PERFORMANCE EVALUATION OF CO_2 HEAT PUMP HEATING SYSTEM

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ABSTRACT

Carbon dioxide as refrigerant is especially suitable for heat pump cycles with high heat rejecting temperature such as heating boilers and water heaters. In Japan, heating is one of the major parts of residential energy consumption, so an efficient heating system could reduce much energy consumption. We evaluated the heating capacity and COP of CO_2 heat pump heat generator, which is based on a heat pump water heater unit. The average COP of CO_2 heat pump heating system was calculated by using the climate conditions and heating load data. The effect of an additional incoming air heat exchanger was also evaluated, which improved the system COP by lowering the heat-transfer fluid temperature.

Conclusion: A CO_2 heat pump heating system can reduce the CO_2 emission in comparison with an oil boiler.

1. INTRODUCTION

Carbon dioxide is now being watched with interest as an environmental solution for various heat pump applications because it is non-flammable and non-toxic. CO_2 refrigerant is especially suitable for the heat pump cycle with high heat rejecting temperature because of its low critical temperature. Therefore, the CO_2 heat pump water heater was commercialized and became popular in Japan. In Japan, heating is a major part (approx. 28%) of residential energy consumption, which is almost as much as the hot water supply (approx. 27%). The energy consumption of heating is especially high in cold areas, so an efficient heating system can reduce much energy consumption. CO_2 heat pump heating system may replace conventional oil boilers or electric thermal storage heaters because its capacity and efficiency is high even at very low ambient temperature, and also because its heat rejecting temperature is enough high for a radiator panel. We evaluated the heating capacity and the COP of CO_2 heat pump heat generator based on the heat pump water heater unit for cold areas. The average COP of CO_2 heat pump heating system was calculated on a climate condition and a heating load. The effect of an additional incoming air heat exchanger was also evaluated, which recovered the heat loss by ventilation and improved the system COP by lowering the heat-transfer fluid temperature.

2. EXPERIMENTAL SETUP

Figure 1 shows the schematic diagram of the CO_2 heat pump heating system. The heat pump space heating system consists of two parts: the heat generator unit which is placed outside of the building and the panel radiator placed inside. The hot heat-transfer fluid (ethylene glycol based water solution) warms the room by being circulated through the heat generator and panel radiator. The heat pump cycle reject much heat and require less input with low heat-transfer fluid temperature returned from the heating device. A fan convector or a large panel radiator can warm the room and lower the heat-transfer fluid temperature.

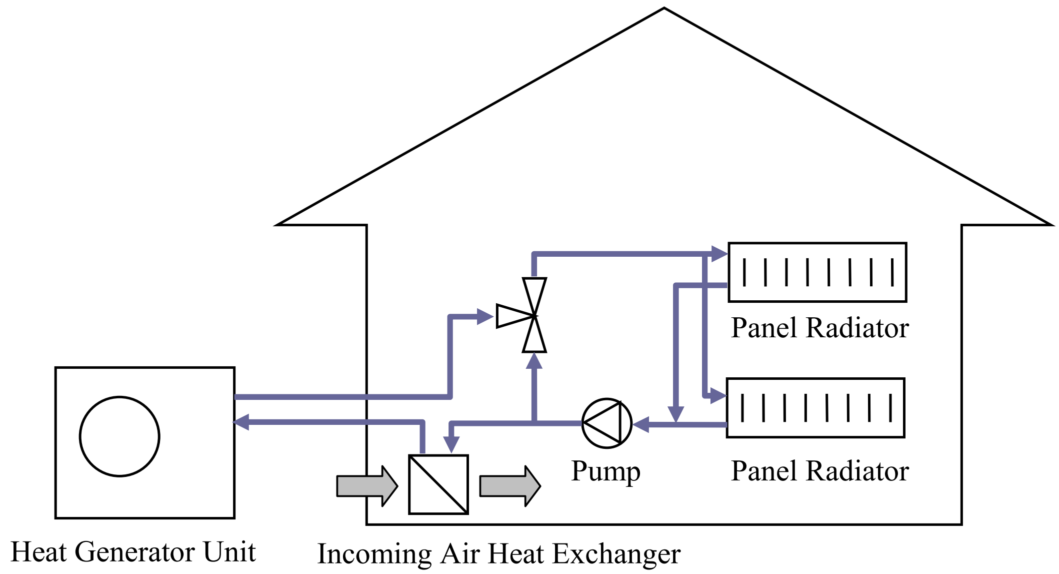


Figure 1. Schematic Diagram of the CO_2 Heat Pump Heating System

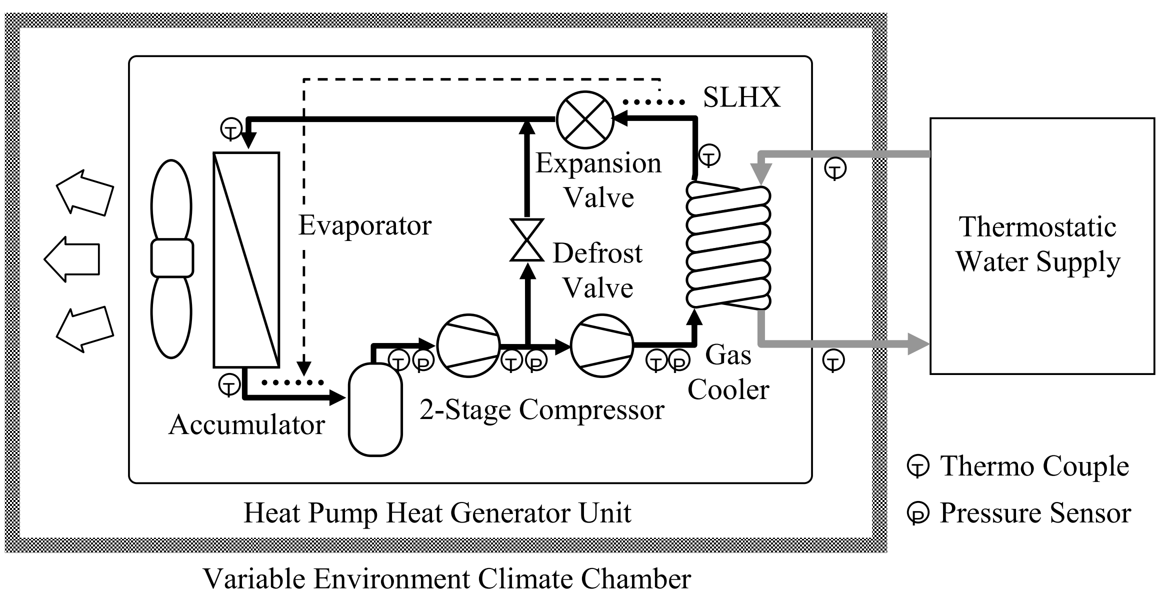


Figure 2. Experimental Setup of Heat Generator Unit

Figure 2 shows the experimental setup of the CO_2 heat pump cycle. The refrigeration circuit consists of a 2-stage compressor, gas cooler, expansion valve and an evaporator. The refrigerant discharged from compressor passes the gas cooler and heat the heat-transfer fluid, reduces pressure at expansion valve, evaporates at evaporator, goes back to compressor via the accumulator. The heat generator unit is placed in a variable climate environmental chamber. The Temperature and the humidity of evaporator inlet air are changed. Humidity is controlled when the inlet air temperature is 7°C or higher. When the inlet air temperature is 0°C or lower, the humidifier is stopped to prevent the moisture from freezing on the evaporator coil.

In this setup, water is used as heat-transfer fluid. Water is provided to the gas cooler by a thermostatic water supply, and a valve is controlled to keep the flow rate constant. The gas cooler has counter-flow channels for the water and the refrigerant. The compressor speed and the expansion valve are controlled to keep the heating capacity constant. The compressor speed is controlled by a variable frequency inverter drive. The expansion valve is driven by a stepping motor, and is set manually. The upper limits of the Compressor speed, discharge pressure, discharge temperature and the inverter current set limit to the operating condition.

The heating capacity is calculated from the temperature difference between the inlet water and the outlet water of the gas cooler, and its flow rate. The input power, which is the sum of the compressor, evaporator fan and the controller board, is measured for the heat generator unit. The COP is calculated using the input power of the heat generator unit. The suction, intermediate and discharge pressures of the refrigerant are measured with pressure sensors. The air, water and refrigerant temperatures are measured with thermocouples.

The additional incoming air heat exchanger, which recovered the heat loss by ventilation, is evaluated. The heat-transfer fluid returned from panel radiator heats the incoming air from outdoors at the heat exchanger. The heating capacity of the heat exchanger is calculated from the temperature difference between the water inlet and outlet temperatures, and the water flow rate. The water flow rate and the air flow rate are set to certain points.

3. COMPONENTS AND TEST CONDITIONS

The specifications of the heat generator unit and its components are shown in Table 1. All of the components are the same as the heat generator unit of water heater system, the heating capacity of which is 6.0kW.

The air inlet temperature was varied from -20 to 7°C. The heating capacity was set to the maximum, and set to 4.5kW when the maximum capacity was higher than 4.5kW. The evaporator fan speed was fixed at 650 RPM (1600m^3/h). The water inlet and outlet were set at various temperatures between 30 and 50°C. The amount of the refrigerant charge was 860g.

The air flow rate of the incoming air heat exchanger was set to 150 and 200m3/h, and water flow rate was varied between 2 and 4L/min. The temperature difference between inlet water and inlet air was varied between 40 and 70K. These test conditions are summarized in Table 2.

Table l. Specifications of the Heat Generator Unit

2-Stage Rotary Compressor	Cylinder Volume ($1^{st}/2^{nd}$)	3.9/2.5cm^3
	Rated Output	1300W
Fin Tube Type Evaporator	Face area (W*H)	810*630mm
Dimensions (W*H*D)		840*690*290mm
Weight		65kg

Table 2. Test Conditions

Heat Generator Unit		
Evaporator Inlet Air	Temperature	-20, -10, 0, 7°C
	Flow Rate	1600m^3/h
Gas Cooler Inlet Water Temperature		30-50°C
Gas Cooler Outlet Water Temperature		45-75°C
Heating Capacity		4.5kW and the maximum
Incoming Air Heat Exchanger		
Inlet Air	Temperature	-10, 0°C
	Flow Rate	150, 200m^3/h
Inlet Water	Temperature	40, 50, 60°C
	Flow Rate	2, 3, 4L/min

4. SIMULATION CONDITIONS

The annual electric power consumption was calculated as follows.

It is assumed that the temperature of the panel radiator inlet water is set according to the ambient temperature. The hourly heating load of a house was calculated based on the ambient temperature data with a simulation program, taking the heat gain from the sun and the heat loss of ventilation. The temperature of the panel radiator outlet water or the incoming air heat exchanger outlet water was calculated from the temperature of the panel radiator inlet water and the heating load. The COP was evaluated approximately from the ambient temperature and the gas cooler outlet water temperature. The electric power consumption was then calculated from the COP and heating load. The simulation was carried out based on the climate data of Sapporo, a city located northern in Japan.

The house is detached and average area. The room temperature was set to 20°C. The total heating capacity of the panel radiators was 8.6kW at temperature difference 35K. The panel size is approximately 60% larger than that arranged for temperature difference 50K, so that the heat-transfer fluid temperature returned from the panel radiator can be lower than conventional central heating system. The COP and the heating capacity fell at low ambient temperature. If the heating capacity was lower than the heating load, the electric heater (COP=1) compensated. The incoming heat exchanger was placed at the intake of the ventilation, and operated at the heating load higher than 3.0kW. Simulation conditions are summarized in Table 3.

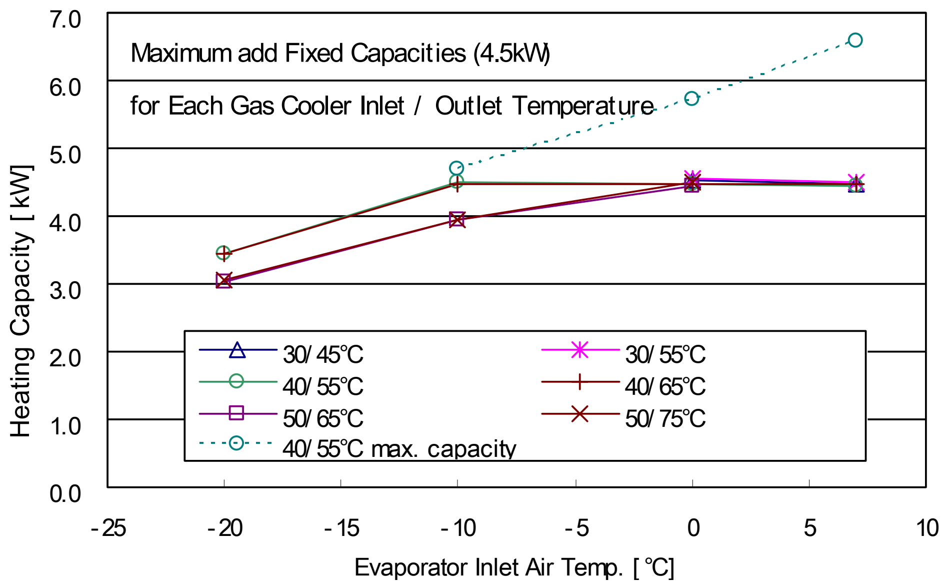
Table 3. Simulation Conditions

Climate in Sapporo (Hourly Climate Data by SHASE)	Latitude	43°N
	Heating Period Average Temperature	2.3°C
	Minimum Temperature	-13.2°C
House Data	Floor area	140m^2
	Isolation(Q-value)	1.5W/m^2/K
	Ventilation	150m^3/h
Heating and Cooling Load Simulation Program		SMASH (Distributed by IBEC)

5. RESULTS AND DISCUSSION

3.1. Test Results and Discussion

The higher gas cooler inlet water temperature or the lower inlet air temperature decreased the COP and the maximum heating capacity while the gas cooler outlet water temperature had minimal effects. The maximum heating capacities were 3.43kW (inlet air: -20°C, inlet/outlet water: 40/55°C), and 6.57kW (inlet air: 7°C, inlet/outlet water: 40/55°C). The heating capacity and the COP are shown in Figure 3 and 4.



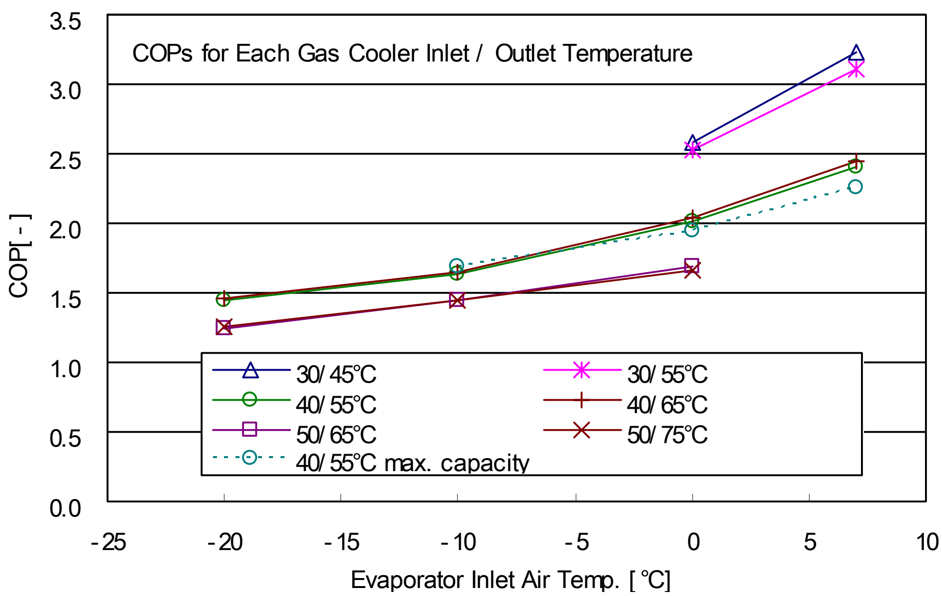


Figure 3 and 4. Heating Capacity and COP of Heat Generator Unit

The temperature differences between the inlet air and the evaporating refrigerant varied between 4 and 8K. There was a suction line heat exchanger, but the superheat varied from -2 to 10K. The upper limit of discharge temperature set the limit to opening of expansion valve at inlet air temperature lower than -10°C. The discharge pressure varied between 8.5 and 13.5MPa. The higher the gas cooler inlet water, the higher the discharge pressure. The temperature differences between the gas cooler outlet water and the gas cooler inlet refrigerant varied between 42 and 70K. The gas cooler outlet water temperature can be higher with even COP, because the temperature difference is large enough. The diagram of the CO_2 heat pump cycle is shown in Figure 5.

The capacity of the incoming air heat exchanger was increased with high water flow rate or high air flow rate. The temperature differences between the outlet air and the inlet water varied between 0.8 and 6.2K. The temperature difference was minimal, because the water-side heat capacity was much larger than that of the air-side, and because the heat-transfer performance of the heat exchanger was high enough.

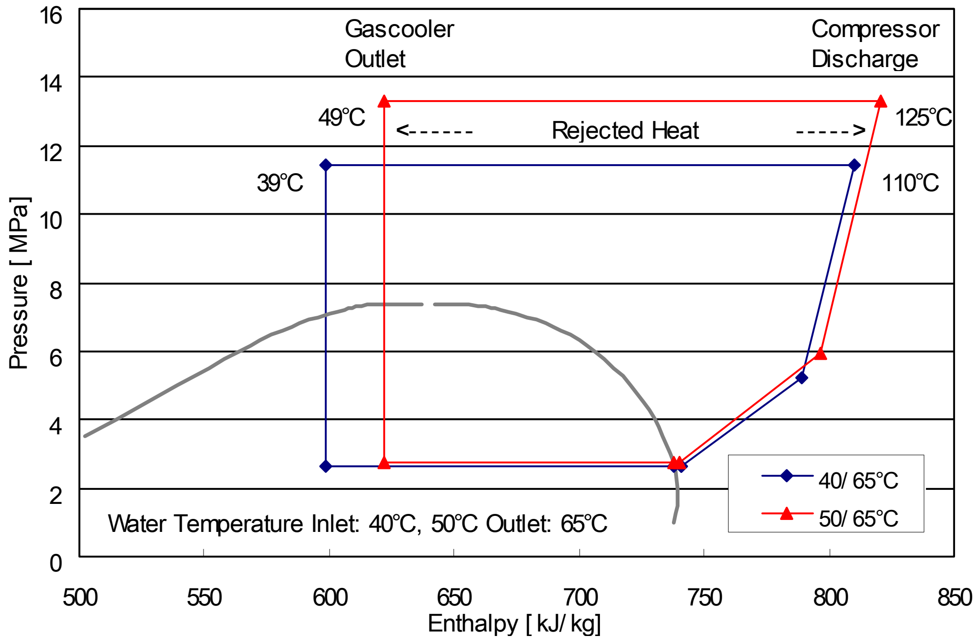


Figure 5. P-h Diagram of the CO2 Heat Pump Cycle

3.2. Simulation Results and Discussion

The sum of heating load for heating period (from Oct. 1st to Apr. 30th) was 10,918kWh, and the peak heating load was 5.68kW. The sum of input power for heating period was 6,513kWh and the average COP was 1.68, without the incoming air heat exchanger. The sum of the electric heater input was 793kWh (12% of input). The incoming air heat exchanger lowered the heat-transfer fluid temperature returned from the panel radiator between 13 and 22K. The sum of input power for heating period was 5,996kWh and the average COP was 1.82, with incoming air heat exchanger. The sum of the electric heater input was 558kWh (9% of input).

The heating capacity of the heat generator unit was lower than the heating load at inlet air temperature lower than approx. -2°C, however, the minimum heating capacity of the electric heater to compensate the shortage of the heating capacity was approx. 2.8kW. The incoming air heat exchanger made the gas cooler inlet water temperature low, and improved the average COP of the heat generator unit from 1.77 to 1.91. It is important for a high average COP to make the gas cooler inlet water temperature low. Radiator devices of high heating capacity with even low temperature heat-transfer fluid are necessary - large panel radiators, fan convector, for example. It is also important to suppress the noise and draft felling from the radiator devices.

The sum of CO_2 emissions from the energy consumption of the CO_2 heat pump heating system and the emissions from other heat generators were calculated by using the average CO_2 emission intensity in Japan. The comparison is shown in Table 4. A CO_2 heat pump heating system can reduce the CO_2 emission in comparison with an oil boiler. The reduction of the CO_2 emission is 366kgCO_2 /year (12%) without incoming air heat exchanger, and is 584kgCO_2 /year (19%) with it.

Table 4. CO_2 Emissions

Heat Generator or Heating System	CO_2 HP with Incoming Air Heat Exchanger	CO_2 HP without Incoming Air Heat Exchanger	Boiler	
Fuel / Input	Electricity	←	Kerosene	LPG
Intensity [kgCO_2/kWh]	0.421	←	0.242	0.217
Boiler Efficiency	-	-	85%	←
CO_2 Emission [kg/Year]	2,524	2,742	3,108	2,787
Ratio to Oil Boiler	81%	88%	100%	90%

6. CONCLUSIONS

The heating capacity of a CO_2 heat pump heating system is enough high for a house in cold areas in Japan. An electric heater of 3kW can compensate the shortage and annual average COP drops minimally. The heat generator unit for a CO_2 heat pump water heater system of 6.0kW can be used for a heating system. A panel radiator of the same type which is used for conventional central heating system can be used, however, high heating capacity with even low heat-transfer fluid temperature is necessary for high COP. A CO_2 heat pump heating system can reduce the CO_2 emission in comparison with an oil boiler. The incoming air heat exchanger let the gas cooler inlet water temperature low, and improves the average COP of the heating system.

The performance data of the heat generator unit with split cycle is going to be tested. The split cycle is consists of a 2-stage compressor, additional internal heat exchanger and an additional expansion valve. The heating capacity and the COP at low ambient temperature will improve with this cycle.