Performance Analysis and Operation Improvement of the Hybrid Ground Source Heat Pump System by Using Performance Prediction Tool

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Abstract: In this paper, the authors introduce the optimum operation method of the hybrid GSHP system by using a performance prediction tool for the GSHP system and an example of operation improvement of the hybrid GSHP system with the cooling tower installed in the office building in Kitakyushu City. The result of analysis of the hybrid GSHP system showed that the measured heating and cooling loads were smaller than the ones calculated before the construction. Also, the measured heating and cooling COPs were smaller than the ones calculated by the simulation model. The optimum operation method for the hybrid GSHP system was calculated by using the performance prediction tool. The results show that the maximum T_{1in} is less than 26 °C and it is better to reduce the operation of cooling tower. Therefore, the cooling tower in the hybrid GSHP system has been not operated.

Key Words: ***Hybrid Ground Source Heat Pump System, Performance Prediction Tool, Performance Analysis and Operation Improvement***

1 INTRODUCTION

Ground source heat pump (GSHP) systems have advantages at the point view of thermal energy efficiency compared to such as air source heat pump systems. However, there is a risk of long-term ground temperature rise or decrease due to excess heat injection or extraction particularly in the case of large scale GSHP systems. Therefore, it is important to establish the optimum operation method for the hybrid GSHP system combined the cooling tower, solar collector, etc.

In this paper, the authors introduce the optimum operation method for the hybrid GSHP system by using the performance prediction tool for the GSHP system developed by the authors (Katsura et al., 2011, Katsura et al., 2009, Katsura et al., 2008, Nagano et al., 2006) and an example of operation improvement of the hybrid GSHP system with the cooling tower installed in a new office building in Kitakyushu city.

2 OUTLINES OF PERFORMANCE ANALYSIS AND OPERATION IMPROVEMENT BY USING PERFORMANCE PREDCION TOOL

Figure 1 shows an example of hybrid GSHP system, which is the subject of performance analysis and operation improvement by using a performance prediction tool. The system mainly consists of the ground heat exchangers (GHEXs) and GSHP units. The system also has the additional heat sources such as a cooling tower, solar collector, boiler, etc. These are utilized to prevent excess temperature rise or decrease of the heat carrier fluid in the GSHP system. However, the additional energy consumption is generated when the additional heat sources are used. Thus it is necessary to control the temperature of heat carrier fluid by using additional heat source and minimize the energy consumption.

Using the performance prediction tool, the performance analysis and operation improvement are carried out as shown in Figure 2. In the final analysis, the optimum operation method for the hybrid GSHP system is calculated. The optimum operation method minimizes the energy consumption of the hybrid GSHP system as shown the following.

$$\min ET_{system} \quad (1)$$

Here, the energy consumption of the system is calculated by the following equation when the system is such as Figure 1.

$$ET_{system} = \sum_i ET_{WHPi} + ET_{AHPj} + ET_{CT} + ET_B + ET_{SP} + ET_{ST} \quad (2)$$

In addition, the following restrains of inlet temperature in the primary side of water source heat pump units are placed.

$$T_{1in} \leq 30\ ^{o}\mathrm{C},\ T_{1in} \geq 10\ ^{o}\mathrm{C} \quad (3)$$

These conditions are given by setting the range in which the heat pumps can maintain the heating and cooling capacities.
In order to improve the simulation's precision, the process 1~3 indicated in Figure 2 is carried out. First, the apparent effective thermal conductivity of the ground is estimated to evaluate performance of the ground heat exchangers. Next, the heating or cooling load is measured and the measured load is compared to the calculated load before construction. If there is a difference between the measured load and the calculated load, the calculated load is corrected in the final analysis. In addition, the energy consumptions of equipment are measured and the coefficients of equipment are calculated by using the measured load and energy consumption. The coefficients are compared to the calculated ones. If there is a difference, the calculated coefficients are corrected in the final analysis. The concrete contents of the process 1~3 are demonstrated in **Chapter 3**.

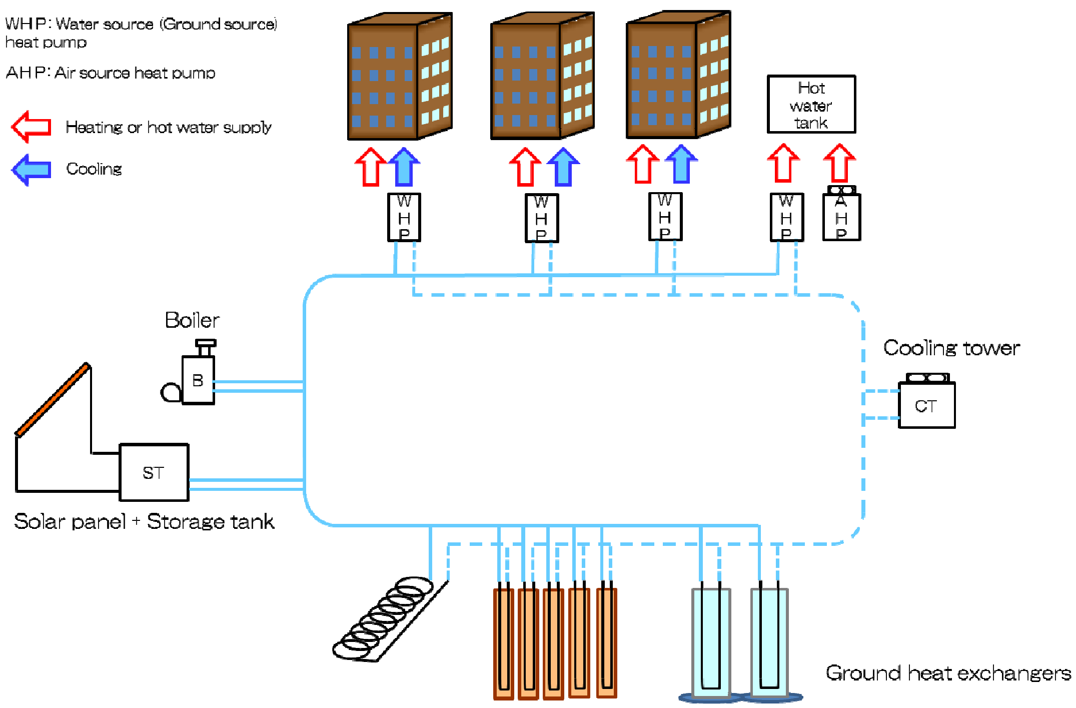


Figure 1 Example of hybrid ground source heat pump system

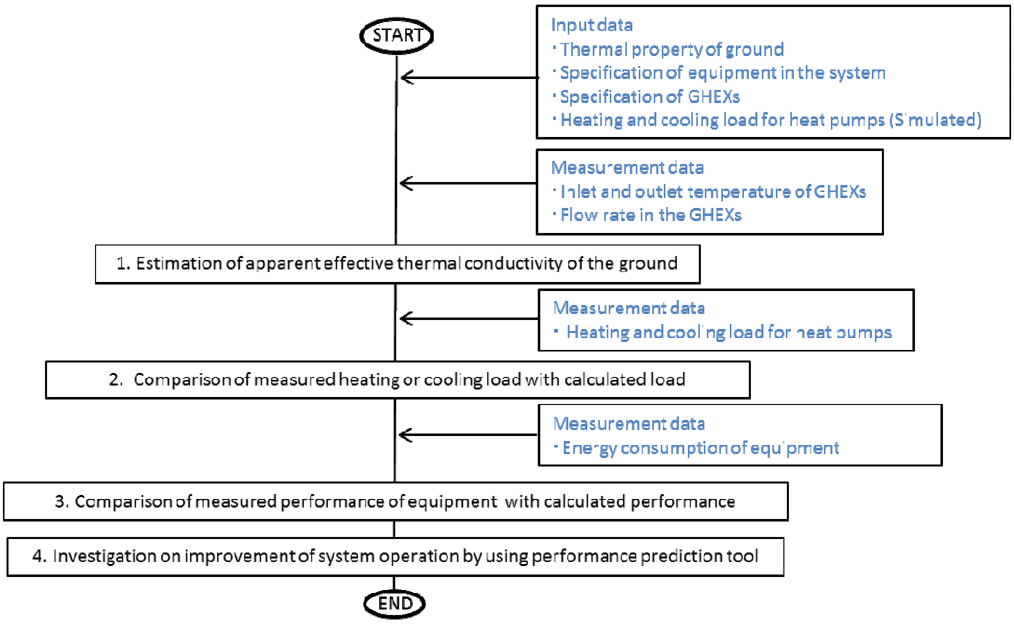


Figure 2 Process of performance analysis and operation improvement by using performance prediction tool

3 AN EXAMPLE OF PERFORMANCE ANALYSIS AND OPERATION IMPROVEMENT BY USING PERFORMANCE PREDCION TOOL

3.1 Outlines of Building and Hybrid Ground Source Heat Pump System

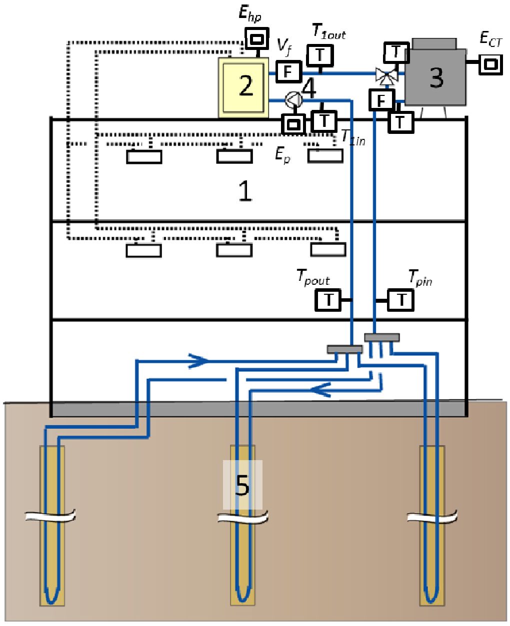
The office building shown in Figure 3 was completed in Kitakyushu City in December 2010. The total area is approximately 10,000 m^2. The building has many energy-saving technologies such as a hybrid ventilation system, PV system, high-efficiency lighting, and energy management system. The hybrid GSHP system described in this study was also installed in the building.

The GSHP system has been in operation since November 18, 2010. Figure 4 shows a schematic diagram of the GSHP system and measurement points for the analysis. The GSHP system consists of 50 borehole ground heat exchangers (BHEXs) with depths of 80 m and water-cooled variable refrigerant flow (VRF) air conditioning (Heat pump) systems. These water-cooled VRF air conditioning systems have scroll compressors, with a total power of 102 hp. The total cooling and heating capacity of all indoor units are 287 kW and 320 kW, respectively. The GSHP system has variable water control (VWV) on the primary side to minimize the electric power consumption of the circulation pump (Katsura et al., 2011). In addition, this system is connected to a cooling tower to prevent a temperature rise from an imbalance in the heating and cooling loads. The system also has the cooling tower's activation control based on the inlet temperature of the heat pump unit basis on the previous study (Katsura et al., 2011). When the temperature T_{1in} is greater than the activation temperature $T_{1inctset}$, the cooling tower is turned on.

Figure 5 shows the standard floor (from second floor to fifth floor) plan view. The GSHP system is applied to the eastern half of the northern office space. The air conditioning area covered by the GSHP system is 2,271 m^2, which is 21.7 % of the entire building.

In addition, thermal response tests have been conducted five times using five BHEXs that are part of the GSHP system. The estimated value of the effective thermal conductivity is 1.87~31.1 W/m/K, which indicates the possibility of ground water flow.

Figure 3 Appearance of office building



Measurement point

[T] Temperature(Pt-100) [F] Flow rate [□] Electric power

1. Air conditioning area : 2,271 m²
2. Water cooled variable refrigerant air-conditioning (Heat pump) system
Compressor : 102 Horse power
Maximum cooling output of indoor unit: 280 kW
Maximum heating output of indoor unit: 320 kW
3. Cooling tower : 100 Refrigeration ton
Electric power : 10 kW
4. Circulation pump(Variable water control)
Rated flow rate : 960 L/min、
Rated electric power : 7.5 kW
5. Borehole ground heat exchanger (Double U-tube)
Borehole diameter : 150 mm
Grout : Silica sand
Length and number : 80m × 50

Figure 4 Schematic diagram of hybrid GSHP system with cooling tower and measurement points for analysis

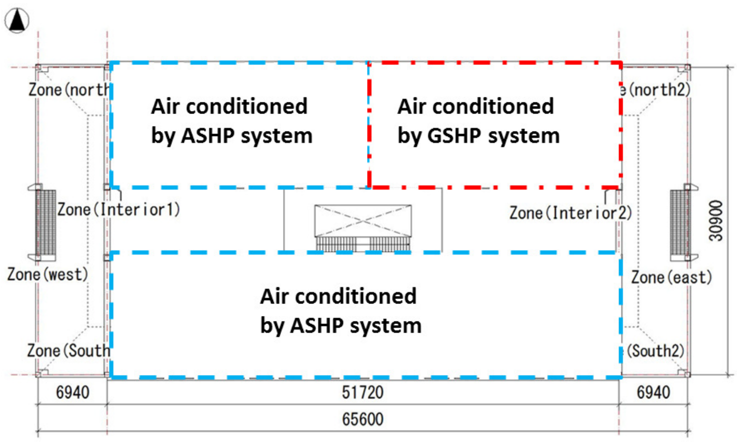


Figure 5 Standard floor plan view

3.2 Simulation Model for Hybrid Ground Source Heat Pump System

In order to performance analysis, the authors developed a simulation model (performance prediction tool) for the hybrid GSHP system shown in Figure 6. The simulation model mainly consists of the ground model, GHEX model, heat pump (water-cooled VRF system) model, pump model and cooling tower model. In the simulation model, the heating or cooling load, outside air temperature, and air humidity are given. Then, the energy consumption in the system, temperature of heat carrier fluid and temperature in the ground surrounding the GHEXs are calculated. The details of calculation are described in the previous papers (Katsura et al., 2011, Katsura et al., 2009, Katsura et al., 2008, Nagano et al., 2006).

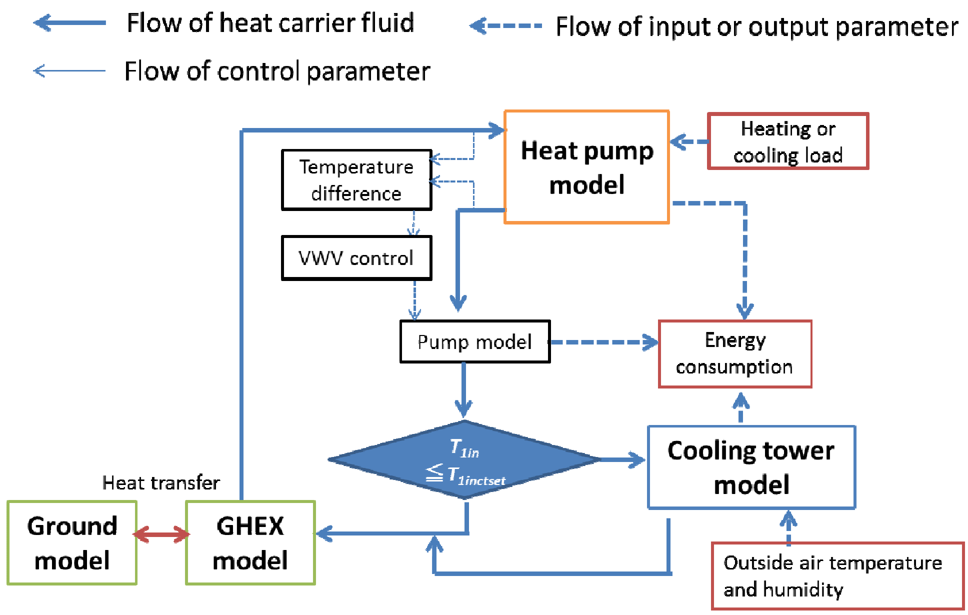


Figure 6 Simulation model (performance prediction tool) for hybrid ground source heat pump

3.3 Estimation of Apparent Effective Thermal Conductivity of Ground

The apparent effective thermal conductivity of the ground is estimated by using the GHEX model in Figure 6. Giving hourly inlet temperature of the GHEXs T_{pin} and hourly flow rate in the GHEXs V_f (The measurement points are pointed in Figure 4), hourly outlet temperature of the GHEXs T_{pout} is calculated. The calculation is carried out several times by changing the ground effective thermal conductivity λ_s. The other calculation conditions are shown in Table 1. The ground temperature is given as 18.8 ℃, which is obtained from the temperature measurement at an observation well.

Figure 7 shows a comparison of the measured T_{pout} and calculated T_{pout} from Nov. 18, 2010, to Oct. 31, 2011. Additionally, Figure 8 compares the measured T_{pout} and calculated T_{pout} in August 2011. The results indicate that the variation in the calculated T_{pout} for λ_s = 1.87 W/m/K, which is the smallest value of λ_s in the TRT, is larger than that for the measured T_{pout}. On the other hand, the difference between the measured T_{pout} and calculated T_{1in} for λ_s = 3.74 W/m/K (double the value of 1.87 W/m/K) is small. Good agreement between the measured T_{pout} and calculated T_{pout} for λ_s = 3.74 W/m/K is observed from the comparison in Figure 8. Therefore, the apparent effective thermal conductivity of the ground can be estimated at approximately 3.74 W/m/K.

Table 1 Calculation conditions

Ground heat exchanger	Specification	Borehole double U-tube
	Borehole diameter	150 mm
	Grout	Silica sand (Effective thermal conductivity : 1.8 W/(m K))
	U-tube specification	HDPE 25A
	Length	80 m×50 boreholes
Soil property	Average ground temperature	18.8 ℃
	Thermal capacity	3000 kJ/(m^3 K))

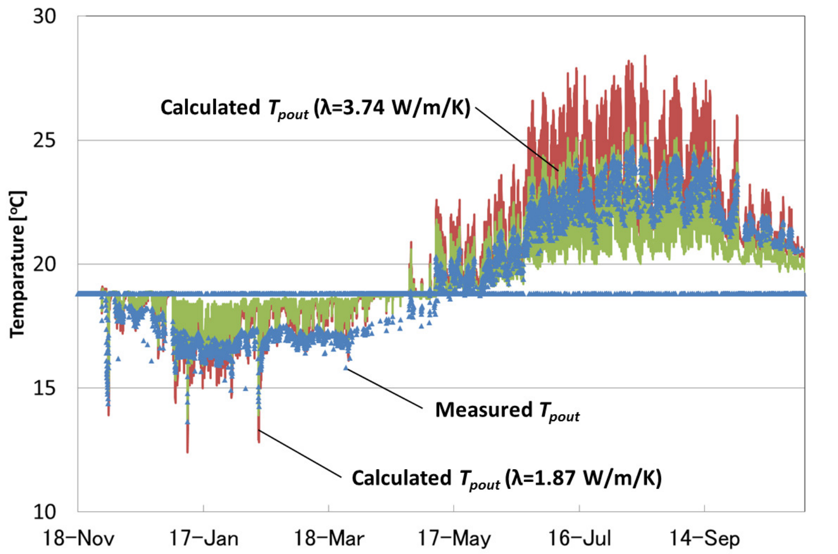


Figure 7 Variations in measured T_{pout} and calculated T_{pout} from Nov. 18, 2010, to Oct. 31, 2011

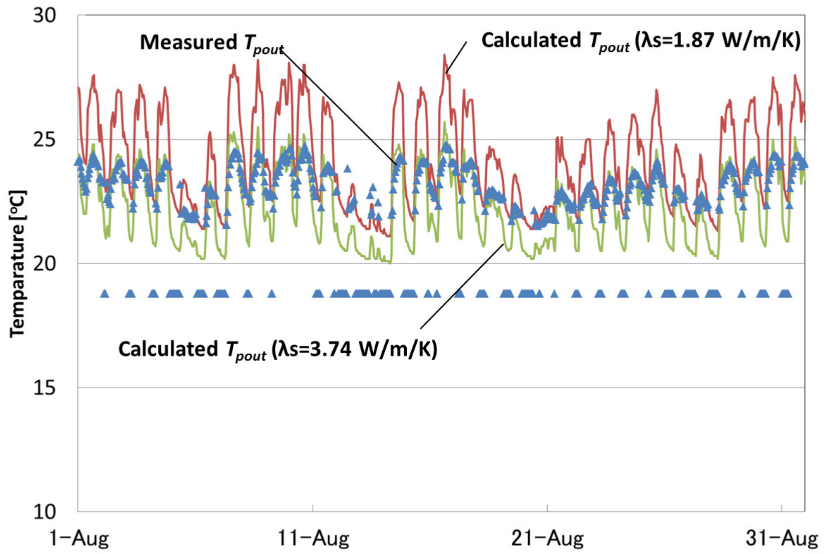


Figure 8 Variations in measured T_{pout} and calculated T_{pout} in August 2011

3.4 Comparison of Measured Heating or Cooling Load with Calculated Load before Construction

Figure 9 shows the variations in the measured heating and cooling load of the GSHP system. Here, the heating load is calculated by using the following equation and giving the measured values pointed in Figure 4.

$$Q_{hph} = c_f \rho_f V_f (T_{1in} - T_{1out}) + E_{hp} \tag{4}$$

Also, the cooling load is calculated by the following equations.

$$Q_{hpc} = c_f \rho_f V_f (T_{1out} - T_{1in}) - E_{hp} \tag{5}$$

The total cooling load is approximately 2.5 times the total heating output. The measured maximum cooling load is 132 kW. This is half of the predicted maximum cooling load of 253 kW (Katsura et al., 2011). This is due to decrease of the indoor heat generated by the lighting and office automation equipment. However, the measured total cooling load is almost the same as the predicted total cooling load of 137 MWh (Katsura et al., 2011). The reason is that the operation time of the office building is longer than the one assumed before construction. There is a difference between the measured load and the calculated load as shown in Figure 9. Therefore, it is necessary to correct the calculated loads in the final analysis.

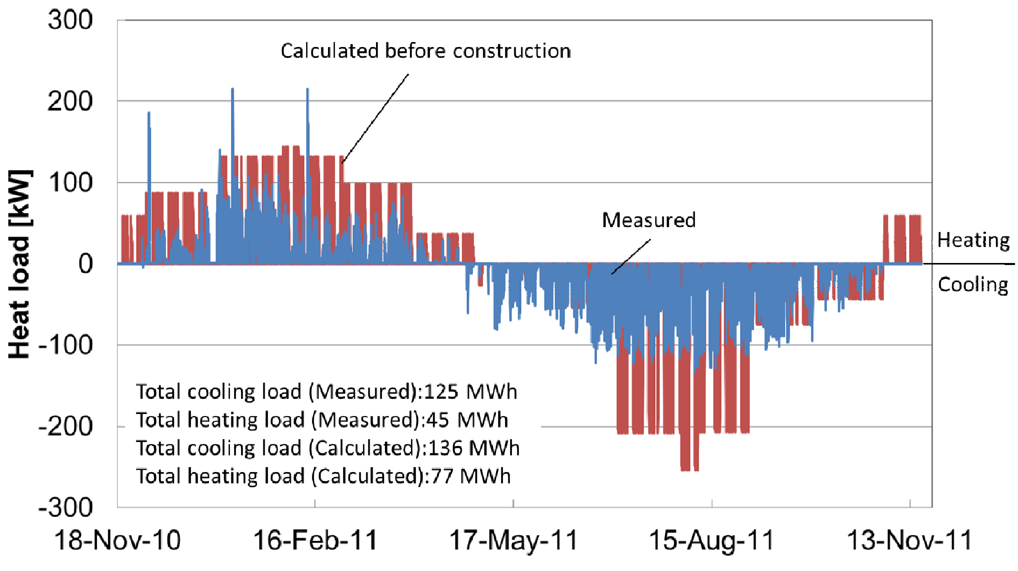


Figure 9 Variations in heating and cooling load of GSHP system

3.5 Comparison of Measured Heating or Cooling COP with Calculated COP

Shown in Figure 10 are the measured heating and cooling COPs of the water cooled VRF air conditioning (Heat pump) according to the heating or cooling load. The COP is obtained by using the following equation.

$$COP = Q_{hp} / E_{hp} \tag{6}$$

The heating and cooling COPs calculated by using the heat pump model (Li et al., 2009) in Figure 6 and giving the measured T_{1in}, Q_{hp}, and V_f are also drawn in Figure 10. The measured heating and cooling COPs are smaller than the calculated ones except for the low values of cooling and heating load. Thus, correction of the calculation model is important in the final analysis.

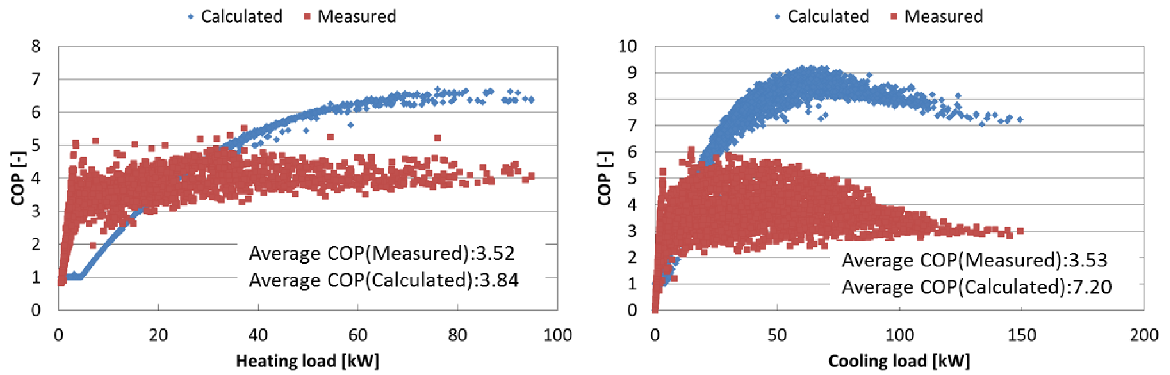


Figure 10 COPs according to heat load (Left: Heating, Right: Cooling)

3.6 Investigation on Improvement of Hybrid GSHP System Operation Using Performance Prediction Tool

The optimum operation method for the hybrid GSHP system is calculated by using the performance prediction tool. The optimum operation method minimizes the energy consumption of the hybrid GSHP system written as Equation (1). The energy consumption of the system is expressed as

$$ET_{system} = ET_{hp} + ET_p + ET_{CT} \tag{7}$$

In addition, the restrains of inlet temperatures in the primary side of water source heat pump units written in Equation (3) are placed. In order to investigate the optimum operation method, the simulation of the hybrid GSHP system is carried out several times by changing the parameter $T_{1inctset}$ indicated in Figure 6.
In the simulation, the measured heating and cooling loads shown in Figure 9 is given. The COP obtained by the calculation model of heat pump is corrected by the following equation.

$$COP_{corrected} = COP_{calc} \times CCOP \tag{8}$$

Here, COP_{calc} is the calculated hourly COP in the simulation. The values of *CCOP* are obtained as the ratio of average COP (Measured) and average COP (Calculated) and given as 0.92 for heating operation and 0.49 for cooling operation, respectively. Also, the effective thermal conductivity of the ground is set at 3.74 W/m/K and the other calculation conditions shown in Table 1 are given.
Figure 11 shows the total energy consumptions of the system as a function of the variations in $T_{1inctset}$. If the $T_{1inctset}$ is set at 26 °C ~ 30 °C, the energy consumption is the smallest. The results suggest that it is better to reduce the operation of cooling tower. The energy consumptions are the same when the $T_{1inctset}$ is set at 26 °C ~ 30 °C. The reason is that the maximum T_{1in} is less than 26 °C as shown in Figure 12 and it is not required to operate the cooling tower.

In the actual operation, $T_{1inctset}$ is automatically kept at 30 °C by the control system based on the simulation model since the beginning. Therefore, the cooling tower has not been operated and the energy consumption of the cooling tower is not generated.

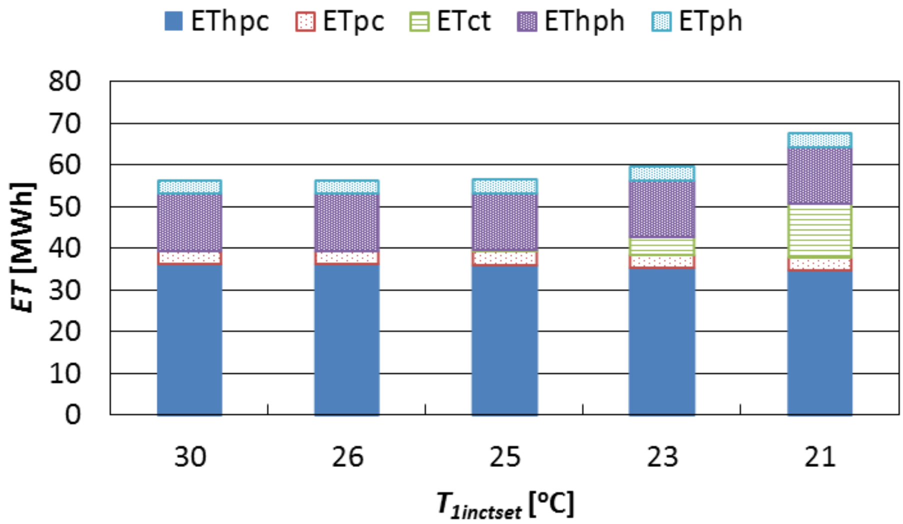


Figure 11 Energy consumption of hybrid GSHP system with respect to variations in $T_{1inctset}$

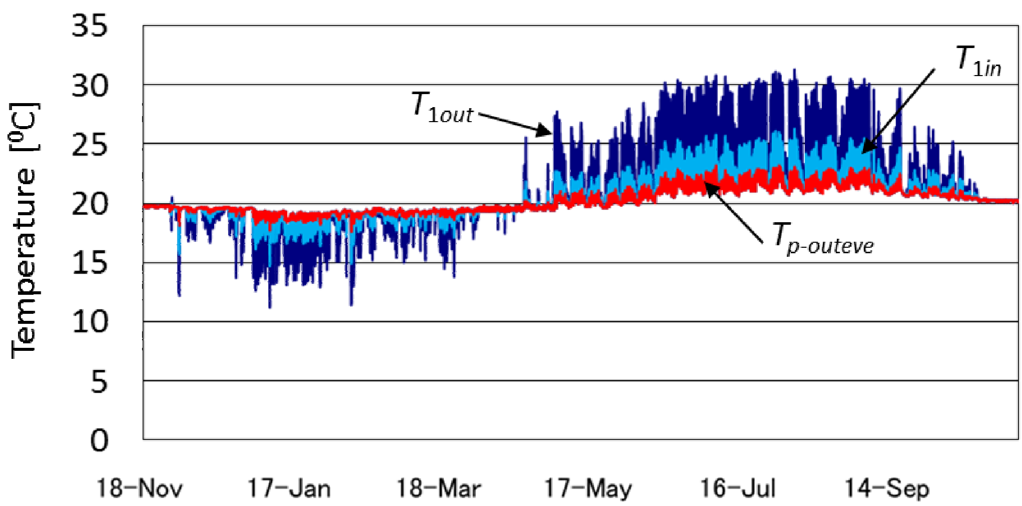


Figure 12 Hourly variations in T_{1in}, T_{1out} and $T_{p\text{-}outave}$ in the second year's operation ($T_{1inctset}$ is set at 26 °C ~ 30 °C)

4 SUMMARIES

1) The authors introduced the optimum operation method for the hybrid GSHP system by using a performance prediction tool for the GSHP system.
2) The hybrid GSHP system installed in the office building in Kitakyushu City was analyzed. The apparent effective thermal conductivity of the ground was estimated at approximately 3.74 W/m/K by using the ground heat exchanger model.
3) The measured maximum cooling load is 132 kW and half of the calculated maximum cooling load of 253 kW. However, the measured total cooling load is almost the same as the predicted total cooling load of 137 MWh. Therefore, there is a difference between the measured load and the calculated load.

4) The measured average heating and cooling COPs are 3.52 and 3.53, respectively. The values smaller than the ones calculated by the simulation model.
5) The optimum operation method for the hybrid GSHP system is calculated by using the performance prediction tool. The results show that the maximum T_{1in} is less than 26 °C and it is better to reduce the operation of cooling tower. Therefore, the cooling tower in the hybrid GSHP system has been not operated.

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NOMENCRATURE

c: Specific thermal capacity [J/kg/K], *E*: Electric power [W], *ET*: Total electric power [Wh], *V*: Flow late [m^3/s], *Q*: Heating or cooling output [W], *T*: Temperature [°C], *ρ*: Density [kg/m^3], *λ*: Effective thermal conductivity [W/m/K]

Subscript

AHP: Air source heat pump, *b*: Boiler system, *ct*: Cooling tower, *f*: Thermal medium, *hp*: Heat pump, *hpc*: Heat pump cooling operation, *hph*: Heat pump heating operation, *p*: Pump, *pin*: Inlet of ground heat exchanger, *pout*: Outlet of ground heat exchanger, *p-outave*: Average of ground heat exchangers' surface, *s*: soil, *system*: system, *SP*: Solar panel, *ST*: Storage tank, *WHP*: Water source heat pump, *1in*: Inlet in the primary side, *1out*: Outlet in the primary side