

Development of a general-purpose simulator for heat pump systems

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1. INTRODUCTION

Against the backdrop of environmental issues, heat management is becoming increasingly important both in homes and in industry. Against this backdrop, heat pump technology, which reuses waste heat from factories, is attracting attention, especially in the industrial sector. Heat pumps are applied to familiar products such as air conditioners and refrigerators, and are extremely environmentally friendly systems because they generate energy without using heat. However, the refrigerants currently mainly used in heat pumps have a very high GWP (Global Warming Potential). High GWP refrigerants are required by the Kigali Amendment to reduce the consumption of HFC refrigerants by about 85% by around 2040, based on the baseline year of around 2015. Therefore, a heat pump simulation tool applicable to various fields is important to select the optimal alternative refrigerant and to evaluate the effect of introducing heat pumps into existing systems. In this study, we used R32, one of the low-GWP refrigerants, with double tubes developed in a previous study, and updated a new heat pump simulation model using the model-based design simulator Simscape to a plate heat exchanger to create a more versatile heat pump system. We have developed a new heat pump simulation model using the Simscape model-based design simulator.

2. METHODOLOGY

2.1 Experimental apparatus and Simscape model

Figure 1 shows the experimental apparatus. The apparatus is a heat pump cycle, consisting of a refrigerant loop and a heat sink/heat source water loop. The apparatus was modeled in Simscape.

The compressor and expansion valve were modeled in “positive displacement compressor (2P)” and “local restriction (2P)” blocks, respectively. The plate heat exchanger was created by referencing a block in Simscape, as Simscape does not have a suitable block model for plate heat exchangers. The refrigerant flow was modeled by referencing the “Pipe (2P)” block in Simscape, and the heat sink/crawling water flow was modeled using a block created by referencing the “Pipe (TL)” block. To improve calculation accuracy, the heat exchanger was divided into 10 segments. This allows for a more accurate representation of heat transfer. The correlation equation from Ayub [1] was used to calculate heat transfer coefficients for single-phase refrigerants and heat sink/source water. For two-phase refrigerants, Yan's correlations [2] and [3] are used for the condenser and Lee's correlation [4] for the evaporator. These correlations are condensation and evaporation heat transfer correlations that account for convective heat transfer. The pressure drop is expressed by the following equation (1)

$$f = \frac{\rho D}{2G^2 L} \Delta P \quad (1)$$

where f is the friction factor and is expressed in single-phase and two-phase conditions, respectively, as follows

$$f = 0.3Re_{lo}^{-0.32} \quad (2)$$

$$f = 6.54 \times 10^{-4} Re_{eq}^{1.247} Re_{lo}^{-0.708} Pr_l^{\frac{1}{3}} \quad (3)$$

The superheat is set to the target value by PI control.

2.2 Conditions and data reduction

Table 1 shows the experimental and simulation conditions. R32 is used as the refrigerant.

The heating cycle COP is calculated as follows,

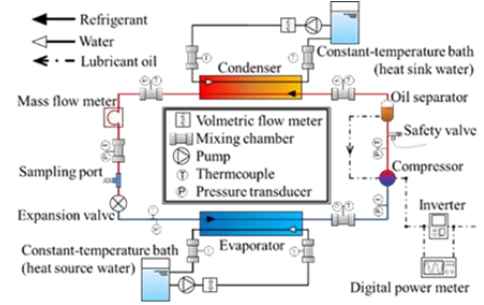


Fig.1 Schematic diagram of experimental apparatus

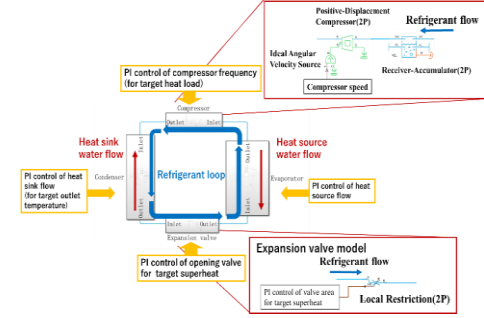


Fig.2 Schematic diagram of heat pump model, compressor, and expansion valve

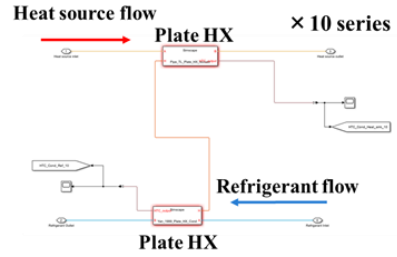


Fig.3 Model of double-pipe heat exchanger

$$COP_{H,cycle} = \frac{Q_{H,Cond}}{W_{Comp}} = \frac{Q_{H,Cond}}{m_{Ref}(h_d - h_s)} \quad (4)$$

where m_{Ref} is refrigerant mass flow rate, h is specific enthalpy. Table 1: Experimental and simulative condition. The heat transfer correlations used were Ayub's correlation (5) for the single phase refrigerant, Yan (6) for the two-phase condensation heat transfer correlation, Lee (7) for the two-phase evaporation heat transfer correlation, and Yan (8) for the heat source

$$Nu = 0.2946Re^{0.7}Pr^{\frac{1}{3}} \quad (5)$$

$$Nu = 4.118Re_{eq}^{0.4}Pr_l^{\frac{1}{3}} \quad (6)$$

$$Nu = 1.84Re_{eq}^{0.58}Re_{lo}^{-0.22}Pr_l^{\frac{1}{3}} \quad (7)$$

$$Nu = 0.2121Re^{0.78}Pr^{\frac{1}{3}} \quad (8)$$

where Re_{eq} is expressed by the following equation (9). Re and Pr denote Reynolds number and Prandtl number. Pr_l and Re_{lo} are the Prandtl number and Reynolds number in the liquid phase.

$$Re_{eq} = \frac{G_{eq} D_h}{\mu_l}, G_{eq} \left[(1-x) + x \left(\frac{\rho_l}{\rho_v} \right)^{0.5} \right] \frac{D_h}{\mu_l} \quad (9)$$

where G is the flux, D is the hydraulic diameter, μ is the viscosity in the liquid phase, ρ is the density, and x is the vapor quality.

Table 1: Experimental and simulative condition

Heat source water temperature[°C]		Q(Heat load) [kW]	Superheat [°C]
condenser	evaporator		
30→45	20→10	1.4 to 2.4	4.0

3. RESULTS AND DISCUSSION

Figure 4 shows the P-h and COP diagram simulation results (UPDATE MODEL has no data only for heat load 1.4-2.4kw *1.8kW). The double-tube (red line in the graph) is a heat pump model with a conventional double-tube heat exchanger. The simple plate HX (purple line) is a plate version of the heat transfer process of the double-tube heat exchanger; the correlation between heat transfer and pressure drop is the same as for the double-tube. Plate HX (no pressure) is the simple plate HX model plus equations (5)~(8); rate HX (updated model) is the simple plate HX model plus equations (2)~(8). These results indicate that simply changing the heat transfer process from the conventional double-tube model to the plate model does not improve the COP. However, a significant improvement in COP is observed for the Plate HX (no-pressure) and the Plate HX (updated model), where heat transfer correlations are introduced for both the condenser and the evaporator. This indicates that heat transfer correlation has a significant impact on COP results. However, the Plate HX (no-pressure) and Plate HX (update model) resulted in almost the same COP. The difference between these models is the introduction of a pressure drop. Therefore, it was found that the introduction of pressure drop did not affect COP very much in the heat pump model developed in this study. This result was attributed to the fact that the refrigerant used is R32, which easily maintains the heat exchange rate even when pressure losses are introduced due to its small clay size and high thermal conductivity. These results also suggest that appropriate and two-phase heat transfer correlation is important for plate heat exchangers because of the greater influence of turbulence compared to double-tube heat exchangers. Therefore, the COP is considered to be lower for the Simple plate HX, which was simulated with a heat transfer correlation that is not suitable for plate heat exchangers.

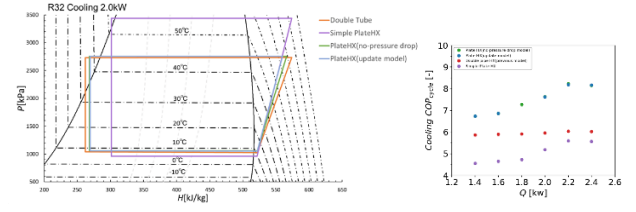


Fig.4 Comparison of experiment and Simulation (R32, Heating)
Figure 5 shows the results of the heat transfer comparison. The results show that there is a significant difference in heat transfer between the heat transfer correlation used in the conventional model as it is and the heat transfer correlation appropriate for a plate heat exchanger. This indicates that it is important to introduce a heat transfer correlation that is appropriate for the heat exchanger.

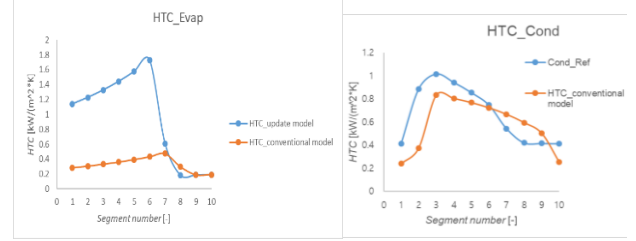


Fig.5 HTC Comparison Results(R32 Cooling 2.0kW)

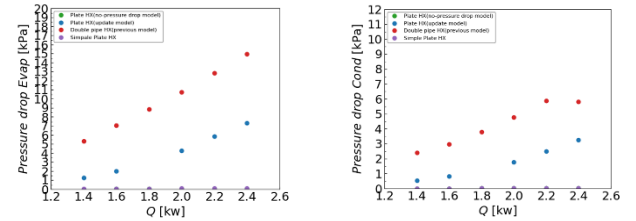


Fig.6 Pressure drop

Figure 6 shows the pressure drop results. This result shows that the introduction of pressure loss correlations has made it possible to express the pressure loss, which previously could not be expressed at all.

4. CONCLUSION

The Simscape heat pump model with a double-tube heat exchanger developed in a previous study was updated to a model with a plate heat exchanger to develop a general-purpose heat pump system. As a result, heat transfer and pressure drop correlations appropriate for plate-type heat exchangers were introduced so that heat transfer and pressure drop can be evaluated more correctly.

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