Performance and defrosting effect study on the air-to-water heat pump with heat storage device

Zhiyi Wang[1,2*], Hongxing Yang[2] and Hao Huang[1]

[1]School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou, 310018, China; [2]Department of Building Services Engineering (Renewable Energy Research Group), The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

Abstract

The heat storage device is proposed to avoid the frequent on–off state under partial load, large variation of the supply and return water temperature and long defrosting time of air-to-water heat pump with plate heat exchanger for heating. The heat storage device is composed of a water tank, the inner double-pipe heat exchanger, appendages and the electric heater. The energy storage can reduce on–off times of the compressor. The energy storage and the electric heater can make up the shortage of heating during defrosting. Performance test shows that on–off times for the heat storage device unit compressor under partial load is about four times per hour compared six times per hour for the plate heat exchange unit. Defrosting time is reduced by 78 s by heat storage device unit and 84 s by heat storage device with electric heater unit. More steady running parameters, inlet heating water temperature of heat storage device or heat storage device with electric heater unit is about 35°C, while that of plate heat exchanger reduces to 30.73°C. Therefore, the designed heat storage device can improve the unit performance and is suitable for the new projects with air-to-water heat pumps.

Keywords: air-to-water heat pump; test; heat storage device; plate heat exchanger; defrosting

*Corresponding author: zywang-wf@163.com

Received 3 November 2013; revised 25 January 2014; accepted 8 April 2014

1 INTRODUCTION

Owing to the advantages of energy saving and environmental protection, air source heat pumps have found worldwide applications. About 90% of the world populations are in the suitable regions where for heat pumps heating and cooling from a global point of view [1].

Air-to-water heat pumps have been used for hot water production, space heating and air conditioning widely in Central and South China since 1990s. Comparison of energy performance between air-to-water and water-to-water heat pump in hotel applications was carried out in Hong Kong. It was found that the coefficient of performance (COP) of heat pumps was in the range of 1.5–2.4; however, the case study applied heat pumps to swimming pools in the subtropical region, and there is no frosting problem of the units [2]. Solar heat pump is also a kind of air-to-water heat pump, application of solar heat pump with tank for hot water production was discussed. The heat pump supplies auxiliary energy to the solar water heater to ensure reliable hot water supply, but the cooling performance and defrosting was not concerned [3]. The heating performance of the air-to-water heat pump driven by gas engine was modeled and analyzed. In the gas engine-driven air-to-water heat pump, waste heat can provide about one-third of the total heating capacity. However, most air-to-water heat pumps are of electric driven and have no waste heat to recovery [4]. How to improve air-to-water heat pump performance just as the frequent on and off under partial load, insufficient heating capacity was not mentioned in the above paper.

Air-to-water heat pump is a kind of air source heat pump. In winter in humid climates, there will be frost formation on the air-side surface of the heat exchanger. An insulating layer of frost will be built up over the air side of the heat exchanger coils and degrade the thermal performance of the air-to water heat pump by reducing airflow area [5]. To improve the heating efficiency of the air-to-water heat pump, frost needs to be removed periodically. Defrosting is a key problem of air-to-water heat pumps.

Some researchers have studied on the air source heat pump frosting and defrosting problems. A solenoid valve for thermal

doi:10.1093/ijlct/ctu020

expansion bypass relieves the shutdown problem. Defrosting and the following process switching can be facilitated by solenoid bypass. But, the defrosting time would not be shortened [5]. On the reverse-cycle defrost operation for an air-to-water heat pump, fan prestart method is used to prevent shutting down. The defrost dynamic characteristics in coil fan prestart and normal-start tests' were discussed. And, the result turned out to be very slight difference in system dynamics between two modes. [6]. Evaporator controlled multicircuit air-to water heat pump was investigated experimentally. Airflow maldistribution, which will result in the intermittent or unceasing hunting during the frosting period, often occurs in fin-and-tube heat exchangers in a medium heat pump. Heat exchangers in a medium heat pump are arranged in V-type or W-type rather than U-type for small heat pump [7]. A simulation model of the frosting process in a water heater unit was developed and validated using the experimental data. The investigation only includes the operational characteristics of the air-side heat exchanger under frosting and their effects on the performance of the unit [8].

Compared with the air-to-air heat pump, the capacity of air-to-water heat pump is larger. Water-side heat exchanger of the unit adopts compact plate heat exchanger nowadays which decreased the water capacity of the system. The unit capacity of air-to-water heat pump is often designed by the peak cooling load. However, the unit is always working at partial load conditions. Constant frequency single compressor unit adjusts the capacity by on and off control. Energy consumption of this intermittent operation control is larger than that of the continuous control [9]. System pressure will reach the equilibrium state at the unit off state. High condensing pressure is rebuilt during the starting period, and heat transfer resistance is to be overcome at the same time. It will last several minutes to reach the steady running conditions. Power consumption is larger, but the cooling or heating capacity is smaller than the steady conditions. On–off losses come into being owing to the lower partial load performance of this variable condition adjust working condition mode not correspond to the environmental load.

In this paper, air-to-water heat pump with water-side heat exchanger adopting heat storage device and electric heater is introduced to solve the problem of frequent on and off under partial load, insufficient heating capacity and larger water temperature fluctuations during frosting with plate heat exchanger.

2 DESCRIPTION OF THE HEAT STORAGE DEVICE

Water-side heat exchanger is double-pipe heat exchanger placed in the heat storage tank as shown in Figure 1. The heat exchanger is connected with the inlet and outlet of refrigerant connector on the tank. There is a vent valve, a relief valve and a drain valve on the tank. The heat storage tank is equipped with the built-in electric heater and the inlet and outlet for water supply and return as shown in Figure 1. The vent valve discharges the air in the tank and makes the double-pipe heat exchanger contact with water to fully enhance the heat transfer effect. The relief valve is used to discharge water to reduce the pressure when the pressure of the water in the system expands is larger than the set value, so as to ensure the security of the system. The impurities are generated when the water qualitative in the system changes and are drained through the drain valve when the water system is cleaned. Refrigerant exchanges heat with water through double-pipe heat exchanger to make water temperature reduce or increase and generate cold or hot water for space heating or air conditioning. Because the tank capacity is much larger, part of the cold or heat can be accumulated when the air condition terminal is out of the full load. The electric heater is turned on automatically by setting parameters. In winter, the electric heater covers the shortage of the heat generating capacity. The electric heater is also turned on to reduce the water temperature fluctuations when the water temperature drops when melting the frost or heating effect becomes worse.

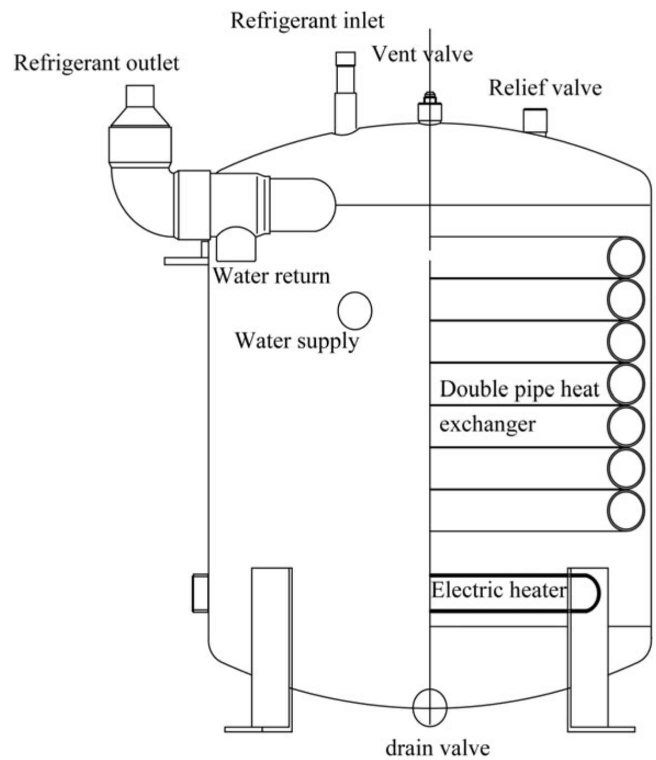

Figure 1. *Construction of the heat storage device.*

In order to obtain the counter current heat exchange, the refrigerant comes into the top copper pipe, which extends to the bottom and goes into the lowest copper pipe of double pipe, then, after several passes of the heat exchanger, comes back to the compressor at left of the top copper pipe as shown in Figure 2. The return water also comes into the double-pipes heat exchanger from the left of the top outer steel pipe, then after several passes of the heat exchanger in the middle of steel and copper pipe, comes out of the steel pipe and goes directly to the tank and finally comes out of the tank from the pipe on the

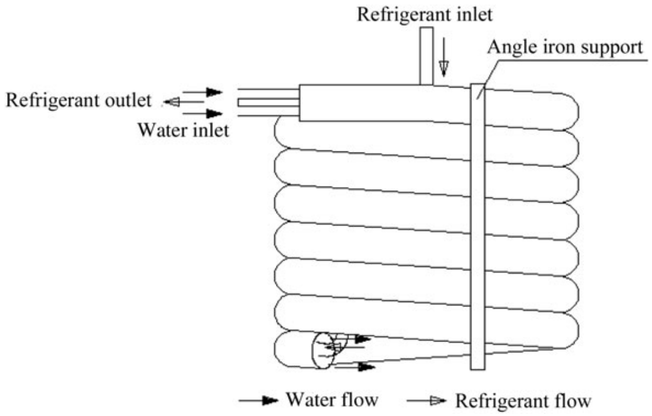

Figure 2. *Refrigerant and water flowchart of the double-pipe heat exchanger.*

upper left of the tank as water supply as shown in Figure 1. The angle iron support is welded in the outer steel pipe and the two heads welded to the water tank in Figure 2.

Unlike in the common air conditioning system, there is no insulation in the out steel tube for the heat transfer of the heat exchanger and water tank. The water has a larger density and thermal capacity to store heat for the system utility.

3 TEST METHODOLOGY

Cooling performance comparison tests on HLRS12.5 air-to-water heat pump were carried out in an air conditioner manufacturing company. The 1# unit water-side heat exchanger is the plate heat exchanger while 2# unit is the heat storage devices with double-pipe heat exchanger. Both of the units were tested in artificial climate chamber, which can provide realistic simulation of Chinese national standard working condition (cooling, heating and defrosting) and ensure the measurement of heat pump performance under repeatable condition. Test parameters of the artificial climate chamber are shown in Table 1. The specifications of the two tested heat pumps are listed in Table 2. The test apparatus consists of an indoor test section, an outdoor test section, a test heat pump and a data acquisition system (DAS). DAS automatically collected and continuously saves the experimental data during the test. There are 24 data channels in data recording instrument. All data channels scan consecutively every 6 s. To reduce experimental uncertainties, all temperature and pressure sensors were calibrated. Accuracies and tolerance of the sensors are shown in Table 3. Power measurement ME4zrt was used to record the electrical power input.

Based on the single-sample method proposed by Moffat [10], data collection uncertainties have been estimated. The artificial climate chamber can maintain environmental and room temperature changes within 0.3°C in a stable state operations. Pressure sensors were used for compressor pressure measurement. The two temperature sensors measure the water supply and return temperatures.

Table 1. *Test parameters of the artificial climate chamber.*

	Temperature	Relative humidity (%)	Fluctuations range of temperature
Indoor (cooling)	25.4	60	±0.56
Outdoor (cooling)	34.9	60	±0.56
Indoor (heating)	21.1	60	±0.56
Outdoor (heating)	−7.5	75	±0.56

Table 2. *Performance of the test unit.*

	Plate heat exchanger unit (1#)	Units with heat storage device (2#)
Nominal cooling capacity (kW)	12.5	12.5
Nominal heating capacity (kW)	15	15
Rated power (kW)	4.53	4.53
Scroll compressor input power (kW)	3.98	3.98
Electrical heater power (kW)	0	2
Fin heat exchanger	High efficiency copper tube bunched aluminum fins	High efficiency copper tube bunched aluminum fins
Water-side heat exchanger	Plate heat exchanger	Double-pipe heat exchanger
Thermal expansion valve	TDEX4	TDEX4
Refrigerant charge R22 (kg)	3.8	4.6
Water flow resistance (kPa)	105.4	70.17

Table 3. *Accuracies and tolerance of the sensors.*

	Type	Measuring range	Accuracies	Tolerance
Thermocouple	TX-GA-W	−50 to 230°C	±0.2	−0.1 to 0.1°C
Pressure sensor	MPM480	0 to 3 MPa	0.25	−5∼5 kPa
Power meter	WT130	0 to 15 kW	±1%	−4 to 4 W

The most common method of air-to-water heat pump frost removal is the reverse-cycle defrosting method. At the beginning of defrosting, a heat pump runs in the cooling mode. After defrosting, the heat pump is switched by four-way reversing valve back to the normal heating operation [8], which produces low pressure at the defrosting initial stage.

Plate heat exchanger units (1#), units with heat storage device of a not-enabled electrical heater (2#) and units with heat storage device of an enabled electrical heater (3#) were tested under defrosting condition in the same artificial climate chamber.

4 RESULT AND DISCUSSIONS

4.1 Cooling performance test result

It took 4 min and 12 s for 1# unit's supply and return water temperatures to reach 7 and 12°C, respectively, as shown in Figure 3. It took 8 min and 18 s for 2# unit's supply and return water temperatures to reach 7° and 12°C, respectively, as shown in Figure 4. The 1# unit was on and off six times from 10:06:01 to 11:05:07 a.m. The 2# unit was on and off four times from 14:11:53 to 15:15:14 p.m. During the test, the water flow resistance of 1# unit was 105.4 kPa, greatly >70.17 kPa of 2# unit. Obviously, the units with heat storage device reduces the on and off times under partial load in an hour, but the resistance is not increased.

4.2 Defrosting results and discussions

The unit discharge and suction pressure, supply and return water temperature under the defrosting condition were obtained by the DAS as shown in Figures 5–8. The extreme values of system parameters during the process of defrosting are listed in Table 4. By observing the discharge and suction pressure and supply and return water temperature during the test when the units were in defrosting, conclusions could be made:

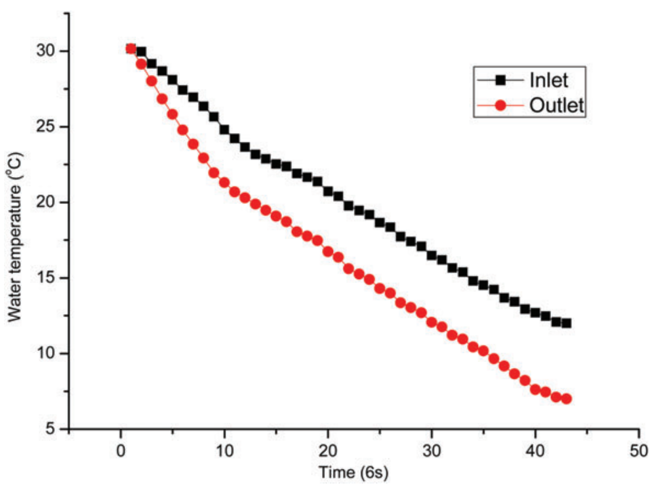

Figure 3. *Water temperature variation of the 1# unit when cooling.*

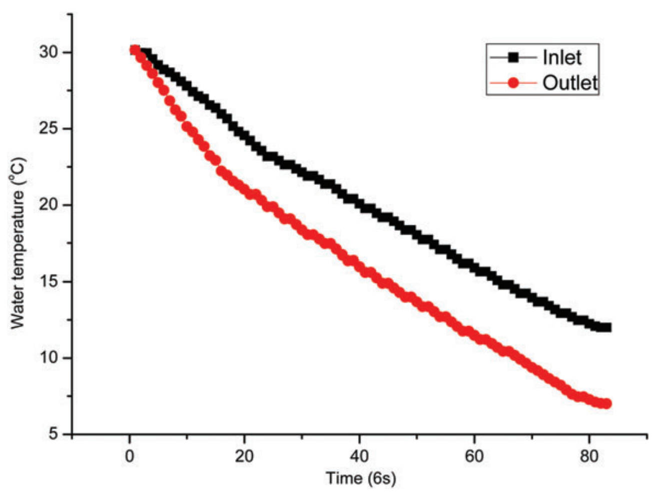

Figure 4. *Water temperature variation of the 2# unit when cooling.*

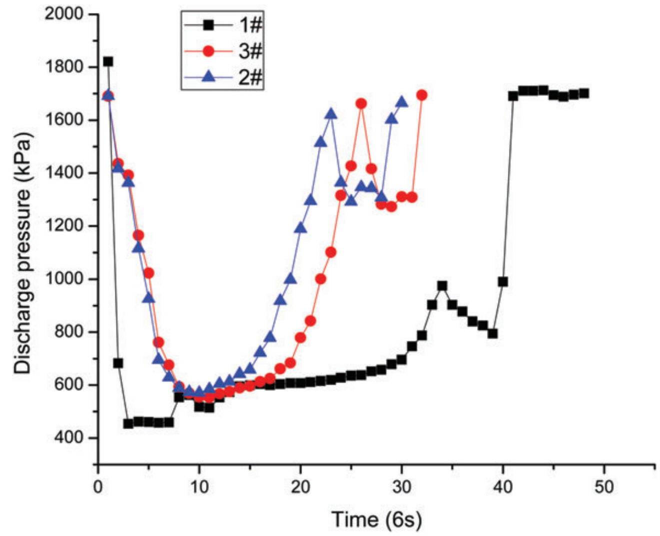

Figure 5. *Comparison of discharge pressure variation during defrosting.*

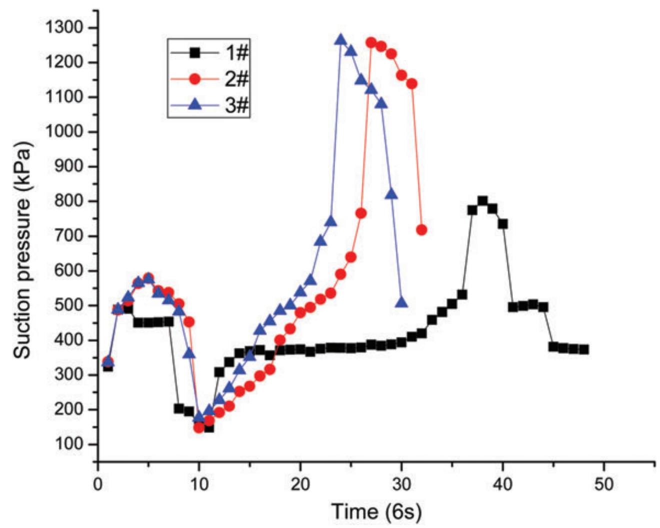

Figure 6. *Comparison of suction pressure variation during defrosting.*

(1) At the beginning of defrosting, three systems were running in steady state. Discharge and suction pressure of the systems had a certain degree fluctuation by the reversing of the four-way reversing valve. Among them, discharge and suction pressure of 3# unit rose rapidly in favor of defrosting. Defrosting time of the 3# unit shortened owing to much larger openness of the thermal expansion valve and higher refrigerant flow rate. Suction pressure rose quickly to avoid the low-pressure protection and impact of the heat pump system. The scenario of 2# unit is slightly worse than 3#, variation tendency of discharge and suction pressures is

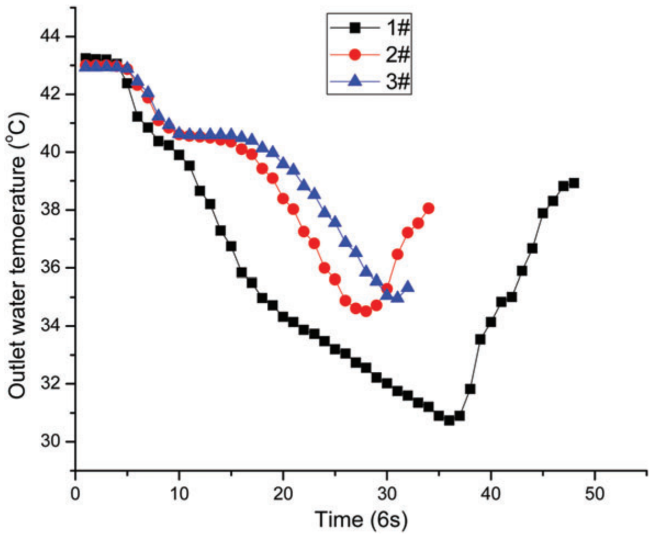

Figure 7. *Comparison of return water temperature variation during defrosting.*

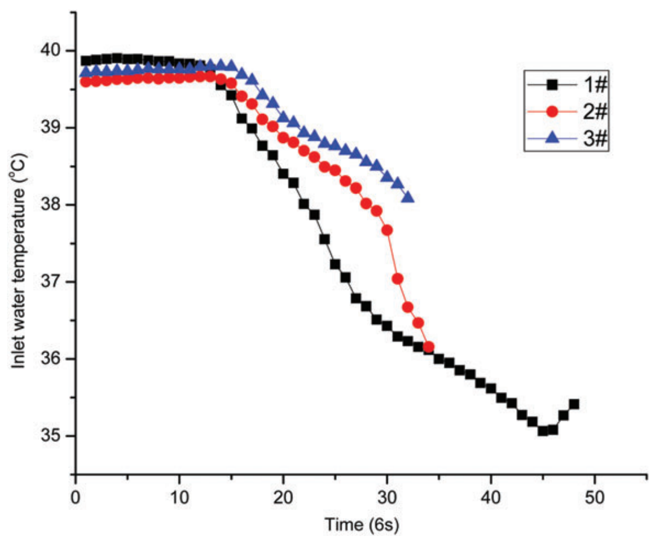

Figure 8. *Comparison of supply water temperature variation during defrosting.*

Table 4. *Extreme parameters and time comparison of defrosting.*

	Plate heat exchanger unit (1#)	Unit of heat storage device with electric heater off (2#)	Unit of heat storage device with electrical heater on (3#)
Minimum water supply temperature (°C)	35.06	36.15	36.37
Minimum water return temperature (°C)	30.73	34.61	34.96
Minimum suction pressure (kPa)	453.45	552.60	571.39
Maximum discharge pressure (kPa)	801.47	1257.59	1263.09
Defrosting time (s)	192	114	108

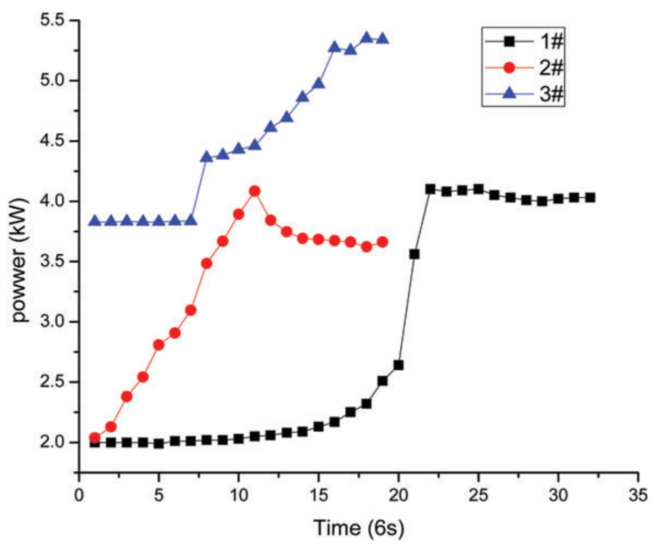

Figure 9. *Comparison of power variation during defrosting.*

similar. Defrosting time is lag behind. Discharge and suction pressure of 1# system increased slowly. The 1# unit had a poor defrosting effect of low suction pressure and slow defrosting speed.

(2) The refrigerant of 2# and 3# units absorbed heat from heat storage device in the defrosting operation. At the same time, the electric heater of 3# unit started to increase the defrosting heat sources thus enhance the defrosting effect. The supply heating water temperature of the unit dropped in the process of defrosting, but was still about 35°C. The inlet cold water temperature of 1# system was reduced to 30.73°C, which caused large temperature fluctuation.

(3) The defrosting time of 1#, 2# and 3# units is: 192, 114 and 108 s, respectively. Apparently, 2# and 3# units have relatively shorter defrosting time and prolonged heating time, which improve the operation performance of the unit.

(4) During the process of defrosting, integral of unit instantaneous input power versus the time is the electric energy consumption. The electric energy consumption of each defrosting process depends on the defrosting time and instantaneous power consumption. As shown in Figure 9, the power of each unit under defrosting conditions was obtained by DAS. The energy consumption of 3# unit is significantly larger than that of 1# and 2# units due to the operation of electric heater. At the same time, the 2# unit has the minimum energy consumption of defrosting due to the heat storage. The energy consumption of 3# unit is 204 kJ during a defrosting course, which is more than 2# unit owing to operation of the electric heater.

(5) Test outdoor air temperature is −7.5°C of winter and 34.9°C of summer during the test. If the outdoor temperature is higher in winter and lower in summer of practical project, the unit has high evaporating temperature and lower condensation temperature, the performance of the heat pump in term of COP is much higher in practical project, and the performance of storage system will also better in the aspect of defrosting and reduces the on and off times in an hour.

5 CONCLUSIONS

(1) The heat storage device of air-to-water heat pump can reduce the water temperature fluctuations by storing a certain number of cooling capacity to reduce the on and off times of compressor, which can save energy and prolong the service life of the unit as well.
(2) The heat storage device with electric heater can improve heating effect of the unit in winter and overcome the defect of air-to-water heat pump frost. Owing to the heat stored in the heat storage device and the heating from electric heater, water temperature variation is quite smooth during defrosting.
(3) During defrosting, the pressure of air-to-water heat pump with heat storage device rises quickly, and the temperature fluctuation is small. Air-to water heat pump with heat storage device has high reliability and stability, good defrosting effect and short defrosting time.

REFERENCES

[1] Nishimura T. Heat pumps-status and trends in Asia and the Pacific. *Int J Refrig* 2002;**25**:405–13.
[2] Joseph CL, Wilco W. Chan Energy performance of air-to-water and water-to-water heat pumps in hotel applications. *Energy Convers Manage* 2003;**44**:1625–31.
[3] Li H, Yang H. Study on performance of solar assisted air source heat pump systems for hot water production in Hong Kong. *Appl Energ* 2010;**87**:2818–25.
[4] Zhang RR, Lu XS, Li SZ, *et al*. Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model. *Energy Convers Manage* 2005;**46**:1714–30.
[5] Ding Y, Ma G, Yi J. Experiment investigation of reverse cycle defrosting methods on air source heat pump with TXV as the throttle regulator. *Int J Refrig* 2004;**27**:671–8.
[6] Huang D, Yuan XL, Zhang XQ, *et al*. Effect of fan-starting methods on the reverse-cycle defrost performance of an air-source heat pump. *Int J Refrig* 2004;**27**:107–12.
[7] Huang D, He ZL, Yuan XL. Dynamic characteristics of an air-to-water heat pump under frosting/defrosting conditions. *Appl Therm Eng* 2007;**27**:1996–2002.
[8] Yao Y, Jiang Y, Deng S, *et al*. A study on the performance of the airside heat exchanger under frosting in an air source heat pump water heater/chiller unit. *Int J Heat Mass Transfer* 2004;**47**:3745–56.
[9] Xiang H. *Air-Conditioning Engineering*. Mechanical Industry Press, 2006, 307–13.
[10] Moffat RJ. Describing the uncertainties in experimental results. *Exp Thermal Fluid Sci* 1988;**1**:3–17.