

The Heating Performance of a CO₂ Heat Pump Water Heater

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ABSTRACT

In this study, an experimental study on the heating performance of a CO₂ heat pump water heater was performed with a variation of operating conditions such as refrigerant charge amount, outdoor temperature, compressor frequency, EEV opening and water mass flow rate. Based on the test results, the optimum charge amount was 1800 g. At the water mass flow rates of 75, 85, and 95 kg/hr, the water heating temperatures were 62, 67, and 74 °C and COPs were 2.6, 2.8, and 3.0, respectively. Besides, the water mass flow rate and compressor frequency were varied to maintain the water heating temperature above 60 °C with the decrease of outdoor temperature. Thus, the compressor frequency increased beyond 60 Hz and the water mass flow rate was 45 kg/hr at the outdoor temperature of -13 °C, 65 kg/hr at -8 °C, 75 kg/hr at -3 °C, and 85 kg/hr at 2, 7 °C. As the outdoor temperature decreased, the COP decreased by 2.5-39.8%.

NOMENCLATURE

COP	coefficient of performance
EEV	electronic expansion valve
WB	wet bulb

DB	dry bulb
Ref	refrigerant

1. INTRODUCTION

The use of CFCs (chlorofluorocarbons), HCFCs (hydrofluorocarbons) and HFCs (hydrofluorocarbons) has been restricted by international treaties due to environmental problems such as global warming and ozone depletion. Carbon dioxide (CO₂) as a natural working fluid has many advantages such as lower global warming potential (GWP), ozone depletion potential (ODP), non-flammability and thermodynamic properties superior to other refrigerants. However, the transcritical CO₂ system showed lower performance than conventional air-conditioning system due to large expansion loss and irreversibility during the gas cooling process. Therefore, it is required to study the performance improvement of the transcritical CO₂ system. Chen and Gu⁽¹⁾ developed a correlation on gascooler pressure and system performance in the CO₂ cycle using internal heat exchanger to improve the performance of the CO₂ cycle. Li and Groll⁽²⁾ showed that the COP of an ejector expansion transcritical CO₂ cycle could be improved by more than 16%. Baek et al.^(3, 4) carried out theoretical and experimental

studies on a piston-cycle type work output expansion device in a CO₂ cycle. Cho et al.⁽⁵⁾ performed study on the cooling performance improvement of the gas injection CO₂ cycle applying twin rotary compressor to control compressor discharge temperature. In addition, using large temperature gradient in the gas cooling process, the CO₂ heat pump water heater supplying hot water with temperature over 60 °C was developed. Kobayashi⁽⁷⁾ performed study on the performance improvement of CO₂ heating and water heating system at low outdoor temperature conditions. Moreover, Murahshi⁽⁸⁾ improved the heating performance of a CO₂ heat pump water heater by applying an ejector to decrease compressor work. Especially, a few studies on the CO₂ heat pump water heater have been reported in literature. So, in this study, the CO₂ heat pump water heater was tested by varying operating conditions such as refrigerant charge amount, outdoor temperature, compressor frequency, electronic expansion valve (EEV) opening and water mass flow rate.

2. EXPERIMENTAL SETUP AND TEST-PROCEDURE

Fig. 1 shows the schematic diagram of the experimental setup. The test setup consisted of a variable speed single-rotary compressor, two heat exchangers (gascooler and evaporator) and electronic expansion valve (EEV). The compressor was a variable speed rotary type with a heating capacity of 6 kW at the standard heating test condition (outdoor conditions of 7 °C DB/6 °C WB, indoor conditions of 25 °C DB/21 °C WB). The finned tube heat exchanger used as the evaporator was made of copper tubes with inner and outer diameters of 5.6 mm and 7 mm, respectively. Fin type was louvered fin and fin pitch was 1.2 mm. The double tube heat exchanger used as the gascooler was designed for the heat exchange between refrigerant and water. The refrigerant flow rate was controlled by the EEV with an orifice diameter of 1.5 mm. The EEV had a full opening of 250 steps. The

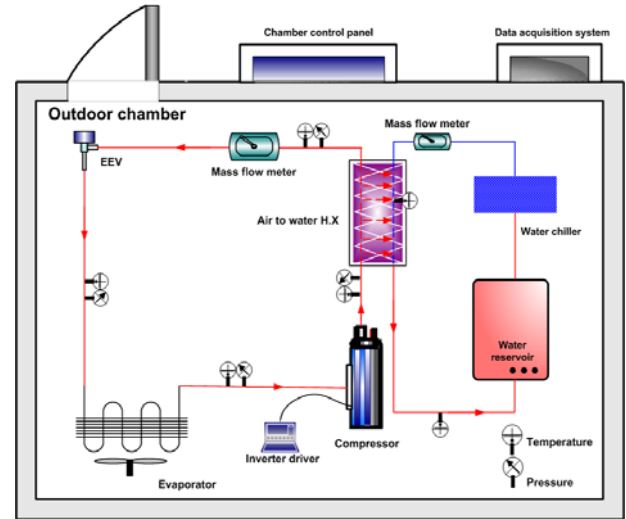


Fig. 1 Schematic diagram of the CO₂ heat pump water heater.

temperatures of refrigerant and water were measured by using T-type thermocouples with an accuracy of ± 0.2 °C. The refrigerant pressure was measured by a pressure transducer with an accuracy of $\pm 0.2\%$ of full scale. The refrigerant flow rate was measured by a Coriolis type mass flow meter with an accuracy of $\pm 0.2\%$. Power input to the compressor was measured by a power meter with an accuracy of $\pm 0.1\%$ of full scale.

The performance of the CO₂ heat pump water heater was measured by varying the refrigerant charge amount at the standard heating test condition (outdoor conditions of 7 °C DB/6 °C WB). The optimum refrigerant charge amount was determined based on the maximum COP of the CO₂ heat pump water heater when the refrigerant charge was varied from 1600 g to 2400 g with an interval of 200 g at the compressor rating frequency of 58 Hz. Once the optimum charge was determined, the performance of the CO₂ heat pump was tested according to EEV opening, compressor frequency, outdoor temperature and water mass flow rate. Especially, the water mass flow rate was adjusted to maintain the temperature of the hot water supply over 60 °C. Table 1 summarizes the test conditions in the present study.

Table 1 Test conditions

	Value
Outdoor temperature (DB, °C)	-13, -8, -3, 2, 7
EEV opening (%)	20, 30, 40, 50, 60, 70
Compressor frequency (Hz)	60, 65, 70
Water mass flow rate (kg/hr)	45, 55, 65, 75, 85, 95

3. RESULTS AND DISCUSSION

3.1 Effects of refrigerant charge on the performance of the CO₂ heat pump

Fig. 2 shows the variations of heating capacity, compressor work and COP with refrigerant charge amount. As the refrigerant charge amount increased, the heating capacity increased due to the increase of the heat transfer between refrigerant and water in the gascooler. However, the COP decreased because the increasing rate of the compressor work was higher than that of the heating capacity above the refrigerant charge amount of 1800 g. Besides, at the standard heating test condition, considering the compressor rating capacity of 6 kW and the compressor reliability with the compressor discharge temperature below 100 °C, the optimum refrigerant charge amount was 1800 g. At the water mass flow rate of 75, 85 and 95 kg/hr, the water heating temperatures were 74, 67 and 62 °C and the COPs were 2.6, 2.8 and 3.0, respectively.

3.2 Effects of operating conditions on the performance of the CO₂ heat pump

The performance characteristics were investigated by varying EEV opening, outdoor temperature, compressor frequency, water mass flow rate at the optimum refrigerant charge amount of 1800 g.

Fig. 3 shows the variations of refrigerant

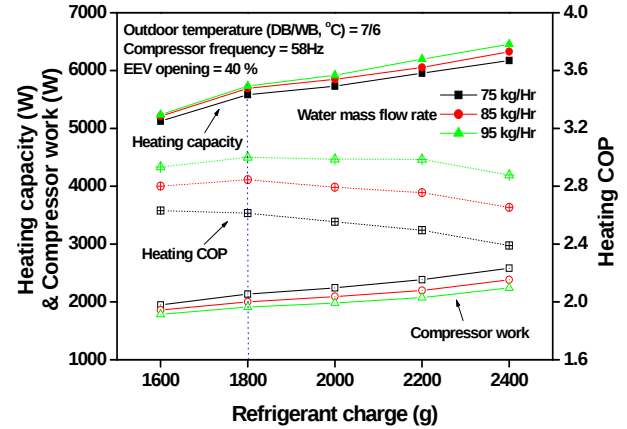


Fig. 2 Variations of heating capacity, compressor work and COP with refrigerant charge.

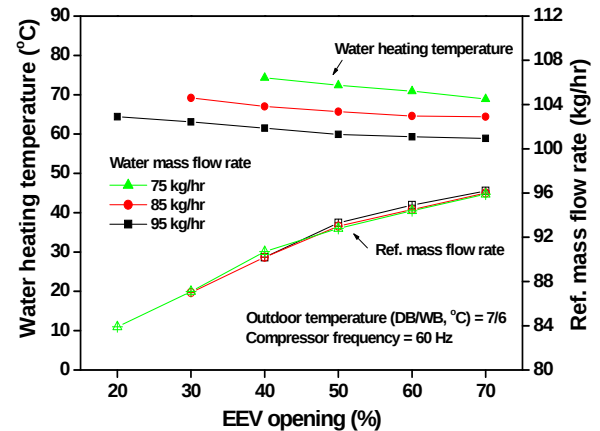


Fig. 3 Variations of refrigerant mass flow rate and water heating temperature with EEV opening.

mass flow rate and water heating temperature with EEV opening. The refrigerant mass flow rate increased with the increase of the EEV opening due to the decrease of the expansion loss in the orifice. The decrease of compressor inlet superheat with the increase of refrigerant mass flow rate resulted in the decrease of the water heating temperature because the heat transfer between refrigerant and water reduced. In addition, as the water mass flow rate increased, the water heating temperature decreased due to the decrease of the temperature gradient at the same EEV opening.

Fig. 4 shows the variations of heating capacity, compression ratio and COP with EEV

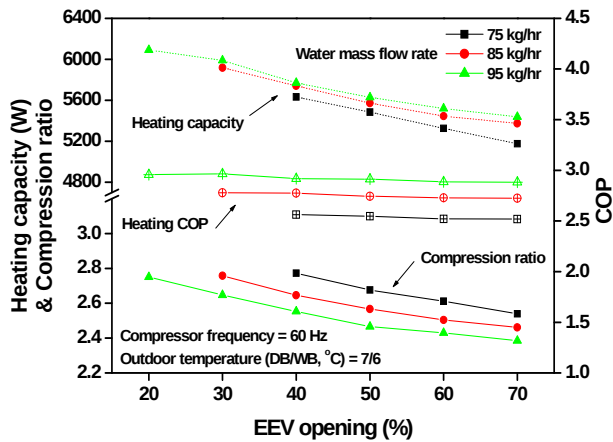


Fig. 4 Variations of heating capacity, compression ratio and COP with EEV opening.

opening. The increase of the refrigerant mass flow rate with the increase of the EEV opening increased the compressor suction pressure, however the compressor discharge pressure decreased with the decrease of the compressor discharge temperature, resulting from the decrease of compressor inlet superheat. Thus, the compression ratio defined as the ratio of the compressor suction pressure to the compressor discharge pressure decreased with EEV opening. In addition, the heating capacity decreased with EEV opening because the decrease of the compressor discharge temperature was larger than the increase of the refrigerant mass flow rate. The compressor work decreased because of the decrease of the compression ratio and compressor inlet superheat with EEV opening. COP maintained constant because the decreasing rate of the heating capacity was the same as that of the compressor work.

Fig. 5 shows the variation of pressure-enthalpy diagram with water mass flow rate. The increase of the water mass flow rate caused the increase of heat transfer between refrigerant and water in the gascooler and the decrease of the evaporator inlet quality. Thus, the heating capacity increased with the increase of the water mass flow rate. In addition, the compressor ratio was decreased by the decrease of the compressor discharge pressure, resulting in decreasing the

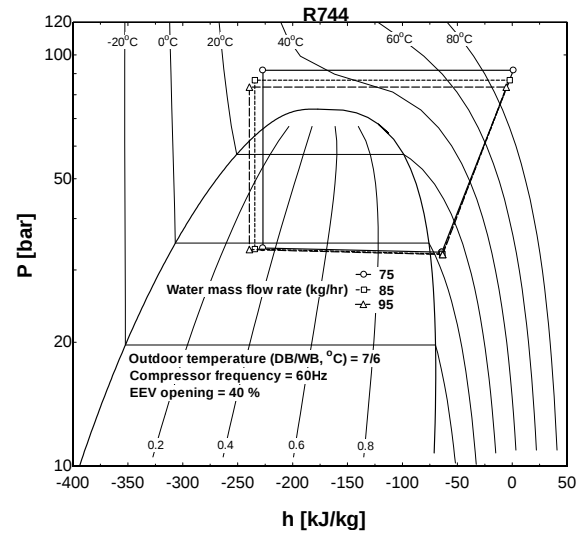


Fig. 5 Variation of pressure-enthalpy diagram with water mass flow rate.

compressor work. At the water mass flow rate of 75 kg/hr, as the water mass flow rate increased by 10 kg/hr, the heating capacity increased by 4.6 and 9.2% and the compressor frequency decreased by 3.9 and 6.2% and COP increased by 9.0 and 16.2%, respectively.

Fig. 6 shows the variation of pressure-enthalpy diagram with outdoor temperature. As the outdoor temperature decreased, the compression ratio increased because the decrease of the compressor discharge pressure was less than that of the compressor suction pressure. At the outdoor temperature of 7°C, as the outdoor temperature decreased by 5°C, the compression ratio decreased by 3.4, 9.4, 15.2 and 23.5%, respectively.

Fig. 7 shows the variations of refrigerant mass flow rate, heating capacity and COP with outdoor temperature. Generally, the increase of compression ratio with the decrease of the outdoor temperature led to refrigerant leakage by the pressure difference between rotor and vane in compressor. This trend caused the decrease of the refrigerant mass flow rate. At the outdoor temperature of 7°C, as the outdoor temperature decreased by 5°C, the refrigerant mass flow rate decreased by 8.5, 18.4, 25.6 and 41.6%, respectively. Besides, as the outdoor temperature decreased, the heating capacity and COP

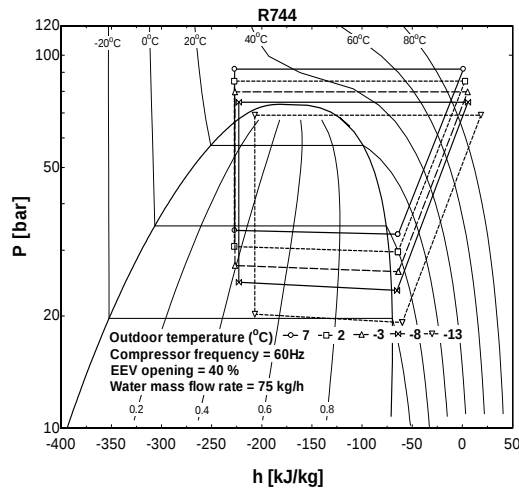


Fig. 6 Variation of pressure-enthalpy diagram with outdoor temperature.

decreased by the reduction of the heat transfer between refrigerant and water. At the outdoor temperature of 7 °C, as the outdoor temperature decreased by 5 °C, the heating capacity decreased by 8.2, 17.5, 26.0 and 43.3% and COP decreased by 2.7, 8.2, 13.4 and 25.9%, respectively.

Fig. 8 shows the variations of compressor discharge temperature and water heating temperature with water mass flow rate. The optimum water mass flow rate of CO₂ heat pump was necessary for hot water supply with temperature over 60 °C and the compressor discharge temperature below 100 °C at all outdoor temperatures. At the outdoor temperature of 7 °C, the range of the water mass flow rate was 20 kg/hr varied from 75-95 kg/hr. As the outdoor temperature decreased by 5 °C, the range of the water mass flow rate was 15, 13 and 10 kg/hr, respectively. Especially, at the outdoor temperature of -13 °C, the range of the water mass flow rate for two conditions did not exist. Therefore, the study on the performance improvement of CO₂ heat pump has to be investigated by technical development controlling the compressor discharge temperature at lower outdoor temperature.

4. CONCLUSIONS

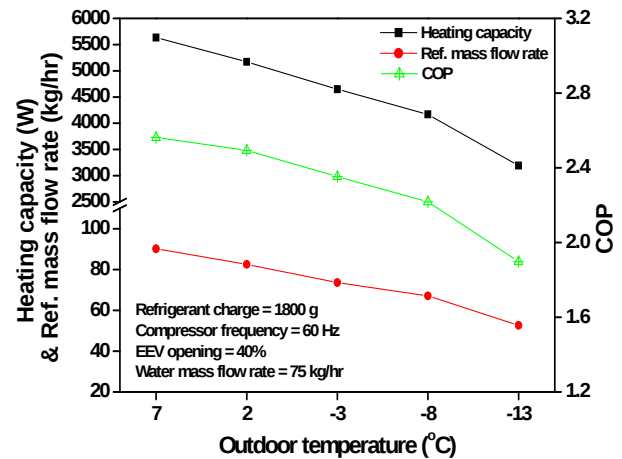


Fig. 7 Variations of refrigerant mass flow rate, heating capacity and COP with outdoor temperature.

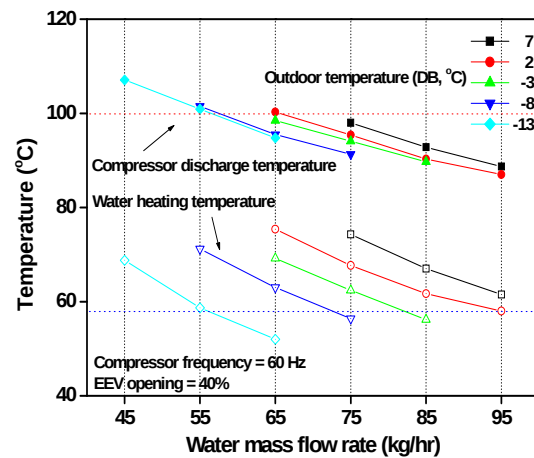


Fig. 8 Variations of compressor discharge temperature, water heating temperature with out-door water mass flow rate.

The heating performance of the CO₂ heat pump water heater was measured with a variation of operating conditions such as refrigerant charge amount, outdoor temperature, compressor frequency, EEV opening and water mass flow rate. As a result, the optimum charge amount was 1800 g. At the water mass flow rates of 75, 85, and 95 kg/hr, the water heating temperatures were 62, 67, and 74 °C and COPs were 2.6, 2.8, and 3.0, respectively. COP increased by 12.6% as the water mass flow rate increased by 10 kg/hr at the EEV opening of 40% and the standard

heating test condition of outdoor temperature of 7°C DB/6°C WB. Besides, compressor frequency and the water mass flow rate were varied to maintain the water heating temperature over 60°C with the decrease of outdoor temperature. Thus, the compressor frequency was beyond 60 Hz and the range of the water mass flow rate decreased by 16.7% as the outdoor temperature decreased by 5°C.

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