figs.6, the discharge and medium pressure increase rapidly, but the evaporating pressure curve is almost stable. The variations of system parameters are accordant with each other whatever the testing conditions are. The heating capacity and COP all decrease according to the condensing temperature and the lower ambient temperature is, the more heating capacity and COP decrease.

### 4.2 The Performance of System

Fig.7 shows that the vapor-injection system can effectively improve the system performance especially in cold regions. The heating capacity increases 7.2% with 4% COP improvement at -7°C ambient temperature and 10°C inlet water temperature, while the heating capacity increases about 40% with 22% COP improvement at -7°C ambient temperature and 50°C inlet water temperature. The heating capacity increases 14% with 8% COP improvement at -15°C ambient temperature and 10°C inlet water temperature, while the heating capacity increases about 64% with 43% COP improvement at -15°C ambient temperature and 50°C inlet water temperature. That's to say, according to the raise of condensing temperature, the improvement ratio of heating capacity and COP will be more visible compared to a conventional system. The air-source HPWH with vapor injection can work more efficiently than the HPWH without vapor injection at low ambient temperature. As we know, water is gradually

heated for the most of heat pump water heater, so it is difficult to keep the optimum improvement for the various water temperatures at the same ambient condition. Generally, for one heating cycle, the maximum improvement ratio of heating capacity is around 20~40% with 10~25% COP improvement as the change of inlet water temperature when the ambient temperature is  $-7^{\circ}\text{C}$  or  $-15^{\circ}\text{C}$ , which means that the small size of vapor injection HPWH can provide the same or even more heating capacity and higher COP in cold regions than the large size of conventional HPWH at certain ambient temperature. The results show that this technique will be more favorable at cold regions.

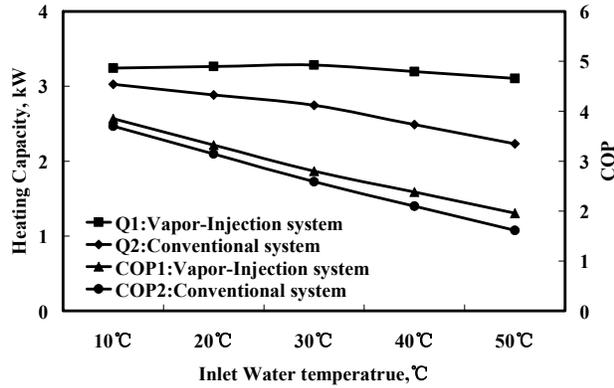


Figure 4: Heating capacity and COP vs. inlet water temperature, ambient temperature  $-7^{\circ}\text{C}$

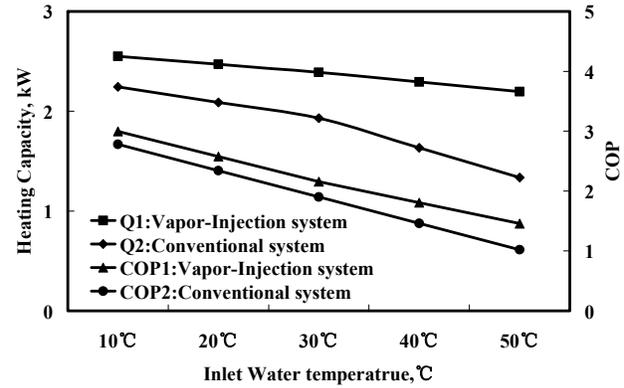


Figure 5: Heating capacity, COP vs. inlet water temperature, ambient temperature  $-15^{\circ}\text{C}$

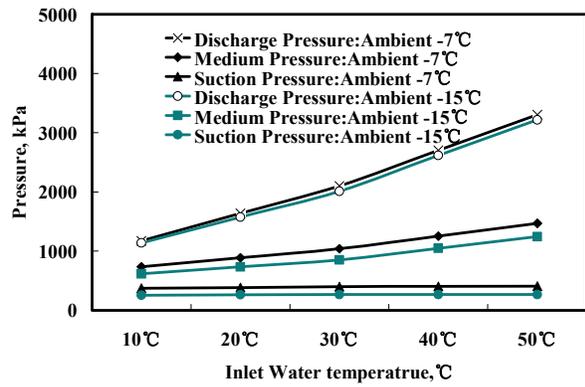


Figure 6: Discharge, medium, and suction pressure vs. inlet water temperature

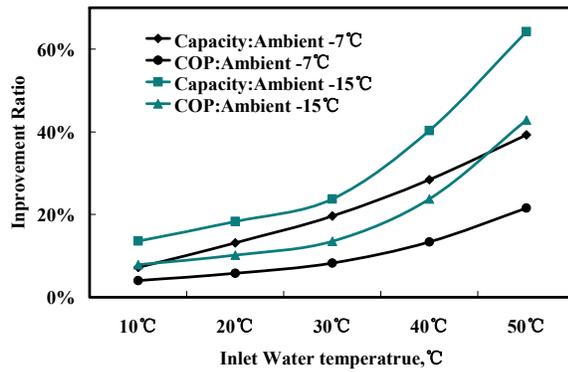


Figure 7: Improvement ratio of heating capacity and COP vs. inlet water temperature

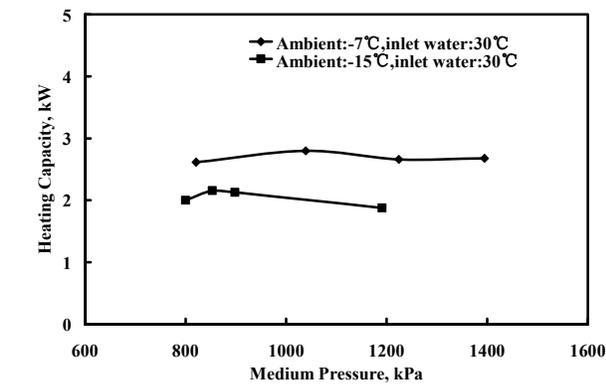


Figure 8: Medium pressure vs. heating capacity Curves

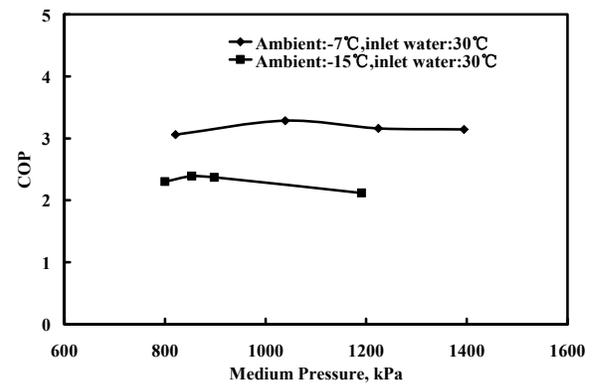


Figure 9: Medium pressure vs. COP

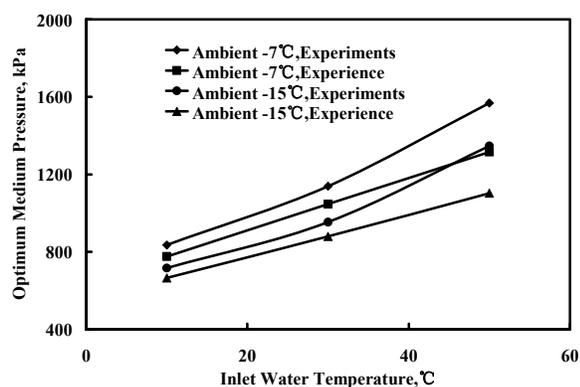


Figure 10: Curves of Optimum medium pressure at various water and ambient temperatures

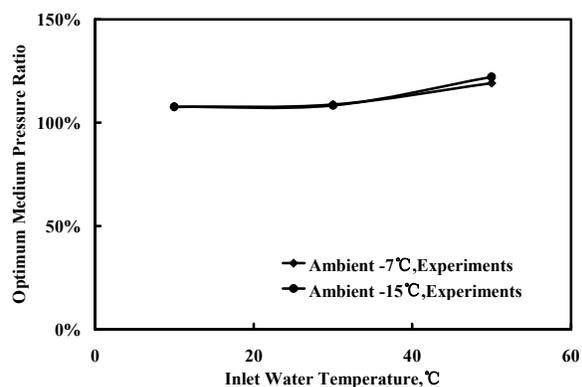


Figure 11: Optimum medium pressure ratio vs. experience

### 4.3 The Influence of Medium Pressure

The heating capacity and COP at different ambient conditions are plotted with different medium pressures in the flash tank in Fig.8 and Fig.9. As shown in Fig.8 and Fig.9, the heating capacity increases and then decreases with the medium pressure, as well as the COP, which means under certain condition, there is an optimum medium pressure and the vapor-injection system is more efficient. It is because the injection stream refrigerant increases as the medium pressure rises, which enhances the discharge refrigerant mass rate effect at the internal heat exchanger. On the other hand, the heating capacity decreases with the increased medium pressure. It is because the refrigerant enthalpy at the evaporator inlet increases with the increased medium pressure so that the enthalpy span across the evaporator reduces, which has a negative effect. The compressor discharges more refrigerant at the second stage and the injection mass flow increases with the increased medium pressure, which leads power consumption to increase. On the other hand, the increased medium pressure raises the liquid refrigerant in the flash tank so that the condenser has little refrigerant, which contributes to reduce power consumption. The combination of the two effects makes the change of the compressor power consumption not obvious. The COP and heating capacity at 30°C ambient temperature have the optimum points with the increased medium pressure.

Fig.10 shows the optimum medium pressure changes with inlet water temperature under several testing conditions. The experimental optimum medium pressure  $P_m$  can be calculated by Equation 4. As we can see, the optimum medium pressure of vapor-injection system increases with the increased inlet water temperature, which is more obvious with higher condensing temperature. It is illustrated by the curves of the experiential and experimental conditions and the optimum medium pressure calculated by experiential equation is always lower than the experimental data, which is various with the change of ambient temperature and inlet water conditions. When the ambient temperature is -7°C, the experimental optimum medium pressures are 835kPa and 1568kPa while inlet water temperatures are 10°C and 50°C, respectively. When the ambient temperature is -15°C, the experimental optimum medium pressures are 715kPa and 1346kPa while inlet water temperatures are 10°C and 50°C, respectively.

Fig.11 shows the difference based on the experiential optimum medium pressure. When the inlet water temperature is below 30°C, the optimum medium pressure is equal to  $1.08 * \sqrt{P_k / P_e}$ , and the ratio increases from 1.08 to 1.22 with the inlet water temperature. For the vapor-injection HPWH, the vapor refrigerant injection ratio is various at different condition. For the sake of higher efficiency, it is important to adjust the pressure in the flash tank to suit the optimum medium pressure. According to the experimental data, the optimum medium pressure is about  $1.08 * \sqrt{P_k / P_e}$  to  $1.22 * \sqrt{P_k / P_e}$ . In one heating cycle, the medium pressure needs to be adjusted with water temperature so that the heating capacity and COP can be optimum values. Because the water is heated gradually, the condensing pressure increases, while the condensing heat decreases, and the increased medium pressure increases the liquid refrigerant in the flash tank so that the vapor-injection circuit has more refrigerant. That is to say, the ratio of optimum medium pressure will increase at higher condensing temperature, with a little increase of power consumption and the heating capacity increases, so that COP increases.

## 5. DISCUSSIONS

When the ambient temperature is below 0°C, the higher condensing temperature is, the larger the improvement ratio of heating capacity is, as well as the COP. On the other hand, because of the resistance of the heat transfer, the condensing temperature is even 10°C higher than the hot water temperature, which causes extremely high discharging temperature and condensing pressure. As a result, HPWH is easy to overload and the life span will sharply decrease. However, the discharging temperature will decrease sharply using the vapor refrigerant injection circuit, and then the system will work under well condition. At the ambient temperature above 20°C, there is a certain improvement for the heat capacity because of the increase of power consumption, while it is gradually not obvious with the raise of ambient temperature.

When HPWH operates at ambient temperature below zero, it is easy to freeze in the evaporator and the ice becomes more and more thick, which causes heating transfer decrease, as well as COP. Based on the defrosting mode of traditional air conditioner, it must be especially considered and optimized according to the vapor-injection system. For the conventional defrosting method, the four-way valve changes the circuit of refrigerant when defrosting mode begins to work. The medium pressure decreases sharply, and liquid refrigerant is observed to flow even full of the flash tank at the beginning. It is difficult to control the level of liquid and the liquid refrigerant is very easy to be injected into the compressor. It absorbs heat from the water to defrost, and the water temperature decreases a little. On the other hand, it is a long time to reach the optimum medium pressure again, so that the optimum heating capacity and COP are difficult to reach for the whole heating cycle. In addition, for the heating operation, at a certain ambient condition, the medium pressure should be adjusted at intervals according to the condensing pressure, and the optimum operation will be obtained all the time.

## 6. CONCLUSIONS

The two-stage compressor with vapor-injection has been developed for HPWH application. The effects of vapor injection have been discussed at low ambient temperature. The vapor injection makes the most of contribution to the increase of heating capacity for water heating. The vapor-injection system can effectively increase the system performance especially in cold regions. For one heating cycle, the maximum improvement ratio of heating capacity is around 20~40% with 10~25% COP improvement as the change of inlet water temperature when the ambient temperature is -7°C or -15°C. For the vapor-injection HPWH, the vapor refrigerant injection ratio is various at different condition. When the inlet water temperature is below 30°C, the optimum pressure is equal to  $1.08 * \sqrt{P_k / P_e}$ , and the ratio increases from 1.08 to 1.22 with the inlet water temperature. Therefore, it is important that the medium pressure should be suitable with the condensing pressure, and the optimum operation will be obtained all the time.

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