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Long-term Operation Management of a Hybrid Ground Source Heat Pump System Combined with a Cooling Tower by Using an Autonomic Optimum Control System in Cooling-dominant Region

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ABSTRACT

In this paper, the authors demonstrate the long-term operation management of a HGSHP system combined with a cooling tower by using an autonomic optimum control system in cooling-dominant region. The autonomic optimum control system consists of the programable logic controller (PLC), monitoring equipment, and software in PC. The monitoring data such as the temperature and the flow rate obtained by the PLC and monitoring equipment is transmitted to software. The software simulates the HGSHP system operation by using the monitoring data and predicts the temperature variation of heat carrier fluid. Then, the temperature of heat carrier fluid in which the cooling tower is operated is determined and transmitted to the PLC. The PLC control the cooling tower basis on the temperature.

The analysis of first year's operation of the HGSHP system indicated that the heat injection rate during cooling season was approximately three times compared to the heat extraction rate during heating season. The apparent effective thermal conductivity was estimated as 4.5 W/(m·K) and it is expected that this high value was caused by the groundwater flow. In addition, the simulation result of HGSHP operation predicted that the maximum temperature of heat carrier fluid would be lower than 30 ^{o}C for the 5th year's operation even in the case where the cooling tower was not operated during cooling season. From this result, the cooling tower was not operated from 2nd year's operation. Also, it was confirmed that the temperature of heat carrier fluid was lower than 30 ^{o}C.

1. INTRODUCTION

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

Long-term monitoring is required to establish the optimum operation method for the hybrid GSHP (HGSHP) system. However, there are a few research works in which long-term monitoring was carried out and operation method was invested even in the case of conventional GSHP systems. Naicker et.al introduced three years' monitoring of a GSHP system with 56 number of GHEs with 100 m depth and mentioned the importance of circulation pump control (Naicker et al., 2018). Spitler and Gehlin analyzed the monitoring result of a GSHP system with 20 number of GHEs with 200 m depth (Spitler and Gehlin, 2019). Kindaichi and Nishina analyzed the monitoring result of a GSHP system with 70 number of GHEs with 100 m depth and indicated the increase of ground temperature due to excess heat injection (Kindaichi and Nishina, 2018). Then, they predicted that the increase of ground temperature could be prevented by reduce the heat injection.

A HGSHP system combined with a cooling tower was installed in an office building in cooling-dominant region (Katsura et al., 2014). And the authors predicted that maximum temperature of heat carrier fluid would be lower than 30 ^{o}C for the 5th year's operation even though the cooling tower would be not operated (Katsura et al., 2014). The autonomic optimum control system installed in the HGSHP system can carry out the similar prediction and the cooling tower's activation control that the authors introduced. Therefore, it is predicted that the cooling tower has never been operated and the temperature of heat carrier fluid would be lower than 30 ^{o}C. In this paper, the result of long-term operation of the HGSHP system is demonstrated.

2. OUTLINES OF AUTONOMIC OPTIMUM CONTROL SYSTEM

Figure 1 shows the concept diagram of the HGSHP system combined with the cooling tower and the autonomic optimum control system. The autonomic optimum control system consists of the programable logic controller (PLC) and the software installed in the PC. As shown in Figure 2, the PLC measures the outlet temperature of ground heat exchangers (GHEs) T_{pout} and control the cooling tower's activation. If the temperature T_{pout} is higher than the set temperature of cooling tower's activation $T_{poutset}$, the cooling tower is operated. In addition, the software, which includes a simulation tool for the HGSHP system (Nagano et al., 2016, Katsura et al., 2008, Katsura et al., 2009), automatically determines the set temperature $T_{poutset}$ with the simulation tool. Figure 3 shows the determination process of set temperature. Firstly, the software received the measurement data of HGSHP system from PLC. By using the measurement data, the software modifies the calculation conditions such as the hourly thermal load, the effective thermal conductivity of ground, and the heat pump COP. The detail of modification will be explained in Chapter 3. After the modification, the software repeatedly simulates the 5 year's operation of HGSHP system by changing the set temperature $T_{poutset}$. Finally, the set temperature $T_{poutset}$ in which the total energy consumption of the system is minimized is determined.

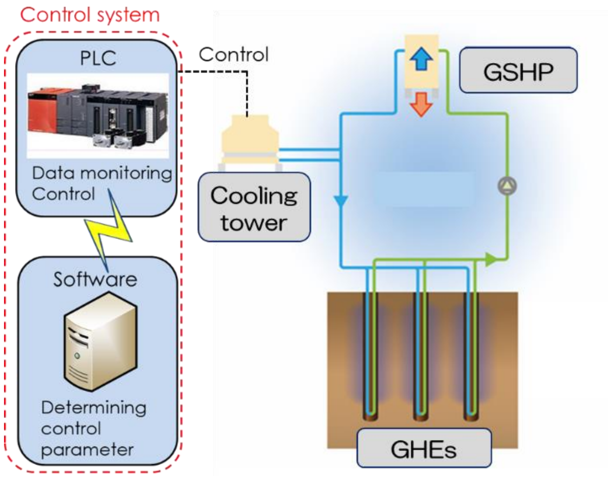

Figure 1: A concept diagram of the HGSHP system and the autonomic optimum control system

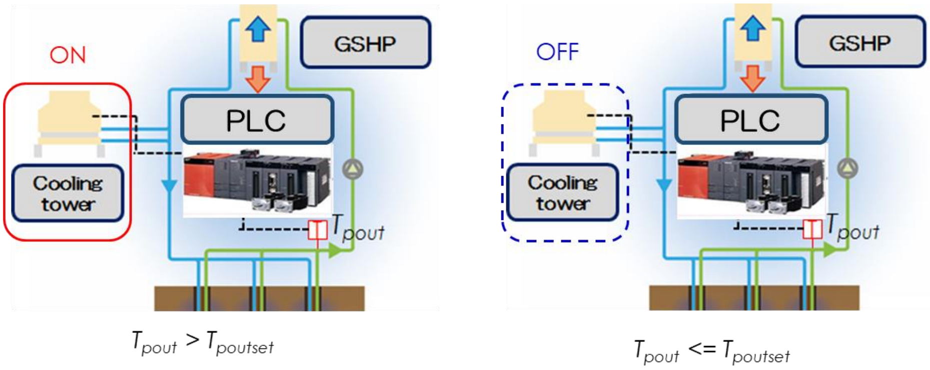

Figure 2: Cooling tower's activation control by PLC

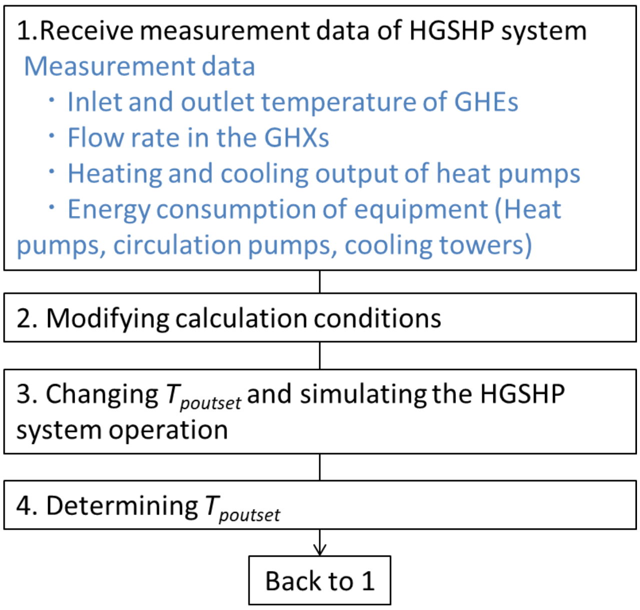

Figure 3: Determination process of $T_{poutset}$ by software

3. LONG-TERM OPERATION MANAGEMENT OF A HYBRID GROUND SOURCE HEAT PUMP SYSTEM IN AN OFFICE BUILDING

3.1 Outlines of office building and hybrid ground source heat pump system

The office building 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 HGSHP system described in this study was also installed in the building.

The HGSHP system has been operated since November 18, 2010. Figure 4 shows a schematic diagram of the HGSHP system and main measurement points. The HGSHP system consists of 50 borehole ground heat exchangers (BHEs) 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. The total cooling and heating capacity of all indoor units are 287 kW and 320 kW, respectively. The air conditioning area covered by the HGSHP system is 2,271 m^2, which is 21.7 % of the entire building. The HGSHP 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 heat extraction and injection. The system also has the autonomic optimum control system.

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

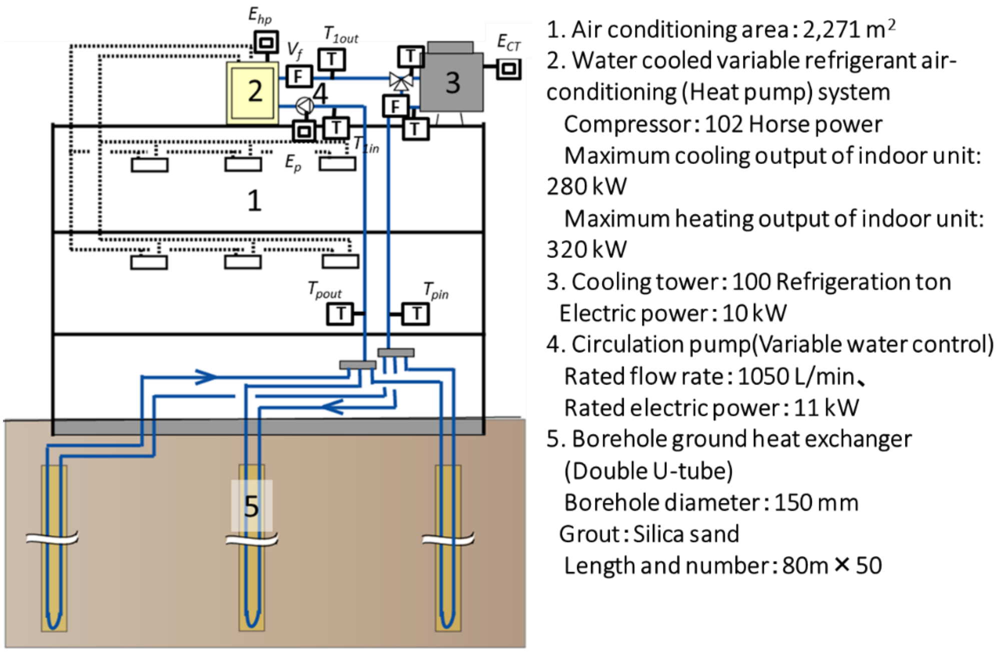

Figure 4: Schematic diagram of HGSHP system and main measurement points

3.2 Modification of calculation conditions

Figure 5 shows the variations of the hourly thermal load of the HGSHP system. The total cooling load is approximately 2.5 times the total heating output. In the determination process, the annual average hourly thermal load is given in the simulation.

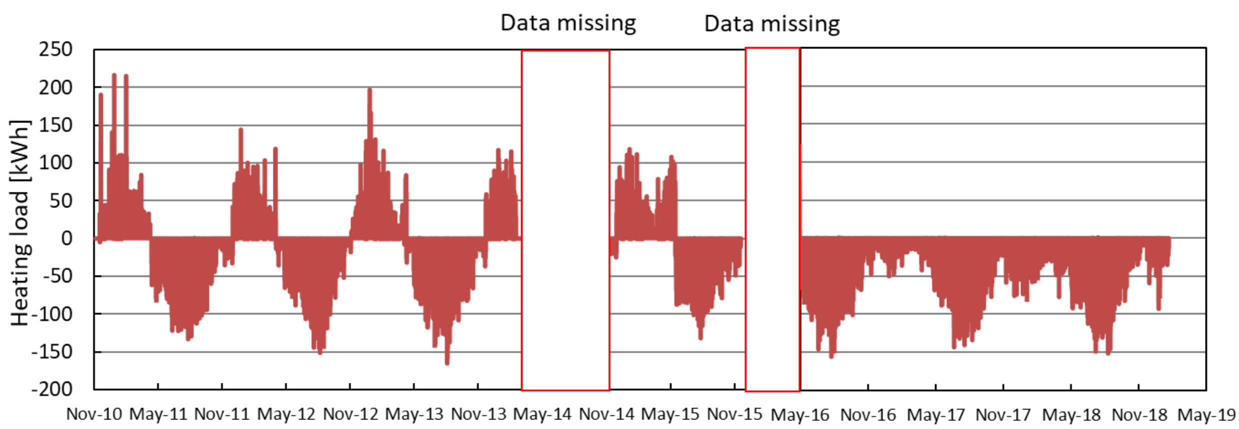

Figure 5: Hourly thermal load of HGSHP system

Next, Figure 6 shows the variations of the hourly heat extraction rate. The hourly heat extraction rate is similar to the hourly thermal load, but the heat extraction rate is small compared to the heating load. The apparent effective thermal conductivity of the ground is estimated by using the GHE model (Nagano et al., 2016, Katsura et al., 2008, Katsura et al., 2009) in software. The estimation flow is shown in Figure 7. Giving hourly heat extraction/injection rate, the hourly outlet temperature of the GHEs T_{pout} is calculated. The calculation is carried out several times by changing the ground effective thermal conductivity λ_s. Then the apparent effective thermal conductivity is determined by minimizing the RMSE calculated by the following equation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(T_{poutm} - T_{poutc}\right)^2}$$

Here, n is the number of data. T_{poutc} and T_{poutm} are the calculated T_{pout} and the measured T_{pout}, respectively.

Figure 8 shows a comparison of T_{poutc} and T_{poutm} from Nov. 18, 2010, to Oct. 31, 2011. As shown in Figure 8. good agreement between T_{poutm} and T_{poutc} is observed when the effective thermal conductivity λ_s = 4.5 W/m/K is given. In addition, the RMSE was minimized in the condition of λ_s = 4.5 W/m/K. Therefore, the apparent effective thermal conductivity of the ground can be estimated as approximately 4.5 W/m/K.

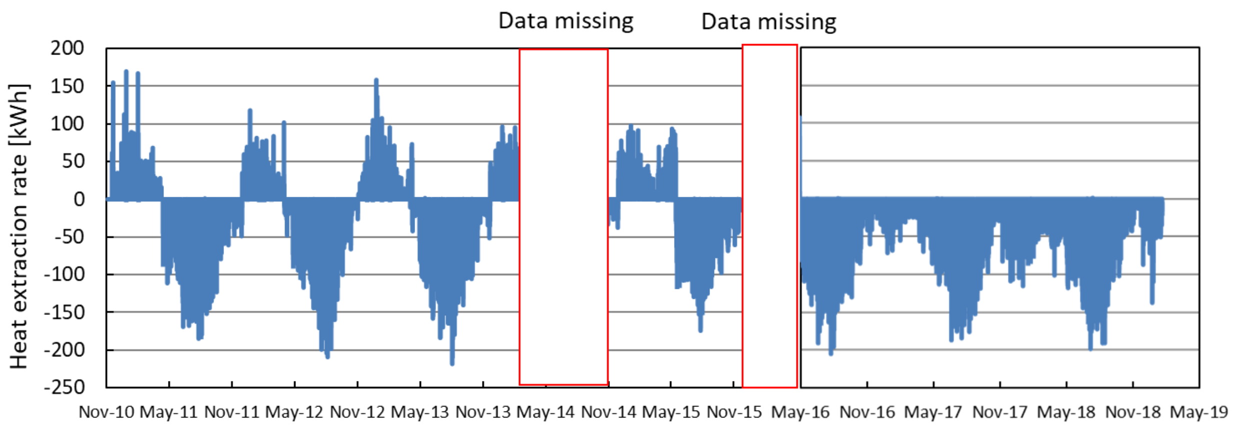

Figure 6: Hourly heat extraction/injection rate

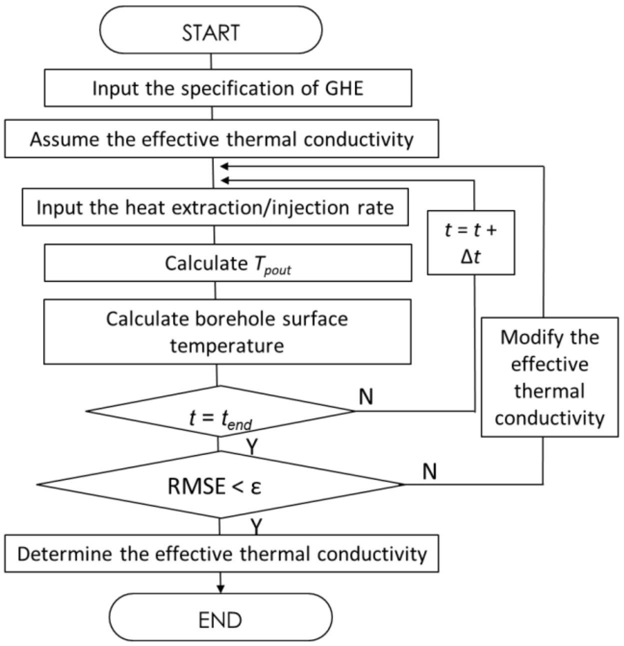

Figure 7: Estimation flow of apparent effective thermal conductivity

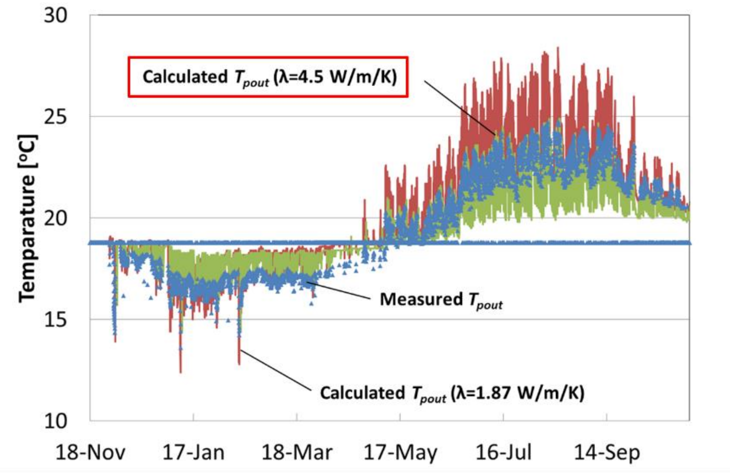

Figure 8: Comparison of T_{poutc} (Calculated T_{pout}) and T_{poutm} (Measured T_{pout})

Shown in Figure 9 are the measured heating and cooling COPs of the water cooled VRF air conditioning (Heat pump) according to the heating or cooling load. The heating and cooling COPs calculated by using the heat pump model (Li et al., 2009) and giving the measured T_{1in}, Q_{hp}, and V_f are also drawn in Figure 9. The measured heating and cooling COPs are smaller than the calculated ones except for the low values of cooling and heating load. Therefore, the COP obtained by the calculation model of heat pump is modified by the following equation.

$$COP_{modified} = COP_{calc} \times CCOP$$

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.

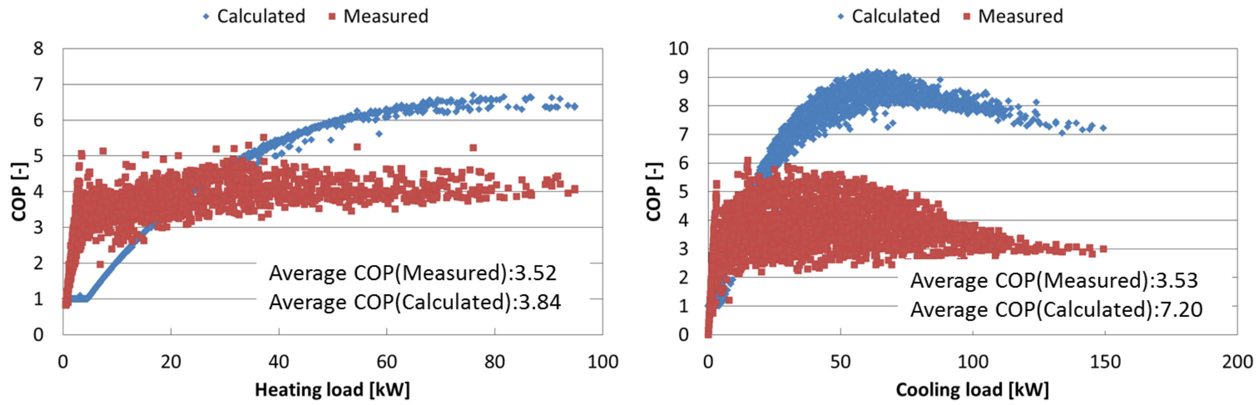

Figure 9: COPs according to thermal load (Left: Heating, Right: Cooling)

3.3 Determination of set temperature

The optimum value of $T_{poutset}$ for the HGSHP system is determined with the simulation in the software. The optimum value of $T_{poutset}$ minimizes the energy consumption of the HGSHP system ET_{system}. The energy consumption of the HGSHP system is expressed as

$$ET_{system} = ET_{hpc} + ET_{hph} + ET_{pc} + ET_{ph} + ET_{CT}$$

Here, ET_{hp} is the energy consumption of heat pump units (ET_{hpc}: Cooling, ET_{hph}: Heating). ET_p is the energy consumption of circulation pumps (ET_{pc}: Cooling, ET_{ph}: Heating). ET_{CT} is the energy consumption of cooling towers. In addition, the following restrains of inlet temperatures in the primary side of GSHP units written are placed.

$$T_{1in} \leq 30\ ^{\circ}\mathrm{C},\ T_{1in} \geq 10\ ^{\circ}\mathrm{C}$$

In order to investigate the optimum value of $T_{poutset}$ for the HGSHP system, the simulation of the HGSHP system is carried out several times by changing the parameter of $T_{poutset}$. In the simulation, the annual average hourly thermal load and the estimated apparent effective thermal conductivity of the ground λ_s = 4.5 W/m/K were given. In addition, the modified values of COP were used.

Figure 10 shows the total energy consumptions of the system as a function of the variations in $T_{poutset}$. If the $T_{poutset}$ is set at 27ºC ~ 30 ºC, 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 $T_{poutset}$ is set at 27ºC ~ 30ºC. The reason is that the maximum T_{pout} is less than 27ºC as shown in Figure 11 and it is not required to operate the cooling tower.

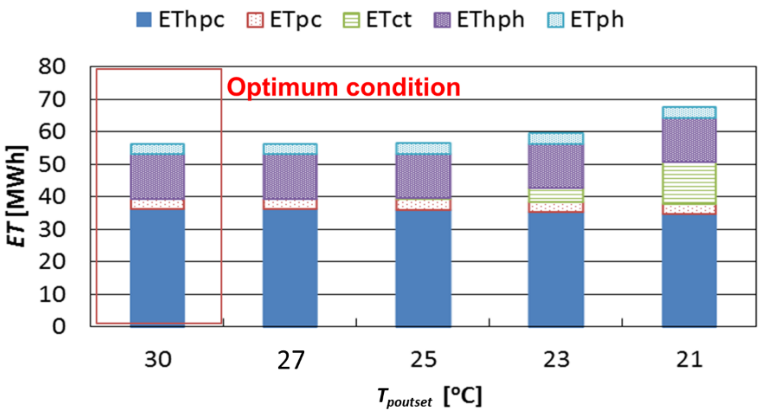

Figure 10: Total energy consumptions of the HGSHP system

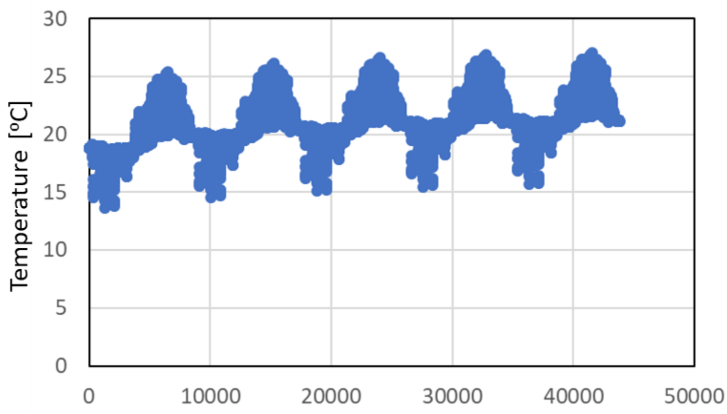

Figure 11: Hourly variation of T_{pout} for 5 years calculated by simulation tool

3.4 Result of long-term operation

Figure 12 shows the hourly variation of T_{pout} for 8 years. The temperature was lower than 30°C as well as the calculation result even though the cooling tower was not operated. In addition, the temperature increase from 1st year to 5 year was hardly observed although the heat injection was much larger than the heat extraction. This is due to the local groundwater flow.

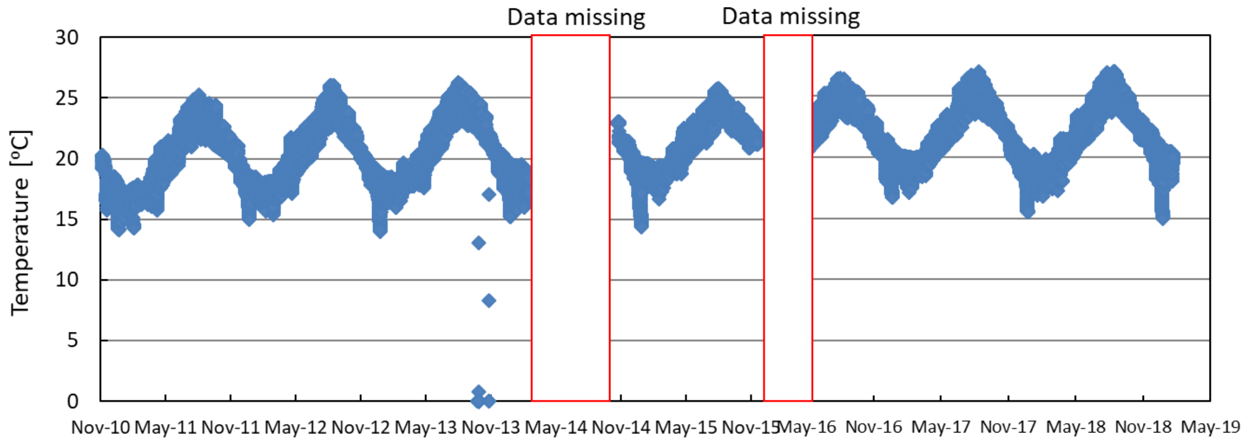

Figure 12: Hourly variation of T_{pout} for 8 years

4. SUMMARY

1) The authors introduced an autonomic optimum control system for the hybrid 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 4.5 W/m/K by using the ground heat exchanger model.

3) The optimum operation method for the hybrid GSHP system is calculated by using the performance prediction tool. The results show that the maximum temperature of heat carrier fluid was less than 27°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.

4) The result of 8 years' operation of HGSHP system showed that the temperature was lower than 30°C as well as the calculation result even though the cooling tower was not operated.

ACKNOWLEDGEMENT

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NOMENCLATURE

COP: Heat pump COP [-]

CCOP: Ratio of average COP (Measured) and average COP (Calculated) [-]

E_{CT}: Electric power of cooling tower [kW]

E_{hp}: Electric power of heat pump [kW]

E_p: Electric power of circulation pump [kW]

ET_{CT}: Energy consumption of cooling tower [kWh]

ET_{hpc}: Energy consumption of heat pump in cooling period [kWh]

ET_{hph}: Energy consumption of heat pump in heating period [kWh]

ET_{pc}: Energy consumption of circulation pump in cooling period [kWh]

ET_{ph}: Energy consumption of circulation pump in heating period [kWh]

Q_{hp}: Heating output from heat pump [kW]

T_{1out}: Outlet temperature of heat pump in the primary side [°C]

T_{1in}: Inlet temperature of heat pump in the primary side [°C]

T_{pin}: Inlet temperature of ground heat exchanger [°C]

T_{pout}: Outlet temperature of ground heat exchanger [°C]

$T_{poutset}$: Set temperature of cooling tower's activation [°C]

t: Time [s]

V_f: Flow rate [m^3/s]

λ_s: Soil effective thermal conductivity [W/m/K]

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