Development of a Performance Prediction Tool for The Heat Pump Air-Conditioning System Applying Refrigeration Cycle

Takashi Yamaguchi, Graduate Student, The University of Kitakyushu, Kitakyushu, Japan
Takao Katsura, Lecturer, The University of Kitakyushu, Kitakyushu, Japan

Abstract: A new performance prediction tool for the heat pump air-conditioning system that considering refrigeration cycle was developed by the authors. The tool has special features such as enough computation speed, extensibility and satisfying precision for annual performance prediction. In this paper, outlines of the tool were firstly introduced. Next, an experiment to verify precision of the tool was conducted. In this experiment, the temperature at several points on the refrigerant pipe in the heat pump unit, the cooling output, and the electrical power consumption of compressor were measured. The measured values were compared with the one calculated by the developed tool and the accuracy of prediction was confirmed. As the result of experiment, the error between the predicted and measured values was less than 1 %. In addition, the authors predicted the performance of heat pump air-conditioning system utilizing ground source in the office building in Kitakyushu city as case study.

Key Words: ***Heat Pump Air-Conditioning System, Performance Prediction Tool, Refrigeration Cycle, Accuracy Verification***

1 INTRODUCTION

Recently, reducing the air conditioning energy for buildings is desired. Heat pump air-conditioning systems that can operate with higher efficiency and apply various heat sources attracts people's attention and the large number of heat pump air-conditioning systems is installed in Japan. However, there are some reports that show difference of COPs between the ones in the catalogs and the ones measured in the actual operation. This problem was caused by differences between the performance prediction experiments to decide a catalog value and field operations in the following conditions - : length of refrigerant pipes, thermal load, etc. Now, development of a new performance prediction tool for the heat pump air-conditioning system considering these factors is needed.
The conventional computation model for performance prediction of the heat pump air-conditioning system is mainly classified into equipment characteristic model (Li et al., 2009) and mathematical model for refrigeration cycle (Togashi et al., 2008). However, these models have some problems. Equipment characteristic model cannot consider influences of indoor equipment and makes different results between the predicted value and the measured value. Mathematical model does not have enough computation speed for annual performance prediction.
Therefore, the authors developed a new performance prediction tool for heat pump air-conditioning systems that can consider the refrigeration cycle. The tool has special features such as computation speed, extensibility and satisfying precision for annual performance prediction. In this paper, outlines of the new tool, results of experiment and a case study to verify accuracy of the tool are introduced.

2 OUTLINES OF DEVELOPED PERFORMANCE PREDICTION TOOL

A new performance prediction tool developed by the authors is constructed by computation model considering the refrigeration cycle to ensure enough computation speed, extensibility and satisfying precision for annual performance prediction. In regards to annual performance

prediction, the tool can respond better than the conventional tool applying the mathematical model because the developed tool carries out only one convergence calculation.
In this tool, it is necessary to input such as the rated cooling output, heating output, and electric power of the indoor unit and outdoor unit. This tool also needs to input specifications of air conditioning equipment i.e. capacities of heat exchanger (evaporator and condensers), capacity of compressor, length of refrigerant pipes. In addition, hourly heat load for the heat pump unit, indoor and outdoor temperature are given in order to conduct annual performance prediction. Figures 1-4 show a building process of computation system in the Mollier diagram. As an example of the performance calculation method, the building process of basic computation model to predict a cooling performance of a heat pump air-conditioning system is explained below.

(1) Assuming the condensing temperature of the refrigerant
(2) The enthalpy of refrigerant at outlet of the condenser is calculated by assuming that the refrigerant state at outlet of the condenser is on the saturation liquid line in Mollier diagram as pointed in Figure 1
(3) Evaporating temperature of the refrigerant is calculated by using the equation in Figure 1 and giving the extracted heat at the evaporator (Equal to cooling load of indoor unit), the room temperature, the area and heat transmission coefficient of the heat exchanger in the indoor unit
(4) Refrigerant pressure at the expansion valve is dropped by assumption of isenthalpic change
(5) Enthalpy at inlet of the evaporator is determined
(6) The enthalpy of refrigerant at outlet of the evaporator is calculated by assuming that the refrigerant state at outlet of the evaporator is on the saturation vapor line in Mollier diagram as pointed in Figure 2
(7) Flow rate within a refrigerant pipe is calculated by dividing the extracted heat at evaporator by the enthalpy difference between inlet and outlet of evaporator based on the refrigerant enthalpy method
(8) Electric power consumption at compressor is approximated as a function of the condensing temperature, evaporating temperature and flow rate of the refrigerant
(9) Injected heat at the condenser is calculated as the sum of electric power consumption of the compressor and the extracted heat at the evaporator
(10) Condensation temperature of the refrigerant is calculated by using the equation in Figure 4 and giving the injected heat at the condenser, the outdoor air temperature, the area and heat transmission coefficient of the heat exchanger in the outdoor unit
(11) Compared the condensation temperatures T_c and $T_{c(a)}$, which has been calculated in (10) and assumed in (1), respectively. If the difference is very small, the tool finishes the calculation. If convergence state isn't confirmed, the assumed condensation temperature is changed to the calculated condensation temperature in (10) and repeat the process of (1) to (11) until-the computation model converges

The Figure 5 shows the calculation flow for cooling operation. Here, the refrigerant enthalpy is determined according to refrigerant properties database (REFPROP 8.0) The Figure 6 shows temperature difference T_c - $T_{c(a)}$ according to calculation time n when it is given the arbitrary heat load and outside air temperature. As the result of The Figure 6, the temperature difference T_c - $T_{c(a)}$ becomes approximately 0 ℃ and the computation model converges when the tool carries out twice of convergence calculation.

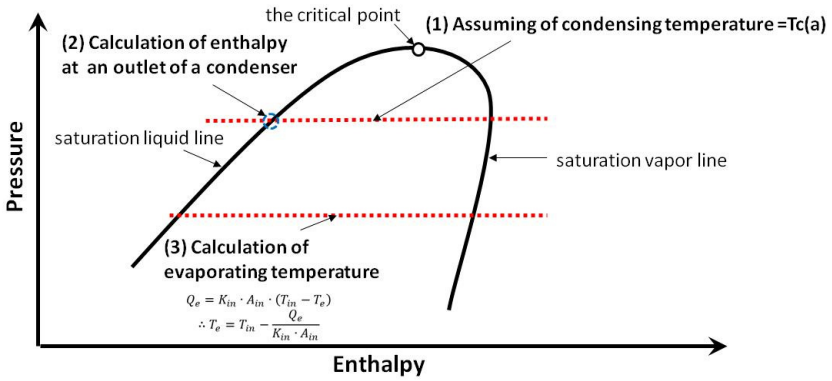


Figure 1: Process of computation model ((1) to (3))

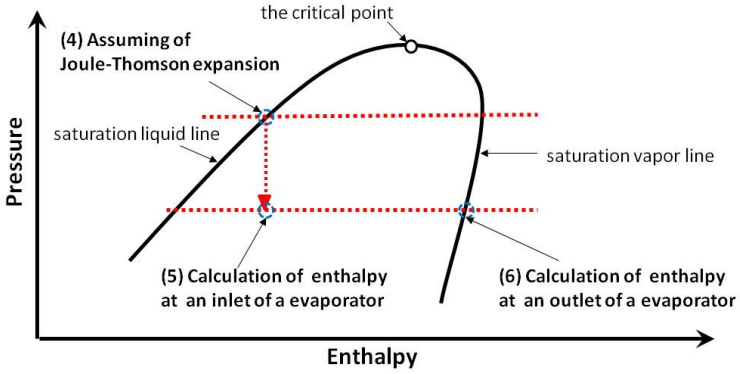


Figure 2: Process of computation model ((4) to (6))

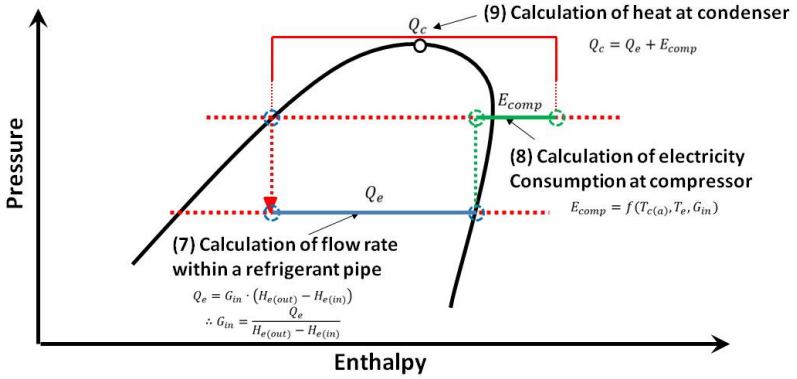


Figure 3: Process of computation model ((7) to (9))

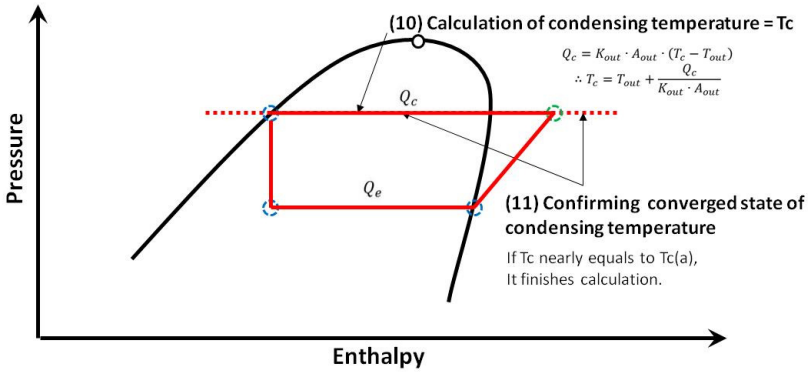


Figure 4: Process of computation model ((10) to (11))

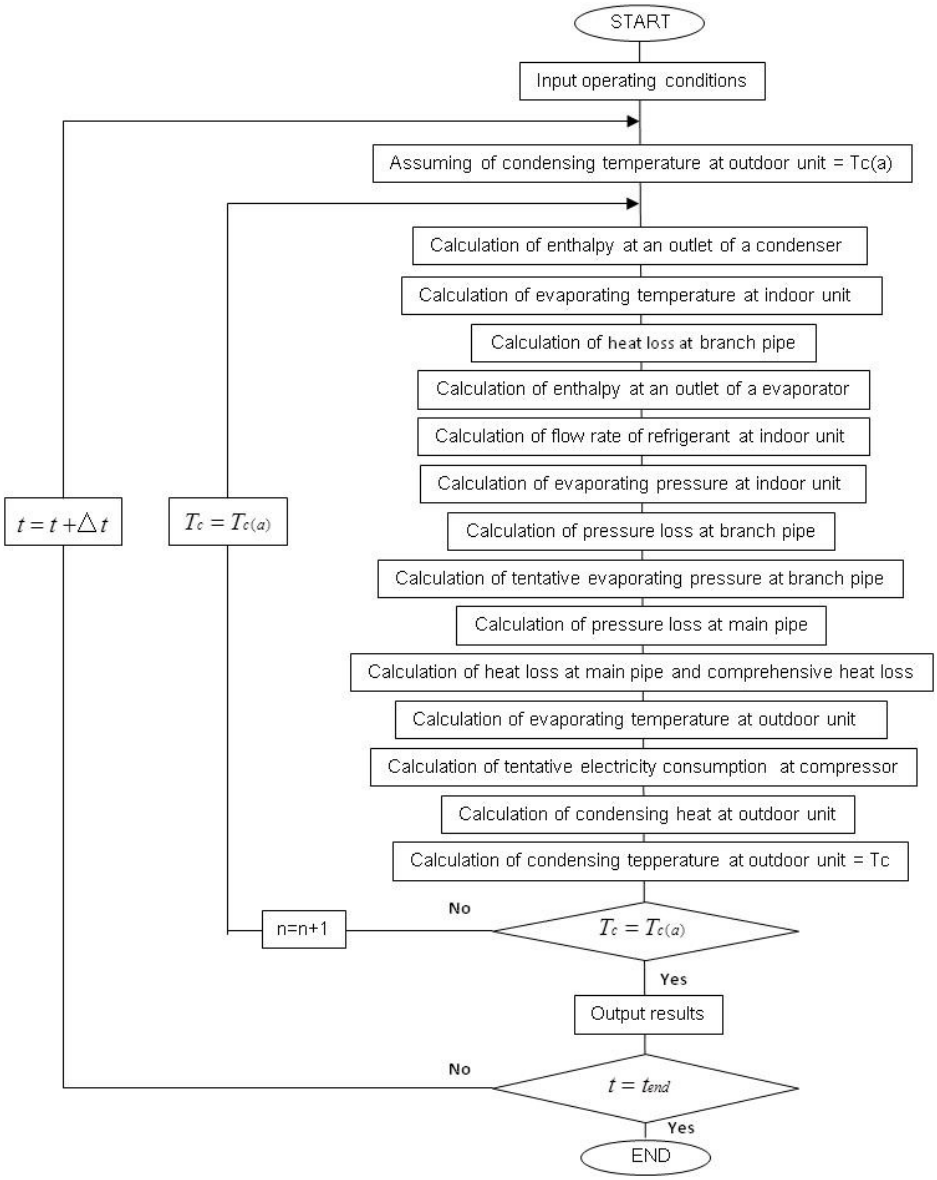


Figure 5: Calculation flow for cooling operation

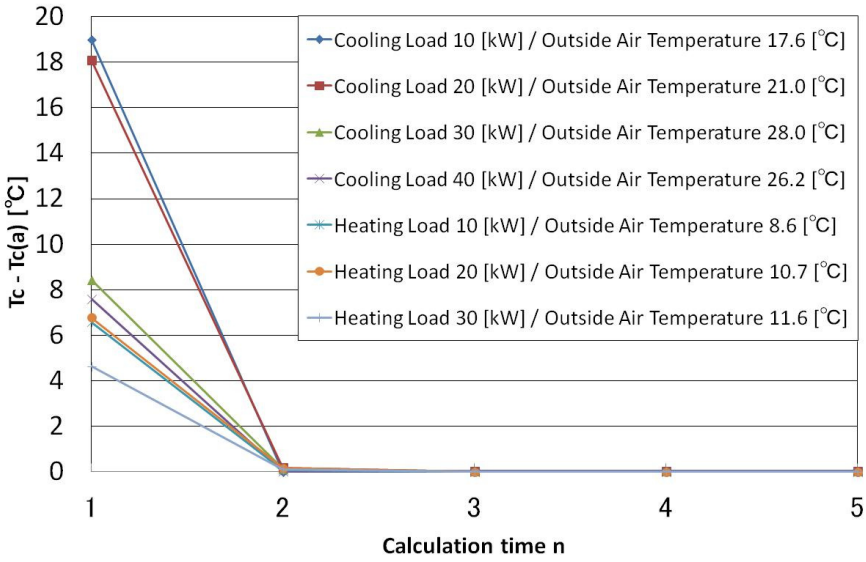


Figure 6: Temperature difference T_c - $T_{c(a)}$ according to calculation time *n*

3 EXPERIMENT TO VERIFY ACCURACY OF THE DEVELOPED TOOL

3.1 Outlines of Experiment

An experiment to verify the accuracy of developed tool was carried out in The University of Kitakyushu in Fukuoka Prefecture on August 30, 2012.. In this experiment, the authors conducted a cooling operation by using the heat pump air conditioning system shown in Figure 7 and measured the refrigerant temperatures, the electric power consumption in the heat pump unit pointed in Figure 8. The refrigerant temperatures and the electric power consumption were also calculated with the developed tool. In the calculation, the specifications of equipment in the heat pump unit i.e. capacities of heat exchangers (evaporator and condensers), capacity of compressor, were obtained from the product catalog. As external conditions such as the heat load, outside air temperature and etc, the measured values are used. An equation to calculate the compressor power consumption is approximated by applying the multiple regression analysis and using the compressor's characteristic data obtained from the manufacturer. Therefore, the calculated conditions are similar to the real operation conditions. The precision of the developed tool was validated by comparing the calculated values with measured values.

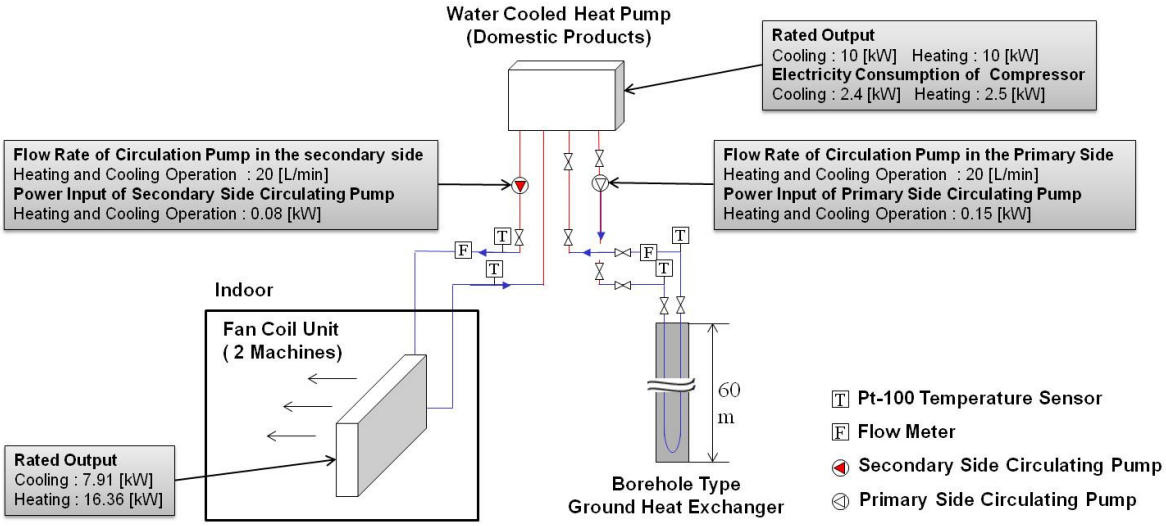


Figure 7: Diagram of experimental apparatus

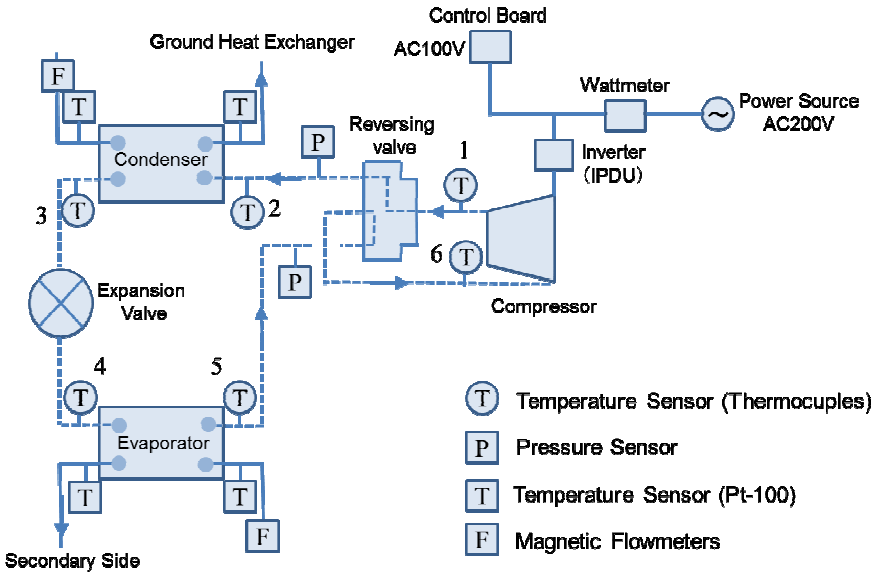


Figure 8: Diagram in heat pump unit (Cooling operation)

3.2 The result of experiment

Figure 9 shows the comparison result of condensation temperatures and evaporation temperatures. Figure 10 shows the comparison result of COPs and the electricity consumptions. As the result of Figure 9 and Figure 10, the errors between predicted and measured values are very small. Table 1 shows summary of experiment result. As shown in Table 1, the errors of measured and predicted temperatures are as small as 3 ℃ or less, and the error of average COPs was 0.034 % and very small. Therefore, it was confirmed that the developed tool has very high prediction accuracy.

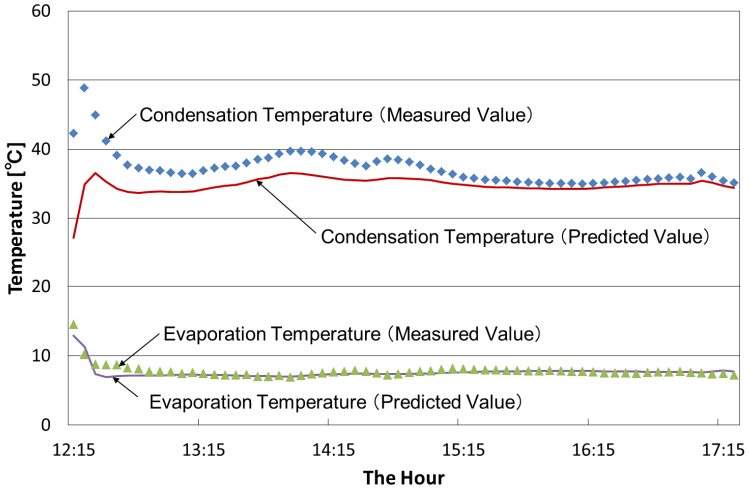


Figure 9: Comparison result of condensation temperatures and evaporation temperatures

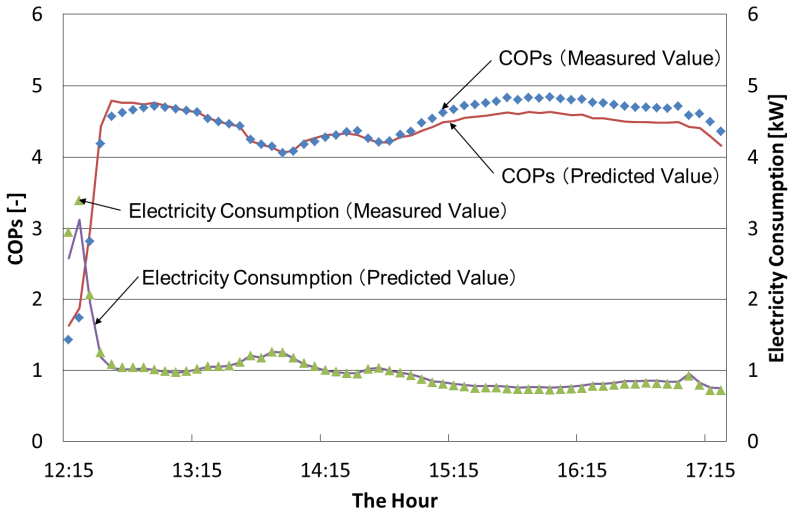


Figure 10: Comparison result of COPs and the electricity consumptions

Table 1: Summary of experiment result

	Measured Result	Predicted Result
Average Value of Indoor Heat load [kWh]	4.2	4.2
Average Condensation Temperature [℃]	37.3	34.8
Average Evaporation Temperature [℃]	7.77	7.61
Average Value of Electricity Consumption [kWh]	1.0091	1.0095
Average COPs [-]	4.164	4.162
The Error of Average COPs [%]	-	0.034

4 CASE STUDY WITH GROUND SOURCE HEAT PUMP AIR-CONDITIONING SYSTEM

4.1 Outlines of Case Study

Performance prediction of a representative period (May 1, 2011 to April 30, 2012) for air-conditioning system installed in the actual building was conducted. In this case study, the authors compared the calculated COPs with the measured one and confirmed reproducibility and extensibility, which are the characteristics of the developed tool. The object office building for the performance prediction was completed in May 2011 in Kitakyushu, Fukuoka Prefecture. Figure 11 shows a standard floor plan of the building and object space for performance prediction and Figure 12 shows overview of ground source heat pump system in the object building. The ground source heat pump system using water-cooled variant refrigerant flow (VRF) system was installed and 8 indoor units are placed in the object space. The specifications of equipment in the heat pump unit i.e. capacities of heat exchangers (evaporator and condensers), capacity of compressor, length of refrigerant pipes were obtained from the product catalog and the drawings. The measured heat load, outside air temperature, and inside air temperature were given to the calculation. An equation to calculate the compressor power consumption is approximated by applying the multiple regression analysis and using the compressor's characteristic data obtained from the manufacturer. The characteristic equation to calculate the compressor power consumption is obtained by making the multiple regression analysis of data obtained from the manufacturer. The temperatures of the heat carrier fluid in the ground heat exchangers are calculated by using a performance prediction tool for the GSHP system. Therefore, the calculated conditions are similar to the real operation conditions. The reproducibility of the developed tool was validated by comparing the calculated values with measured values.

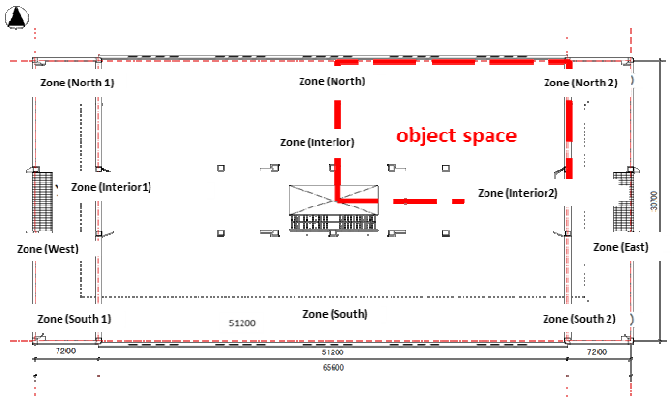


Figure 11: Standard floor plan and object space for performance prediction

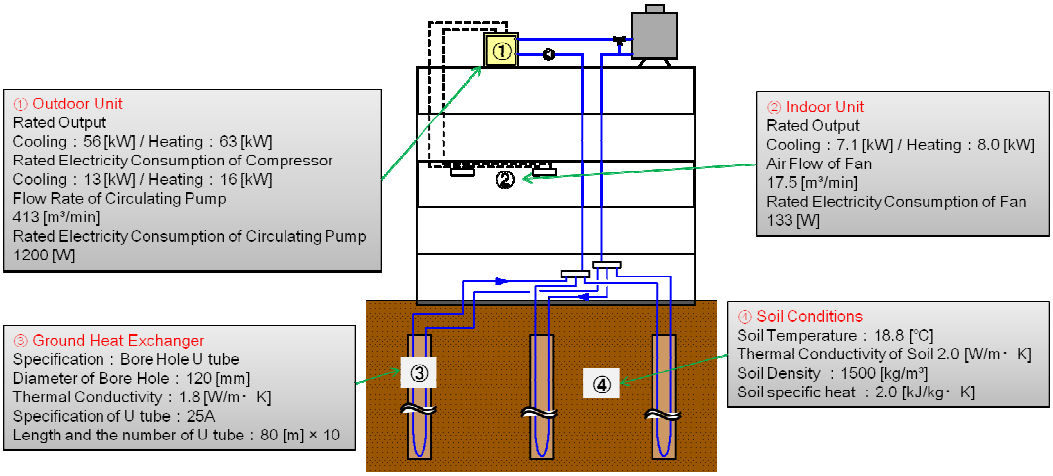


Figure 12: Overview of ground source heat pump system

4.2 The Result of Case Study

Figure 13 shows the comparison result of COPs for cooing load and Figure 14 shows the comparison result of COPs for heating load. The cooling and heating COPs calculated by using the conventional heat pump model (Li et al., 2009) are also drawn in Figure 13 and Figure 14. The measured cooling and heating COPs are smaller than the ones calculated with the conventional model. The reason is that the evaporating temperature of refrigerant during cooling decreases and the condensing temperature of refrigerant during heating increases. These are due to the difference of indoor units and length of refrigerant pipes. It is difficult to consider the difference in the conventional equipment characteristic model. However, the model that the authors developed can consider the difference and temperature change of refrigerant. As the result, the error between calculated and measured value is small. Table 2 shows the summary of case study. As shown in Table 2, the errors of average COPs that measured and predicted are less than 6 % for cooling and 2 % for heating, respectively. Therefore, it was confirmed that the developed tool has high reproducibility. In addition, it was confirmed that the tool has certain extensibility because the tool can correspond with the various performance predictions using the different heat pump air-conditioning systems.

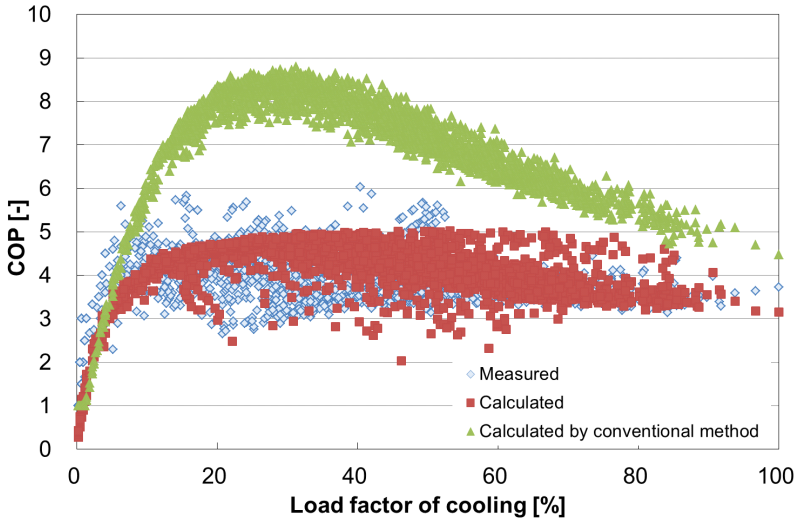


Figure 13: Comparison result of COPs according to cooing load

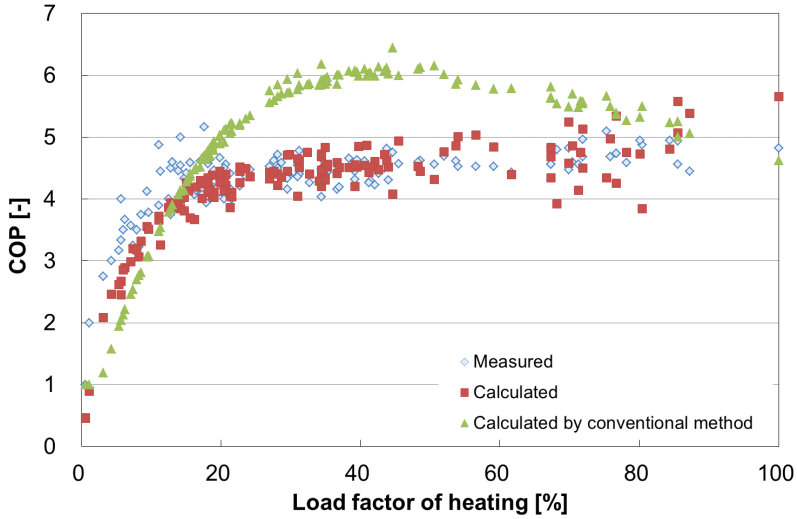


Figure 14: Comparison result of COPs according to heating load

Table 2: Summary of case study result

		Heat Load [kW]	Electricity Consumption [kW]	Average COPs [-]	Error of COPs [%]
Cooling	Predicted Value	37823	9872	3.83	-
	Measured Value	37823	9367	4.04	5.4
Heating	Predicted Value	1732	383	4.53	-
	Measured Value	1732	388	4.47	1.3

5 SUMMARIES

1) In this paper, the outlines of a new performance prediction tool for heat pump air-conditioning system which considering refrigeration cycle was shown. In addition, the authors conducted an experiment and case study to confirm a prediction accuracy and extensibility of the developed tool.
2) As the result of the experiment to verify accuracy of the tool, momentary error of temperature and electricity consumption between predicted value and measured one was very small. Especially, the error of COPs was very small and it was 0.034 %. Then, it was confirmed that the developed tool has very high prediction accuracy.
3) As the result of case study targeted an actual office building, the error of COPs was very small and it was 5.4 % for cooling and 1.3 % for heating. In addition, it was confirmed that the developed tool has certain extensibility because the tool could cope with performance prediction for two different air conditioning systems.

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NOMENCRATURE

A: Area [m²], *E*: Electricity Consumption [kW], *G*: Flow rate [kg/s], *H*: Enthalpy [kJ/kg], *K*: Heat Transmission Coefficient [kW/m²/K], *Q*: Quantity of Heat [kW], *T*: Temperature [℃]

Subscript

(a): Assumption, *c*: Condenser, *comp*: Compressor, *e*: Evaporator, *end*: The last, *In*: Indoor, *(in)*: Inlet, *n*: The number of times, *out*: Outdoor, *(out)*: Outlet, *t*: Time