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Performance Characteristic and Optimization of a Simultaneous Heating and Cooling Multi Heat Pump

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ABSTRACT

In this study, a simultaneous heating and cooling multi heat pump having four indoor units and an outdoor unit was designed and constructed. The working of the system was R-410A. The operating characteristics and performances of the heat pump system were measured at five operation modes: cooling-only, cooling-main, heating-only, heating-main and entire heat recovery operation. To improve the system efficiency and reliability, the system in the heat recovery operation was optimized by varying the compressor rotation speed and EEV opening. In the simultaneous heating and cooling operation, the system COP increased by using the heat recovery operation with the optimization of control parameters.

1. INTRODUCTION

Cooling period in buildings is increasing due to the widespread use of office equipment with high heat flux and the development of architectural engineering technologies. Even in the winter season, both cooling and heating are required in buildings such as office buildings, hotels, hospitals, and convention centers, where cooling load exists in the winter season. Although multi heat pumps are being used more because of their advantages in energy conservation and space saving, conventional multi heat pumps can not satisfy all the needs of various customers because they do not have the function of the simultaneous heating and cooling. Therefore, air-conditioner industry is working hard to develop the simultaneous heating and cooling heat pump and increase the system COP.

Previous studies on multi heat pumps concentrated on the improvement of the system performance in the heating-only and cooling-only operations. However, studies on the simultaneous heating and cooling heat pump are very limited in literature. Therefore, in this study, the state-of-art technologies on the simultaneous heating and cooling heat pump were investigated experimentally. The technologies used in the development of multi heat pumps mainly focused on compressor capacity control, refrigerant flow rate control, and alternative refrigerants. The control of the compressor speed in multi heat pumps has been widely adopted to modulate the compressor capacity. In the early stage of compressor development, alternating current (AC) inverter technology for compressor speed control was widely used (Aprea et al., 2006). However, recently, direct current (DC) inverter technology is increasingly used

because of its energy saving efficiency and high control accuracy. The control of the refrigerant flow rate was remarkably improved by using electronic expansion valve (EEV) (Qifang et al., 2007; Park et al., 2007), which can precisely control the refrigerant flow rate according to the variations of operating conditions. The compressor inverter and EEV are essential components in the development of multi heat pumps (Choi and Kim, 2003; Park et al., 2001)

In this study, a conventional multi heat pump having two operation modes of cooling-only and heating-only was redesigned and reconstructed for the simultaneous heating and cooling operation, with the adoption of EEVs and a variable speed compressor. The operating characteristics and performances of the simultaneous heating and cooling heat pump with R-410A were measured and analyzed at five operation modes: cooling-only, heating-only, cooling-main, heating-main, and entire heat recovery operations. The simultaneous heating and cooling operation was also optimized experimentally by varying control parameters such as the compressor rotation speed and EEV opening, and the optimum control methods were suggested to improve system COP.

2. EXPERIMENTAL SETUP AND TEST PROCEDURE

Fig. 1 shows the schematic diagram of the simultaneous heating and cooling multi heat pump. It was designed to obtain cooling capacity of 8.0 kW and COP of 3.2 in the cooling-only operation mode listed in Table 1. Four indoor units were connected to one outdoor unit, and the designed capacity of each indoor unit was 2.0 kW. A hermetic rotary compressor having a brushless direct current (BLDC) motor was adopted for the optimum control of compressor speed. Its cooling capacity and power consumption were 8.0 kW and 2.5 kW, respectively, at the compressor speed of 3,500 rpm and the ARI test condition, where evaporation and condensation temperatures were 7.2 °C and 54.4 °C, respectively. An EEV, consisting of a stepping motor and a needle valve, was adopted for the optimum control of refrigerant flow rate, and its orifice diameters were 1.4 mm for the indoor unit and 1.8 mm for the outdoor unit, with control resolution of 500 steps. The EEV was fully-closed at 0 step and fully-opened at 500 steps. The heat exchangers for the indoor and outdoor units consisted of micro-fin tubes and slit-fins. The indoor heat exchanger had an evaporation capacity of 2.2 kW at the evaporation temperature of 7.2 °C and the air flow rate of 6.0 m³/min. The outdoor heat exchanger had the condensation capacity of 11.34 kW at the condensation temperature of 54.4 °C and air flow rate of 37.5 m³/min.

As shown in Table 2, the simultaneous heating and cooling heat pump has five operation modes: heating-only, cooling-only, heating-main, cooling-main, and entire heat recovery operations. In the heating-only or cooling-only operation mode, all the indoor units operate at the same mode. In the heating-main operation mode, the number of cooling-operation indoor units is more than that of heating-operation indoor units, and vice versa in the cooling-

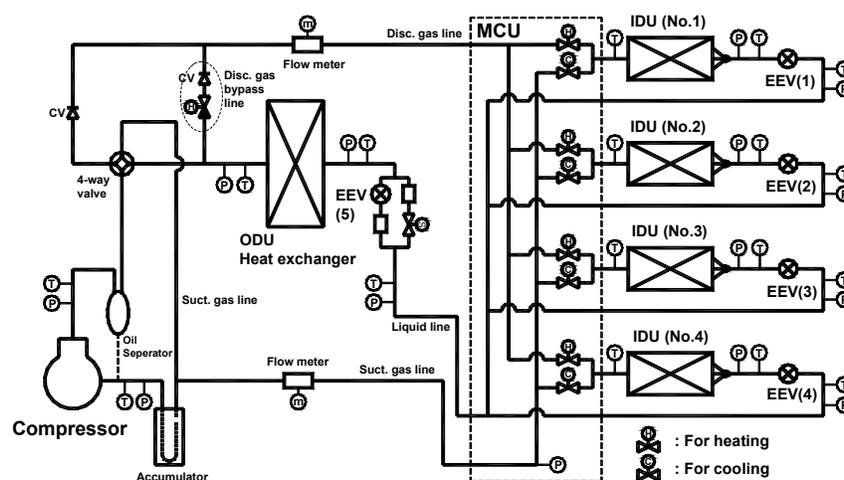


Figure 1: Schematic diagram of the experimental setup

Table 1: Experimental conditions

Operating mode	IDU for cooling	IDU for heating	ODU
Cooling-only	27.0 °C / 47.0% RH	--	35.0 °C / 40.4% RH
Cooling-main	27.0 °C / 47.0% RH	20.0 °C / 59.0% RH	35.0 °C / 40.4% RH
Entire-heat recovery	27.0 °C / 47.0% RH	20.0 °C / 59.0% RH	7.0 °C / 86.9% RH
Heating-main	27.0 °C / 47.0% RH	20.0 °C / 59.0% RH	7.0 °C / 86.9% RH
Heating-only	--	20.0 °C / 59.0% RH	7.0 °C / 86.9% RH

Table 2: Operating status of indoor units with operation modes

Operation mode	IDU (no.1)	IDU (no.2)	IDU (no.3)	IDU (no.4)
Cooling-only	Cooling	Cooling	Cooling	Cooling
Cooling-main	Cooling	Cooling	Cooling	Heating
Entire heat recovery	Cooling	Cooling	Heating	Heating
Heating-main	Cooling	Heating	Heating	Heating
Heating-only	Heating	Heating	Heating	Heating

main operation mode. In these operation modes, the total or partial heat absorbed by cooling-operation indoor unit is reused for heating; this is referred to as heat recovery operation. In the entire heat recovery operation mode, the number of cooling-operation indoor units is matched with that of heating-operation indoor units without refrigerant flow to the outdoor heat exchanger, and all the heat absorbed by cooling-operation indoor units is reused for heating. For the individual heating and cooling operations of indoor units, a mode changing unit (MCU) was installed between the outdoor unit and indoor units. It consisted of header pipes, branch pipes and solenoid valves, and on/off operations of the solenoid valves were determined according to the operation modes of indoor units. The three connection pipes of discharge-gas, suction-gas and liquid pipes were installed between the MCU and the outdoor unit, whereas the conventional multi heat pump had only two connection pipes of gas and liquid pipes between the indoor units and the outdoor unit.

The performance of the simultaneous heating and cooling multi heat pump was measured in an air-enthalpy type calorimeter. The measurement devices for air flow rate, temperature and humidity were attached to each indoor unit to measure individual performance of each indoor unit. A resistance temperature detector (Pt 100 Ω) was used to measure dry and wet air temperatures, and its accuracy was ± 0.15 °C. The air flow rate of the indoor unit was measured by using the nozzle method. The nozzle diameter was 76.2 mm, and the measurement range was between 4.2-9.7 standard m³/min (SCMM). The pressure difference across the nozzle was measured by using an electronic differential pressure transducer with an accuracy of $\pm 0.25\%$. The power consumption of the heat pump was measured by using an electronic power meter with an accuracy of $\pm 0.2\%$. The operating status of the indoor units according to operation mode is shown in Table 2. The temperature and humidity conditions for the indoor and outdoor rooms in each operation mode are shown in Table 1. The air flow rate and capacity of each indoor unit were calculated based on ISO/DIS 15042.

3. RESULTS AND DISCUSSION

In the cooling-only operation at the compressor rotation speed of 3,500 rpm, the optimum system COP was observed at the refrigerant charge of 3,900g and the EEV opening of 110 steps in the indoor units. When the operation mode changed from the cooling-only to cooling-main, the evaporation pressure decreased due to the decrease in the number of cooling-operation indoor unit. The condensation pressure also decreased because the heating-operation indoor unit worked as a condenser in the cooling-main operation. The total and average cooling capacities in the cooling-only operation were 8,248.9 W and 2,062.2 W, respectively. The total capacity in the cooling-main operation was 8,120.9 W, which was 1.6% lower than the value in the cooling-only operation. The average cooling capacity in the cooling-main operation was 2,276.3 W, which was 10.4% higher than the value in the cooling-only operation. However, the heating capacity in the cooling-main operation was 1,291.9 W, which was much lower than the designed capacity of 2.0 kW, because the bypassed refrigerant flow rate to the heating-operation indoor unit was very low, only 15.4% of the total flow rate. The COP in the cooling-main operation was

3.461, which was 10.8% higher than the value in the cooling-only operation due to the heat recovery operation in the cooling-main operation.

In the cooling-main operation, the bypassed refrigerant flow rate to the heating-operation indoor unit had to be controlled optimally to improve the heating capacity and system efficiency. The bypassed flow rate was increased by decreasing the EEV opening of the outdoor unit. The bypass flow ratio R_{bp} was defined as the ratio of the bypass flow rate to the total flow rate. As the bypassed flow rate increased from 15.4% to 38.0%, the flow rate to the heating-operation indoor unit was increased by 84.3%. However, at the bypassed flow rate of 38.0%, the total flow rate was decreased by 25.3% over the value at the bypass flow rate of 15.4%, due to the generation of uncondensed refrigerant at the exit of the heating-operation indoor unit. Fig. 2 shows the variations of average cooling and heating capacities with the bypassed flow ratio to the heating-operation indoor unit. With the increase of the bypassed flow ratio, the heating capacity increased until the bypass flow ratio of 31%, while the average cooling capacity decreased from the bypass flow ratio of 31% with the rapid decrease of the total flow rate. At the bypassed flow ratio of 27%, the average cooling and heating capacities were 2,283.6 W and 2,070.1 W, respectively, satisfying the designed capacity of 2.0 kW. With the optimization of refrigerant flow rate to the heating-operation indoor unit, the COP in the cooling-main operation was 3.807 which increased by 21.8% over the value in the cooling-only operation.

The operating characteristics in the heating-only operation were measured at the refrigerant charge amount of 3,900 g and the compressor speed of 3,500 rpm, maintaining the EEV openings of the indoor and outdoor units at 500 and 320 steps, respectively. The operating characteristics in the heating-main operation were also measured at the same conditions as the heating-only operation, except that the EEV opening of the cooling-operation indoor unit was changed to 110 steps. In the heating-main operation, the evaporation pressure increased due to the cooling operation of an indoor unit. Simultaneously, the condensation pressure also increased due to the decrease in the number of heating-operation indoor unit. The total flow rate in the heating-main operation was increased by 11.2% over the value in the heating-only operation due to the increase of compressor suction pressure.

The average flow rate to the heating-operation indoor unit in the heating-main operation increased by 48.4% over the value in the heating-only operation, while the flow rate to the cooling-operation indoor unit decreased by 43.6% from the average flow rate to the heating-operation indoor unit. In the heating-main operation, the imbalance in refrigerant distribution resulted in lower cooling capacity. The average heating capacity in the heating-main operation was 2,662.1 W, which was 34.0% higher than the value of 1,986.7 W in the heating-only operation. The cooling capacity was 1,761.5 W, which was 33.8% lower than the average heating capacity in the heating-main operation.

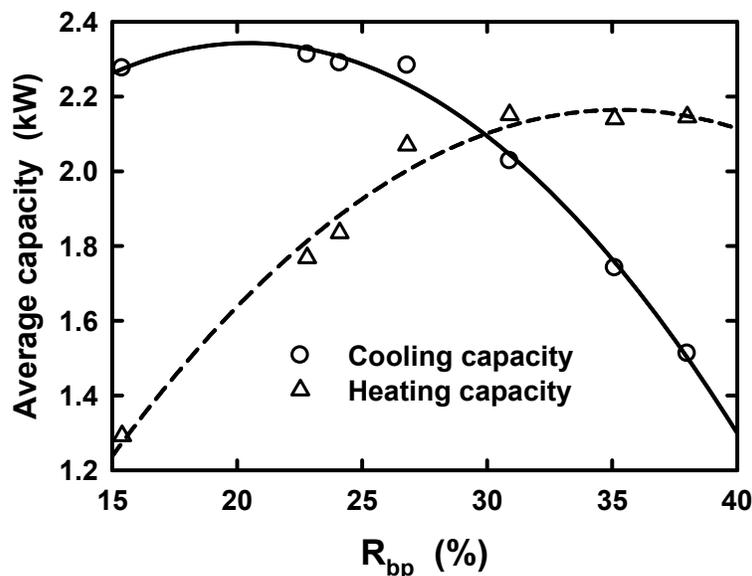


Figure 2: Variations of average cooling and heating capacities with bypassed flow ratio in cooling-main operation

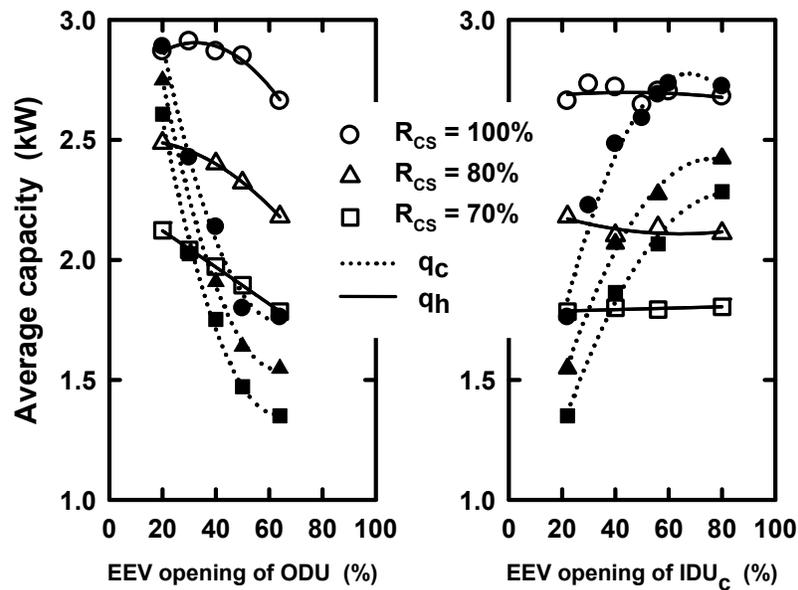


Figure 3: Variations of average cooling and heating capacities with EEV openings in heating-main operation

In the heating-main operation, the cooling capacity can be increased by increasing the refrigerant flow rate to the cooling-operation indoor unit. To increase the flow rate to the cooling-operation indoor unit, two methods were considered in this study: (a) decreasing the EEV opening of the outdoor unit and (b) increasing the EEV opening in the cooling-operation indoor unit. An experiment by adopting the first method was performed: the EEV opening of the outdoor unit was decreased from 320 steps (64% of full opening), and the EEV opening in the cooling-operation indoor unit was maintained at 110 steps (22% of full opening). The flow rate to the cooling-operation indoor unit was increased by decreasing the EEV opening in the outdoor unit, even though the total flow rate was decreased. The experiment with the adoption of the second method was conducted by increasing the EEV opening from 110 steps, while the EEV opening in the outdoor unit was maintained at 320 steps. As the EEV opening in the cooling-operation indoor unit increased, the flow rate to the cooling-operation indoor unit increased with the slight increase in the total flow rate.

Fig. 3 shows the variations of average cooling and heating capacities with the EEV opening and compressor speed in the heating-main operation. As the EEV opening in the outdoor unit decreased from 64% to 20% at the compressor speed of 3,500 rpm, the cooling capacity increased from 1,761.5 W to 2,889.2 W, showing an increase of 64.0% due to the decrease of the superheat region in the evaporator. The average heating capacity increased from 2,662.1 W to 2,869.1 W, showing an increase of 7.8% due to the increase of the condensation pressure. However, the condensation pressure increased significantly with the decrease of the EEV opening in the outdoor unit. As the EEV opening in the cooling-operation indoor unit increased from 22% to 80% at the compressor speed of 3,500 rpm, the cooling capacity increased from 1,761.5 W to 2,723.2 W, showing the increase of 54.6%, while the average heating capacity showed no difference with a constant condensation pressure. The cooling capacity remained constant beyond the EEV opening of 60%, because the superheat region did not exist beyond the EEV opening of 60%.

The compressor speed was optimized to increase the system COP. The compressor speed ratio R_{cs} was defined as the ratio of the actual compressor speed to the reference value of 3,500 rpm. From the experiments with the variations of the EEV opening in the outdoor unit and the compressor speed, the average heating and cooling capacities were 2,025.7 W and 2,041.5 W, respectively, at the EEV opening of 30% and the compressor speed ratio of 70%. From the experiments with the variations of the EEV opening in the cooling-operation indoor unit and the compressor speed, the average heating and cooling capacities were 2,067.8 W and 2,102.3 W, respectively, at the EEV opening of 40% and the compressor speed ratio of 80%. To improve the system efficiency in the heating-main

operation, the method decreasing the EEV opening in the outdoor unit with the modulation of the compressor speed is recommended, while the condensation pressure should be monitored and restricted not to increase over a limit.

In the entire heat recovery operation, the EEV openings in the cooling-operation indoor units were set to 110 steps and those in the heating-operation indoor units were set to 500 steps (full opening) with the refrigerant charge amount of 3,900 g. In the preliminary tests at the compressor speed of 3,500 rpm, the condensation pressure increased up to 4,500 kPa, resulting in an abnormally-high compression ratio. It was impossible to maintain continuous operation at the compressor speed of 3,500 rpm due to the possibility of compressor malfunction, even though the average cooling and heating capacities were higher than the values in the other operation modes. For the reliability and efficiency of the system, therefore, the compressor speed should be controlled at an optimum value.

Fig. 4 shows the variations of average capacity and power consumption with compressor speed in the entire heat recovery operation mode. The average cooling capacity at the compressor speed ratio of 50% was 2,367.1 W, which was 14.8% higher than the value in the cooling-only operation. The average heating capacity at the compressor speed ratio of 50% was 2,232.6 W, which was 12.4% higher than the value in the heating-only operation. The power consumption at the compressor speed ratio of 50% was 1,196.6 W, which was 45.3% and 49.6% lower than the values in the cooling-only and heating-only operations, respectively. For the entire heat recovery operation mode, the average capacity of each indoor unit satisfied the designed capacity of 2.0 kW at the compressor speed ratio of 50%, resulting in lower power consumption.

Fig. 5 shows the variation of COP with the compressor rotation speed in the entire heat recovery operation mode. The COP at the compressor speed ratio of 50% was 7.688, which was 246.0% and 233.3% higher than the values in the cooling-only and heating-only operations, respectively. This was due to lower power consumption with the decrease of compressor speed. The variation of COP in the entire heat recovery operation mode was higher than the values in the cooling-only and heating-only operations. Therefore, in the entire heat recovery operation mode, the control resolution on the compressor speed must be considered to minimize the variation of the system efficiency. The test results showed that the system efficiency of the simultaneous heating and cooling heat pump was improved by using the heat recovery operation with the optimization of the compressor speed.

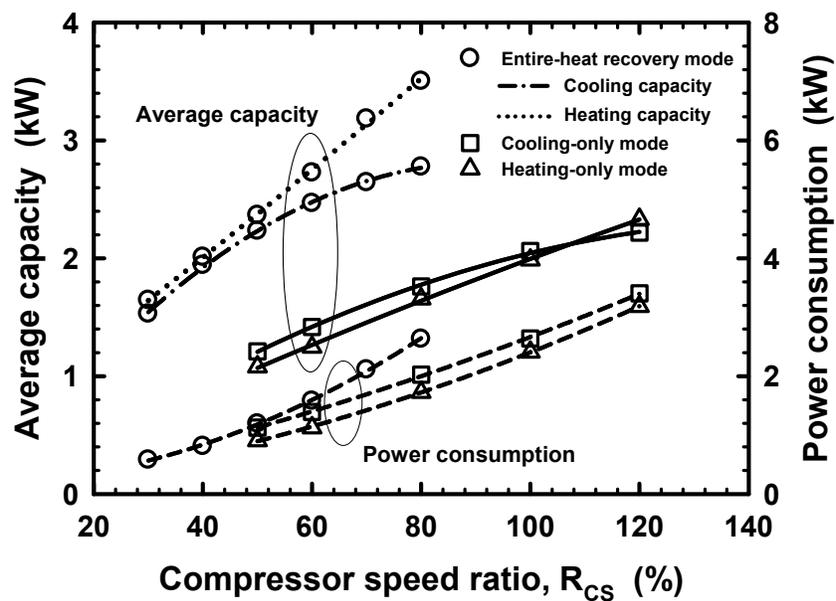


Figure 4: Variations of average capacity and power consumption with compressor speed in entire-heat recovery operation

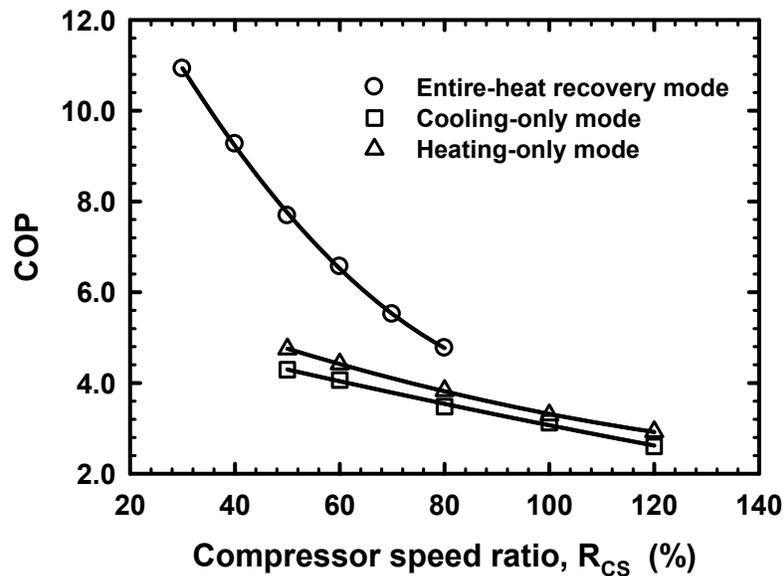


Figure 5: Variation of COP with compressor speed in entire-heat recovery operation

5. CONCLUSIONS

For the simultaneous heating and cooling operations of each indoor unit, the multi heat pump having four indoor units and one outdoor unit was redesigned and reconstructed with the adoption of EEVs and a variable speed compressor. The operating characteristics and performance of the simultaneous heating and cooling heat pump were measured and analyzed in five operation modes: cooling-only, heating-only, cooling-main, heating-main and entire heat recovery operations. The heat recovery operation was optimized by varying the control parameters such as the compressor speed and the EEV opening.

With the optimization of the bypassed flow rate to the heating-operation indoor unit, the COP in the cooling-main operation increased by 21.8% over the value in the cooling-only operation due to heat recovery. In the heating-main operation, the method decreasing the EEV opening in the outdoor unit showed higher system COP than the method increasing the EEV opening in the cooling-operation indoor unit. The COP in the heating-main operation was 53.5% higher than the value in the heating-only operation. For the entire heat recovery operation, the average capacity of each indoor unit satisfied the designed capacity at the compressor speed ratio of 50%, resulting in lower power consumption and thus yielding the COP of 7.688, which was 246.0% and 233.3% higher than the values in the cooling-only and heating-only operations, respectively. From the experimental results, in the simultaneous heating and cooling operation, the system COP increased by using the heat recovery operation with the optimization of control parameters.

NOMENCLATURE

<i>COP</i>	coefficient of performance
<i>IDU</i>	indoor unit
<i>ODU</i>	outdoor unit
<i>rpm</i>	rotation per minute
<i>R</i>	ratio
<i>RH</i>	relative humidity

Subscripts

c	cooling
cs	compressor speed
bp	bypass
h	heating

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