DEVELOPMENT OF HEAT PUMP WATER HEATER USING CO_2 FOR COMMERCIAL USE

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Abstract: New heat pump water heater system using CO_2 has been developed to spread the electrical heat pump water heater from the point of view of the global warming prevention. Most of the conventional water heaters for commercial use are combustion heaters using fossil fuel. The developed system consists of a water tank, the refrigeration circuit with a suction line heat exchanger(SLHX) ,a bypass line and heat recovery heat exchanger(HRHX) for the defrost. This system has three operating modes; hot water storage mode, heating up mode and defrost mode using HRHX. In the hot water storage mode, 17℃ tap water is heated up to 65℃ hot water and sent into the tank and 40kW heating capacity is generated. In addition, in the heating up mode, 60℃ hot water supplied from the tank is heated up to 80℃ and 19kW heating capacity is generated. The SLHX can make the inlet quality of the evaporator lower than the conventional cycle without the SLHX, therefore excessive amount of refrigerant can be stored in the air heat exchanger(evaporator) without accumulator under the various condition. Furthermore, in the defrost mode, the HRHX makes defrost capacity increase and the air heat exchanger is used as the condenser. The SLHX are used as the gas cooler (high pressure side) and the evaporator (low pressure side) by the bypass line. This defrost circuit can prevent the liquid return to the compressor and ensures high reliability without accumulator.

Key Words: ***heat pump water heater, CO_2, efficiency, defrost, heat recovery***

1 INTRODUCTION

The electric heat pump water heater has been highly valuated in terms of safety, convenience, saving energy, and CO_2 emission compared to the conventional combustion heaters using fossil fuel. Therefore it becomes widespread in Japan recently. Also, some refrigeration equipments using natural refrigerants (such as R600a, NH_3 and CO_2) have been developed instead of those using HFC refrigerants (such as R410A, R407C, R404A). Especially, highly- efficient products utilizing CO_2 characteristics have been developed in the heat pump water heating market. In commercial use, large capacity heat pump water heaters have been developed and adopted as hot water supply device for welfare facility or accommodation.

The heat pump water heater we have developed shows the high performance with inverter driven compressor. It has also three operating modes; the hot water storage mode, the heating up mode and the defrost mode. A suction line heat exchanger (SLHX) was adopted to keep the high pressure proper value under the various conditions without an accumulator. In addition, the defrost circuit can prevent the liquid return to the compressor and the heat recovery heat exchanger (HRHX) makes large defrost capacity in defrost mode. In this paper, the development overview of this heat pump water heater is described.

2 CONCEPT OF REFRIGERATION CIRCUIT

The simple refrigeration cycle without an accumulator was selected to simplify the refrigeration circuit. However, in the refrigeration circuit without an accumulator, the liquid return to the compressor can occur both in the heating up mode and in the defrost mode. The suction line heat exchanger (SLHX) was adopted to solve this problem. The SLHX enables the excess amount of refrigerant accumulated in the evaporator under both the heating up mode and defrost mode. In the defrost mode, discharge gas exchanges the heat with two phase refrigerant of the evaporator outlet and makes the suction state of the compressor super heated.

Also, the heat recovery heat exchanger (HRHX) was set in the inlet of the gas cooler. The HRHX enables the heat of the discharge gas recovered for the defrost mode and prevents the boiling of the cooling water in the gas cooler. As a result, the frequency of the compressor and defrost heat can be increased.

In this study, experimental study was performed to confirm this concept and verify practical effectiveness.

3 HEAT PUMP WATER HEATING SYSTEM USING CO_2

Figure 1 shows the overview of the water heater system and Table 1 shows the specification of the system. The developed water heater system has the hot water storage mode which heats up a tap water and the heating up mode which heats up a hot water in the tank. In the hot water storage mode, this system heats up a tap water form a low temperature (ex. 17℃) to high temperature (ex. 65℃) and supply the hot water into the tank(40kW heating capacity). When the hot water volume reaches the target level, the hot water storage mode will stop. On the other hand, the heating up mode will start when the storage temperature become lower than the setting point (ex. 60℃) due to the heat loss released from the water pipe and the tank. In the heating up mode, this system heats up from setting temperature (ex. 60℃) to higher temperature (ex. 80℃). If water temperature in the tank reaches the target level, the heating up mode will stop. As a result, the water temperature in the tank can be kept high level(19kW heating capacity).

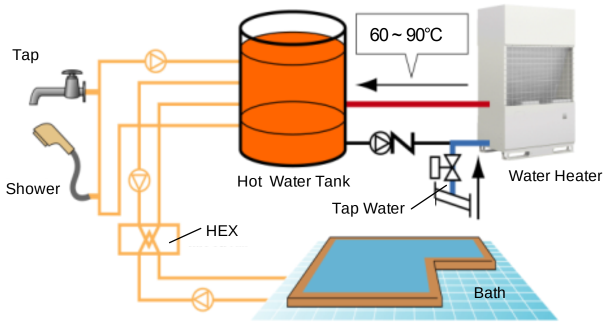

Figure 1: Heat pump water heater system

Table 1; System specification

Refrigerant	R744 (CO_2)	
Mode	Hot water storage mode [1)]	Heating up mode [2)]
Heating Capacity	40 kW	19 kW
Outdoor temperature	-15℃ ~ 40℃	
Inlet water temperature	5℃ ~ 63℃	
Outlet water temperature	60℃ ~ 90℃	

1) Air temperature:16degC DB/12 WB，Inlet water temperature:17degC，Outlet water temperature:65degC

2) Air temperature:16degC DB/12 WB，Inlet water temperature:55degC，Outlet water temperature:75degC

4 EXPERIMENTAL APPARATUS

Figure 3 shows the experimental apparatus of the water heater and Table2 shows the specification of the apparatus. The refrigeration circuit is the cycle without accumulator. It consists of a compressor, water heat exchanger (Gas cooler), linear expansion valve (LEV), plate fin and tube heat exchanger (Evaporator), suction line heat exchanger (SLHX) and heat recovery heat exchanger (HRHX). The compressor is inverter driven scroll compressor with DCBLM. The heating capacity was controlled optimally due to the heat load with the control of the compressor frequency from 30rps to 100rps. Five water heat exchangers (Gas cooler) for a domestic water heater were used. These are connected in parallel and make the countercurrent flow to the water flow. The linear expansion valve was controlled to make the outlet state of the SLHX (low-pressure side) superheated gas.

The temperature and pressure were measured by the thermocouples and pressure transducers respectively. The power consumption and the frequency of the compressor were measured by an electrical power meter. The defrost capacity is calculated using the difference between the power consumption of the compressor and released heat from the gas cooler. The released heat from the gas cooler is calculated using refrigerant flow rate and the enthalpy difference in the gas cooler.

The hot gas defrost was used for defrost of air heat exchanger. In the hot gas defrost, the high temperature gas discharged from the compressor (between 90℃ and 120℃) is bypassed to the inlet of the SLHX (high-pressure side) through the bypass line. The SLHX makes the two-phase state at the outlet of the evaporator superheated gas and prevents liquid return to the compressor. Also, as the inlet temperature of the gas cooler is controlled by the HRHX, the boiling of the water in the gas cooler was suppressed and defrost capacity can increase by the increase of the compressor frequency. The opening ratio of the expansion valve was fixed during the defrost mode.

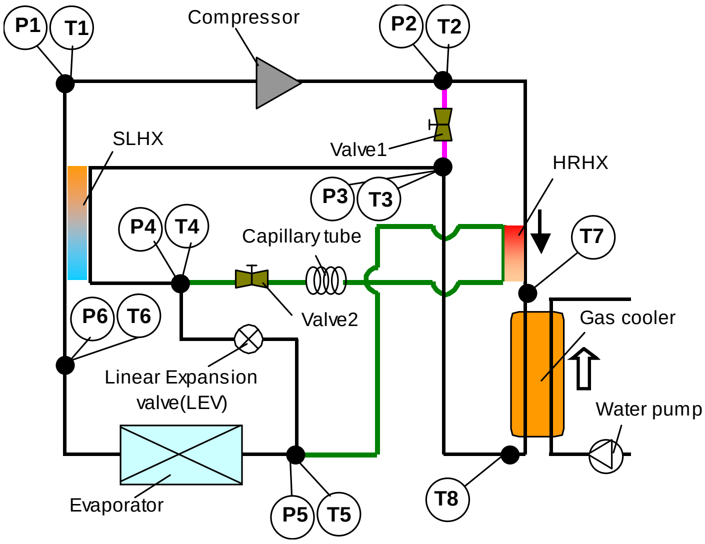

Figure 2: Experimental apparatus

Table 2; Specification of the experimental apparatus

Item	Type
Compressor Type×Number of pieces	Inverter scroll compressor×1
Fan	0.6kW×1
Water Pump	0.1kW×1 (Spiral type , Inverter control)
Evaporator	Plate fin and tube
Gas cooler	Twist and spiral heat exchanger
Refrigerant	R744 (CO_2)
Oil	PAG
Type of Defrost	Hot gas defrost

5 EXPERIMENTAL RESULTS

5.1 Profile of excess amount of refrigerant

Table 3 shows an experimental result in the hot water storage mode and the heating up mode. Figure 3 shows the refrigerant state on the pressure-enthalpy diagram in the hot water storage mode and the heating up mode. The enthalpy difference between gas cooler inlet (2) and gas cooler outlet (3) in the hot water storage mode is larger than that in the heating up mode. That is why the inlet temperature of the tap water in the hot water storage mode is lower (17℃) than that in the heating up mode(40℃). In the heating up mode, high pressure (12.04MPa) is restrained near the upper limit because the heat flow rate in the SLHX increases. It means that the excess amount of refrigerant is accumulated in the air heat exchanger (Evaporator).

Table 3; Experimental results

Term	Unit	hot water storage mode	heating up mode
Air temperature	℃	16	16
Inlet water temperature	℃	17	40
Outlet water temperature	℃	65	80
Heating Capacity	kW	44.4	37.6

Rotation frequency of compressor		Rps	76	83
Pressure	Compressor suction	MPa	3.90	4.16
	Compressor discharge	MPa	9.85	12.04
	Outlet of gas cooler	MPa	8.92	10.88
	Outlet of SLHX (high pressure side)	MPa	8.72	10.79
	Inlet of evaporator	MPa	3.94	4.23
	Outlet of evaporator	MPa	3.92	4.20
Temperature	Inlet of compressor	℃	11.9	10.9
	Outlet of compressor	℃	92.0	106.0
	Outlet of gas cooler	℃	18.9	41.5
	Outlet of SLHX (high pressure side)	℃	14.3	35.6
	Inlet of evaporator	℃	6.1	8.7
	Outlet of evaporator	℃	7.3	6.5

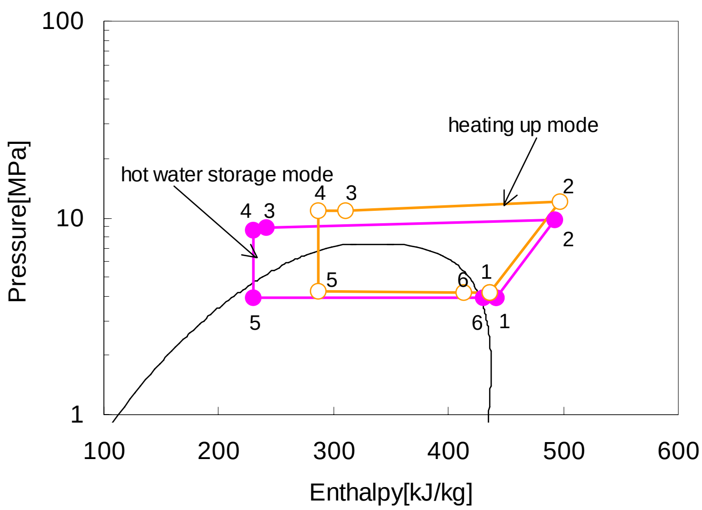

Figure 3: Refrigerant state on the P-h diagram.

5.2 Prediction of defrost operation

Figure 5 shows the simulation result in the defrost mode. The high temperature and pressure discharged from the compressor (10.0Mpa, 100℃) flows into the gas cooler and bypass line. A part of discharged gas form the compressor flows through the heat recovery heat exchanger (HRHX) and flows into the gas cooler at 70℃(3). The refrigerant flow at the gas cooler(3') joins the bypass circuit flow 77℃(4) and flows into the SLHX. The refrigerant flow at the outlet of the SLHX (5) is divided into the heat recovery circuit (6') and bypass circuit (6'''). The refrigerant pressure of the heat recovery circuit is reduced by the capillary tube and the refrigerant pressure of the bypass circuit is reduced by the LEV. The low pressure (3.8MPa) refrigerant exchanges the heat in the heat recovery circuit(6'') and joins the refrigerant of bypass circuit at the inlet of air heat exchanger(6). The low quality refrigerant (6) condensed in the air heat exchanger (7) evaporates in the SLHX, and flows into the compressor (1).

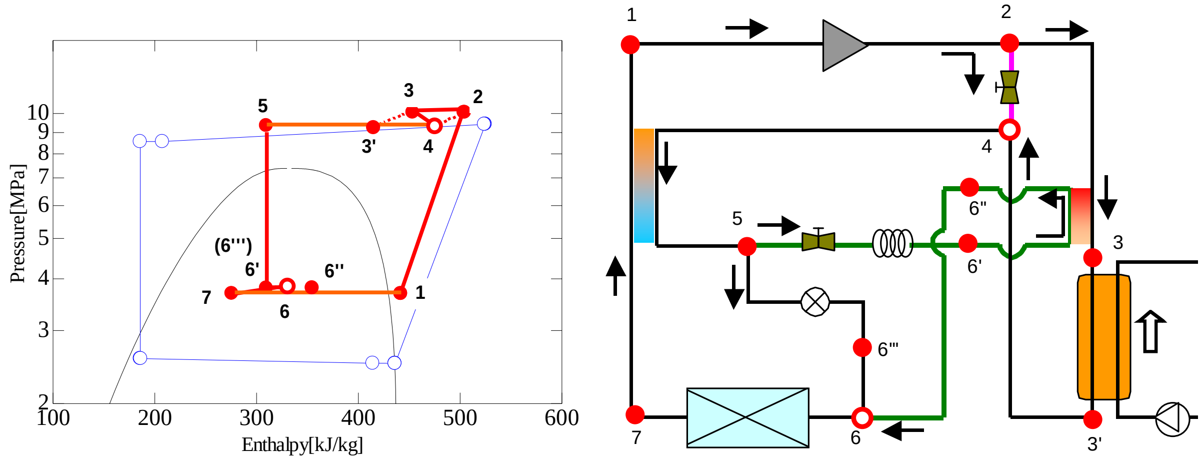

Figure 4: Calculation model for the defrost circuit.

5.3 Experimental result of the defrost operation

Figure 5 shows the experimental result in the defrost mode. When the suction pressure become below 2.0MPa, bypass valve (between 2 and 4) and the heat recovery valve (between 5 and 6') were opened and high pressure becomes low temporarily. In the defrost mode, the inlet of gas cooler is 68℃ ~ 71℃, but the discharge temperature is 90℃ ~ 95℃. It means that the heat loss equivalent to ΔT=22℃ ~ 25℃ is recovered as defrost heat. The superheat of the suction line SH (=Ts-Tss) is 0℃ ~ 12℃ except for the start and end of the defrost mode.

On the other hand, ice on the air heat exchanger starts to melt and suction pressure (Ps) suddenly increases. When the suction pressure increased to 4.5MPa, the defrost mode finished because all ice on the heat exchanger melt. The defrost time was 14minutes in this case.

In this experiment, the opening ratio of linear expansion valve (LEV) was constant. If the opening ratio of the LEV could be controlled, the defrost capacity would be increased.

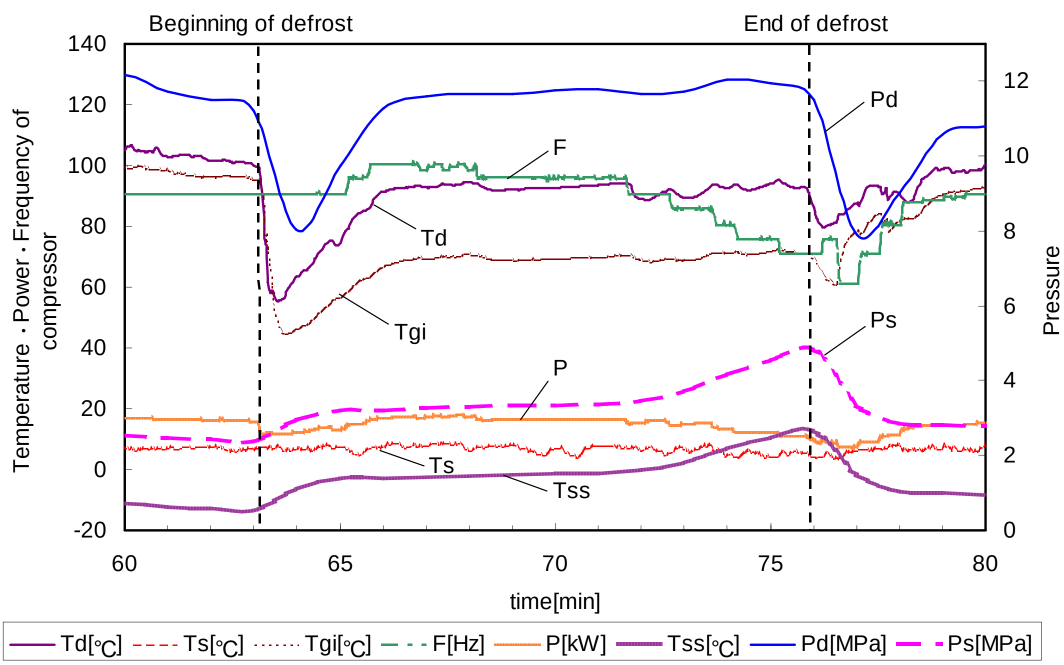

Figure 5: transient data for defrosting mode.

(Td :discharge temp., Ts :suction temp., Tgi :gas cooler inlet temp., F :frequency of comp., P :power consumption, Tss :suction saturation temp., Pd :discharge pressure, Ps :suction pressure)

5.4 Improving the defrost capacity with the heat recovery heat exchanger (HRHX)

In the defrost mode, refrigerant flow discharged from the compressor is divided into the bypass line and the gas cooler line. 70rps is upper limit of the compressor frequency because the water in the gas cooler boils without the HRHX. The inlet temperature (over 100℃) of the gas cooler was lowered by the HRHX.

Figure 6 shows the effect of the HRHX on condition that outdoor air temperature is 2℃. The inlet temperature of the gas cooler was lowered to 70℃～95℃ by the HRHX. As a result, the boiling of water in the gas cooler is prevented and 60% of the heat released from the gas cooler was recovered. The frequency of the compressor can be increased from 70rps (conventional maximum value) to 100rps. Also, the defrost capacity becomes double and the defrost time becomes half compared with those without the HRHX.

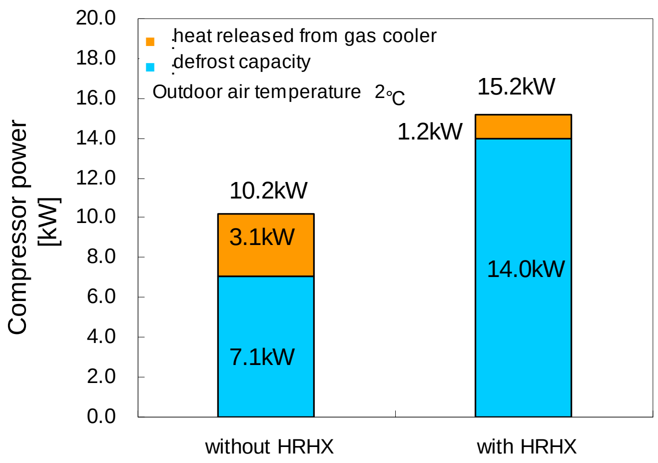

Figure 6: Comparison between with and without HRHX.

6 CONCLUSION

The heat pump water heater using CO_2 has been developed for commercial use. The main features of this system are as follows;
(1) The new refrigeration circuit has the heat recovery heat exchanger (SLHX) and the HRHX. The SLHX exchanges the heat between the gas cooler outlet and the suction line and makes excessive refrigerant charge accumulated in the evaporator without accumulator. As a result, extreme high pressure and liquid return to the compressor can be prevented and high reliability is confirmed.
(2) The HRHX makes defrost capacity larger and defrost time reduced compared with the system without the HRHX.

7 REFERENCES

Kataoka M. 2007. *Refrigeration*, Vol. 82, No.95, pp. 4–7.
Hihara E. 2004. “Non fluorocarbon technology,” *Ohm Corp.*, Tokyo, pp. 40.