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A study on the performance of heat pump by mixing ratio of isobutane/propane mixed refrigerants

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Abstract

Natural refrigerants have global warming potential (GWP) and ozone depletion potential (ODP), but typical natural refrigerants have low COP, too. On the contrary, hydrocarbon refrigerants have high performance. In this study, using the characteristics of mixed refrigerants that can maintain a constant temperature difference during phase change, performance of the cycle according to the change in mixing ratio of isobutane and propane was calculated and measured. At outdoor temperature of 35℃ and indoor temperature 27℃, COP of the cycle was maximized at isobutane ratio is near 0.8.

Keywords: natural refrigerant; mixed refrigerant; isobutane; propane; COP

1. Introduction

As environmental problems such as global warming and the destruction of the ozone layer have emerged around the world, regulations on existing CFCs, HCFCs, and even HFCs refrigerants are being tightened. Therefore, research on heat pumps using natural refrigerants with low GWP and ODP is actively underway. There are many kinds of natural refrigerants, such as hydrocarbon, carbon dioxide, and water. Especially, isobutane shows low compressor work because of low compression ratio, and propane has a high cooling capacity. There are many studies on mixed refrigerant using isobutane and propane.

Nawaz *et al.* [1] studied water heaters using a mixed refrigerant of isobutane and propane, and Wu *et al.* [2] studied absorption heating cycles using natural refrigerants and low-GWP refrigerants mixtures. He *et al.* [3] calculated COP and cooling capacity of propane and isobutane mixed refrigerant with varying mixing ratios. Simulation was performed after fixing the cooling capacity, and the condensation temperature was 54.4℃, and the evaporation temperature was -23.3℃. Jung *et al.* [4] also conducted a study on the performance coefficient and the cooling capacity per unit volume due to changes in the mixing ratio of propane and isobutane. It fixed the cooling capacity at 130 W, fixed the secondary fluid inlet temperature is -15℃, and outlet temperature at -21℃. Chen *et al.* [5] conducted experimental studies on isobutane and propane mixed refrigerants, in which case only results were found when the propane ratio was 0.30 to 0.55 without conducting for the overall mixing ratio.

In this study, the performance of the heat pump according to the mixing ratio of the hydrocarbon refrigerant, isobutane and propane mixture is analyzed through a simulation and experimental study.

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2. Simulation result

2.1. Characteristics of mixed refrigerant

In the case of a single refrigerant, the temperature remains constant when fluid phase is changed, and there is a pinch point where the heat exchange rate decreases. Therefore, the heat exchange with secondary fluid is not uniform. However, in the case of mixed refrigerant, temperature gradients exist even when phase change occurs, which has the advantage of maintaining heat exchange with secondary fluid.

2.2. Simulation condition

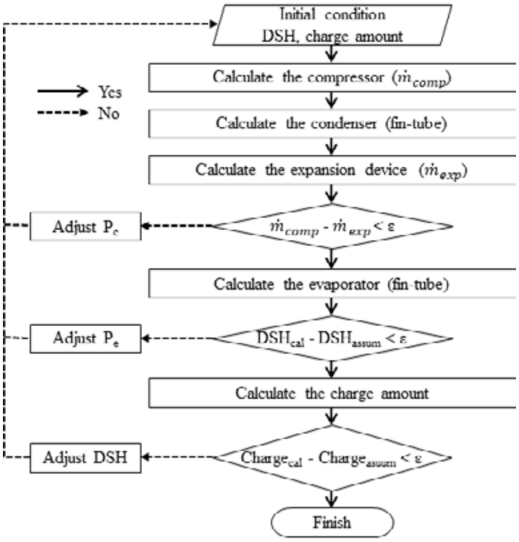


Fig. 1. Flow chart of simulation

The flow chart used of simulation is shows in Fig. 1. To maintain accuracy in the comparison between cycles, the degree of superheat was fixed at 5 K, and calculations were performed with the condenser pressure and evaporator pressure as variables to ensure the convergence of the cycles.

COP of cycles is calculated by equation (1) through compressor work and cooling capacity.

$$COP = \frac{Cooling\ capacity}{Compressor\ work} \tag{1}$$

In this simulation, reciprocating compressor model was used. Isentropic efficiency depends on pressure ratio, degree of superheat, etc., and isobutane and also have different isentropic efficiency in previous papers [6]. The enthalpy of compressor outlet can be calculated by equation (2)

$$h_{comp,out} = \frac{h_{comp,out,is} - h_{comp,in}}{\eta_{is}} + h_{comp,in} \tag{2}$$

The discharge mass flow rate of compressor, and compressor work are as shown in equation (3) and equation (4), respectively.

$$\dot{m}_{comp} = V_s \rho_{comp,in} Hz \left(1 - V_c \left(\frac{\rho_{comp,out}}{\rho_{comp,in}} - 1\right)\right) \tag{3}$$

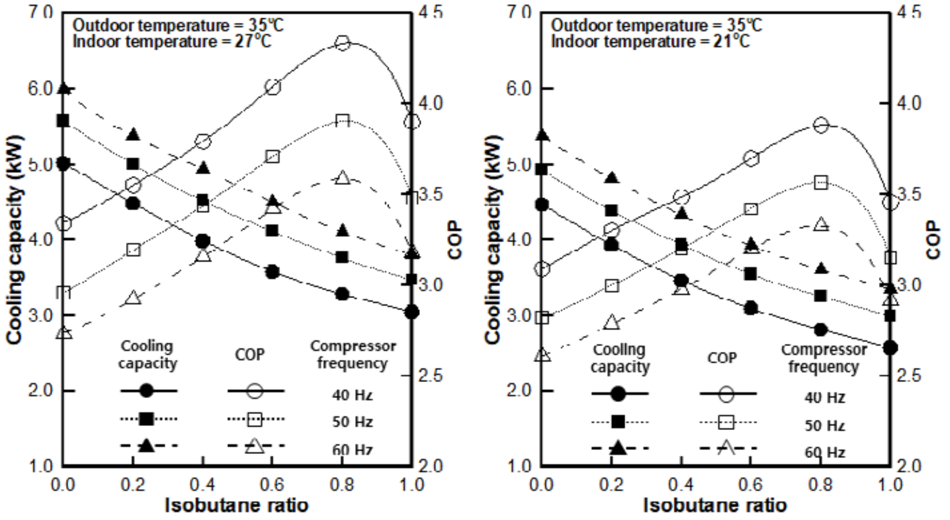
$$W_{comp} = \dot{m}_{comp}\left(h_{comp,out} - h_{comp,in}\right) \tag{4}$$

In this paper, simulation analysis of mixed refrigerants has been performed, and a corresponding heat transfer coefficient calculation expression is required. For mixed refrigerants, the heat transfer coefficient of condenser was calculated by referring model of Shah [7], and heat transfer coefficient of evaporator was calculated by referring model of Choi [8]. Heat transfer coefficient of Shah and Chis are represented in equation (5) and equation (6)

$$h_{tp,cond} = 0.023Re_{lo}^{0.8}Pr^{0.4}\left[(1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{Pr_{cd}^{0.38}}\right]\frac{\lambda}{D} \quad (5)$$

$$h_{tp,eva} = E\left(0.023Re^{0.8}Pr^{0.4}\frac{\lambda}{D}\right) + SF_m\left(207\frac{k_1}{bd}\left(\frac{qbd}{k_1T_s}\right)^{0.674}\left(\frac{\rho_v}{\rho}\right)^{0.581}Pr^{0.533}\right) \quad (6)$$

Cycle calculation was performed using the above equations.



(a) 35°C/27°C (b) 35°C/21°C

Fig. 2. Cooling capacity and optimal COP according to isobutane ratio

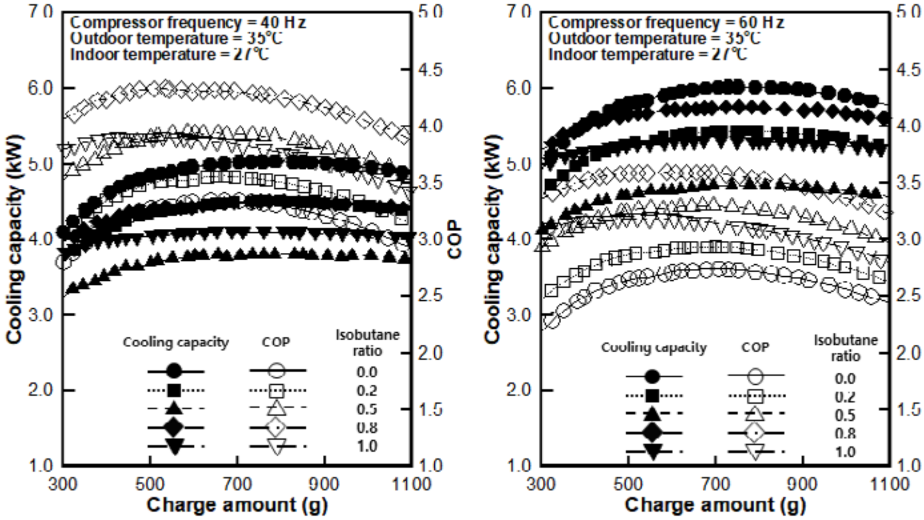
2.3. Simulation results

Simulation was performed on indoor temperature of 27°C, 21°C under outdoor temperature of 35°C. The compressor frequency sets in the simulation are 50 Hz, 60 Hz, and 70 Hz. Fig. 2 is the cooling capacity and optimal COP according to the change of isobutane ratio at outdoor temperature is 35°C. Indoor temperature of (a) and (b) are 27°C and 21°C, respectively. Isobutane ratio in x-axis is calculated by equation (7)

$$Isobutane\ ratio = \frac{m_{isobutane}}{m_{isobutane}+m_{propane}} \quad (7)$$

As isobutane ratio increases, cooling capacity decreases. This phenomenon due to the properties of isobutane and propane refrigerants. Propane refrigerant has better thermal properties that isobutane. However, isobutane has low compression ratio, so this leads low compressor work. Therefore, optimal COP exists between decreasing compressor work and increasing cooling capacity. Accordingly, as isobutane ratio increases, COP increases and decreases. The optimal isobutane ratio under all simulation compressor frequency and temperature conditions is approximately 0.8.

Calculation of the optimal amount of refrigerant according to the isobutane ratio was also carried out. The results can be seen in Fig. 3

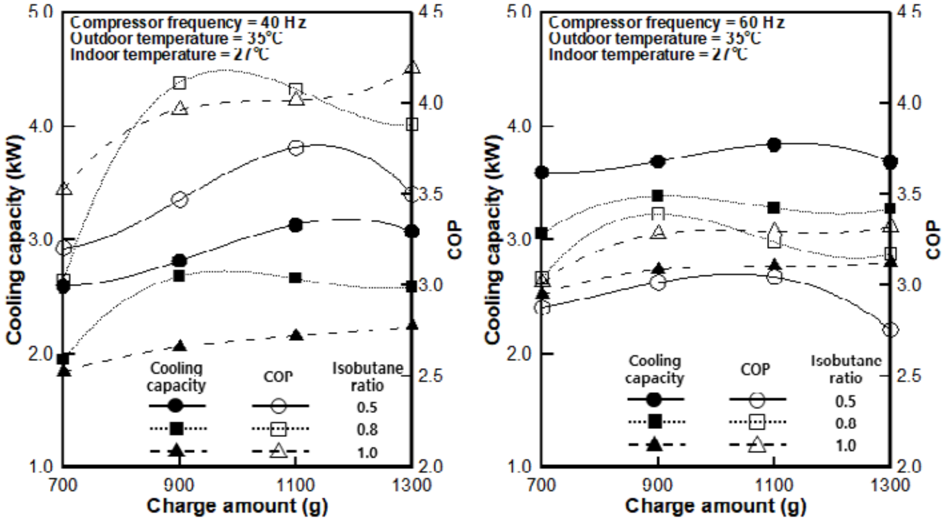


(a) Compressor frequency = 40 Hz

(b) Compressor frequency = 60 Hz

Fig. 3. Cooling capacity and COP according to refrigerant charge amount

Since isobutane and propane have different specific volume and the optimal refrigerant charge is present according to their respective isobutane ratio, calculation of the optimal refrigerant charge for each isobutane ratio is required to know the exact effect on the mixing ratio. As can be seen in Fig. 3, it can be seen that the optimum cooling capacity and the optimal refrigerant charge amount representing the optimal COP differ depending on the change in the isobutane ratio. This will be verified through further experiments.



(a) Compressor frequency = 40 Hz

(b) Compressor frequency = 60 Hz

Fig. 4. Cooling capacity and COP according to the isobutane ratio and refrigerant charge amount

3. Experiment result

Based on the simulation results, experiments were conducted on the isobutane ratios of 0.5, 0.8, and 1.0, not on the overall mixing ratio. Furthermore, the simulation results showed that the optimal charge amount varies as the isobutane ratio changes, so the experiment was performed by varying the refrigerant volume. Outdoor temperature condition is 35°C, and indoor temperature condition is 27°C.

Fig. 4 shows experiment results. As the results of the simulations, the experiments also showed optimal COP near the isobutane ratio is 0.8. The cooling capacity also decreased as the isobutane ratio increased. In addition, experiment have identified the temperature distribution within the heat exchanger, shown in Fig. 8. As a result of the simulation, for single isobutane and propane refrigerants, the temperature remains constant before the superheated region, and the temperature glide occurs as the mixing takes place. The results of experiment have verified that the simulation results are close to reality.

4. Conclusions

In this study, a research was conducted on heat pump using mixed hydrocarbon refrigerants with very low GWP and zero ODP in preparation for continuously strengthened refrigerant regulations.

Simulation and experimental studies were conducted by mixing propane refrigerants with large cooling capacities and isobutane refrigerant with low compressor work. Simulation studies have shown that optimal COP near the isobutane ratio of 0.8 under various temperature conditions, and the temperature distribution inside the heat exchanger has also been calculated.

Simulation results were verified through experiment using a double-pipe heat exchanger, which allowed the optimal isobutane ratio of mixed refrigerants to be derived.

Acknowledgements

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