STUDY ON THE THERMAL PERFORMANCE OF GROUND HEAT SOURCE HEAT PUMP SYSTEM

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Abstract: In this paper, the operation performance for ground heat source heat pump system is discussed. For the model building, the ground heat source heat pump system is designed and the operation performance of that was evaluated by using the energy simulation. And, the analysis for operation performance was conducted under the different driving schedules of system. Also, the operation performance of ground heat source heat pump was compared with that of air heat source heat pump system, introducing the proper driving schedule for ground heat source heat pump system.

Key Words: ground heat source heat pump (GHP), operation scheme, control strategy, system COP, air heat source heat pump (AHP)

1 INTRODUCTION

A GHP system consists of water heat source heat pump equipment and ground heat exchangers (GHEs) which can extract and inject heat from/into the ground. Through the process of heat extraction and injection from/into the ground, efficient operation is attained as compared to AHPs. For this reason, such systems are attractive from the point of view of energy conservation measures. Moreover, since the release of heat into the air can be suppressed, it is expected that GHEs can be used as an effective measure against thermal pollution in urban areas and heat islands.

To promote the geothermal heat pump system, it is necessary to reduce initial costs and to improve system efficiency. Firstly, to reduce the drilling cost for GHEs, a construction method which embeds heat exchange pipes in advance is under active development. In this regard, it is considerable that the combined application of different types of GHEs and borehole types can yield high efficiency (Gao, Zhang et al. 2008). Moreover, when combined application of these is considered, it is thought that more suitable combinations exist from the viewpoint of cost performance.

Secondly, regarding improvements in system efficiency, a main issue is determining an effective means of achieving sufficient performance and output during the year. For this issue, the thermal performance of GHE must be understood and the system operation must be well managed. Furthermore, the load to be handled by the system must be considered with regard to the heat supply plan for the entire HAVC system.

In this paper, a geothermal heat pump system is designed for a model building. The complex usage of different types of GHEs is proposed in order to reduce the initial costs of GHEs.

Numerical simulations are conducted to determine whether or not the designed system can satisfy the design criteria. Furthermore, the proper system operation schedule was introduced by comparing with the operation performance of GHP and AHP.

2 OUTLINE OF SUBJECT SYSTEM

Figure 1 shows the dimensions of a model building and the installation zones for GHEs. The building area is 4,800 m2 (60m×80m) and the total floor space is 20,000 m2, envisaging an office building existing in Osaka, Japan. It is assumed that the building has an air conditioning heat source system consisting of a water heat storage system, an air-cooled heat pump (HP), and a centrifugal refrigerator. The greatest equipment load of the building is about 1.8 MW. It is further assumed that we have a GHP system of 175 kW (50RT) equivalents to about 10% of the greatest equipment load.

Figure 2 schematically shows a water heat storage system and a geothermal HP system. It is assumed that the geothermal HP system is connected to the water heat storage tank and performs at full rated operation. As shown in the figure, we adopt three different types of ground heat exchangers: borehole, SMW (soil mixing wall), and pile-foundation.
Table 1 shows the details of the three types of GHEs. The popular borehole-type GHE consists of two U-shaped tubes made of PVC which are inserted into a borehole. In addition, GHEs of the SMW type use the soil mixing wall technique to fix the U-shaped tube in place in order to reduce the cost of drilling a hole. The last method involves the utilization of cast-in-place concrete foundation piles. These GHEs are coupled in parallel with heat pump equipment.

Table 2 shows the design conditions of GHP system. From the restrictions of the building, 20 units of SMWs and 2 units of pile foundations are installed. It is assumed that borehole type units are installed in the adjacent parking space where there is no limitation on the number of units to be installed. In the pre-study, since the air heat source heat pump system can be obtained as a seasonal mean COP ; 4.0 in cooling, 3.4 in heating, the target COP (coefficient of performance) of the geothermal HP was assumed to be 4.0 in the cooling period and 3.4 in the heating period.

In this study, a GHP system of 50RT is assumed. It was determined that the numbers of heat exchangers are: 20 SMWs, 2 pile-foundations, and 27 boreholes since the GHP performance should be larger than 4.0 at the period of cooling and larger than 3.4 at the period of heating (Yoon et al., 2010). With this, the flow from heat source water, 665 L/min, is distributed between boreholes 418 L/min (63%), SMWs 177 L/min (27%) and pile foundations 70 L/min (10%).

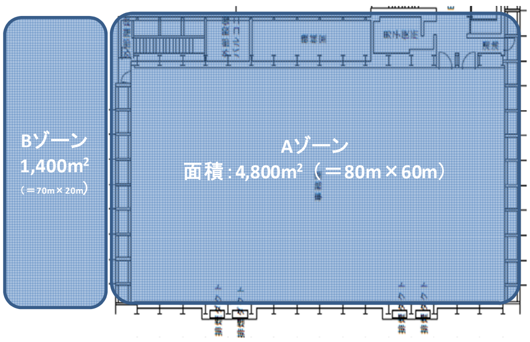


Figure 1: Plan of building

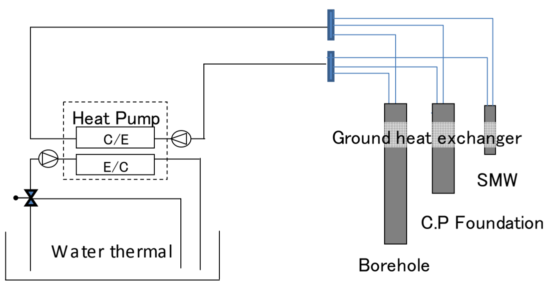


Figure 2: Layout of subject system

Table 1: Three types of ground heat exchangers

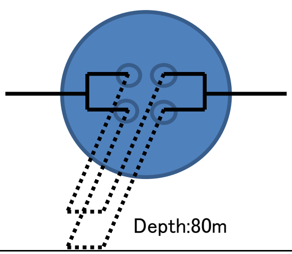
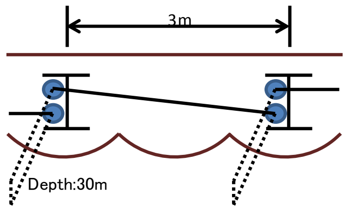
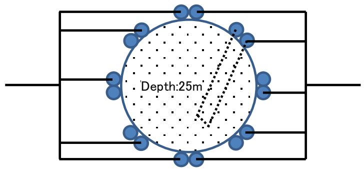
	Borehole type	SMW type	C.P pile foundation type
Diagram			
Dimensions per 1 unit	Depth : 80 m Two U-shaped tubes	Depth : 30 m Two serially connected loops	Depth : 25 m Eight U-shaped tubes
Pipe section area	1.2e-3 m^2	1.2e-3m^2	5.0e-3m^2
Heat transfer area	0.25m^2/m	0.25m^2/m	1.01m^2/m

Table 2: Design conditions

GHP	Capacity	50RT
	Heat source water flow rate	665lit/min（⊿T=5℃）
Maximum number of GHEs can be installed		Borehole：no limited SMW：up to 20 units, C.P. foundation：up to 2 units
Goal of COP of GHP		Cooling season COP：4.0 (From 1st May. to 31th Oct.) Heating season COP：3.4 (1st Nov. to 31th April)

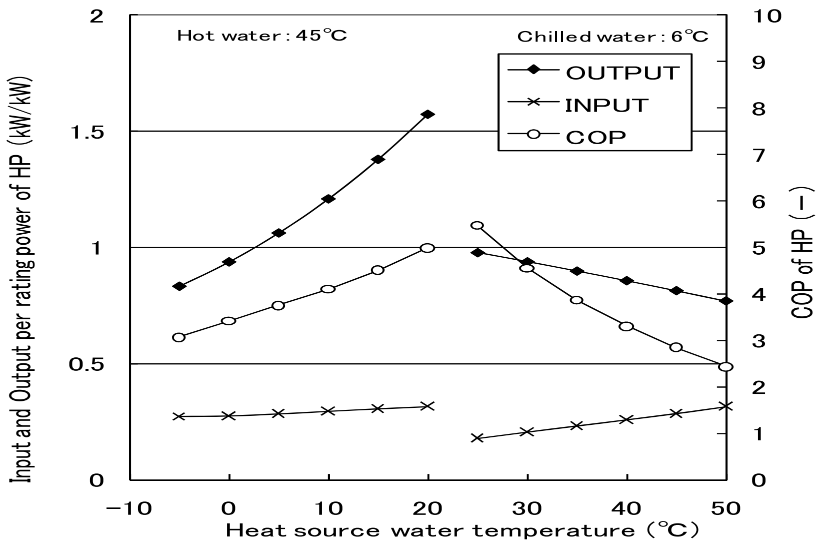


Figure 3: Performance of heat pump equipment

3 SIMULATION MODEL FOR GHP SYSTEM

In this section, we discuss numerical simulations, which were conducted to evaluate the efficiency of the designed system. The three types of GHEs presented above are modeled as shown in Figure 4. Although each type of GHE involves U-shaped tubes made of circular

PVC pipes with a diameter of 20 mm, the shape of the cross-section of the U-shaped tube was converted into a rectangular one for the sake of simplifying the model and the simulations (Yoon et al., 2006). Also, the conversion was conducted in such a way as to avoid changes in the heat transfer area and the water flow rate of the pipes. In addition, although the eight of U-shaped tubes are arranged in a circular enclosure in a C.P. pile foundation with a diameter of 2.2 m, the model was constructed by arranging the U-shaped tubes in a rectangular formation, with the result that the distance between the tubes was changed a little.
Except in the case of SMW, the ground surrounding the GHEs was modeled as a calculation domain in the shape of a rectangular parallelepiped which is 20 m wide in both horizontal directions and 100 m deep as shown in Figure 5.

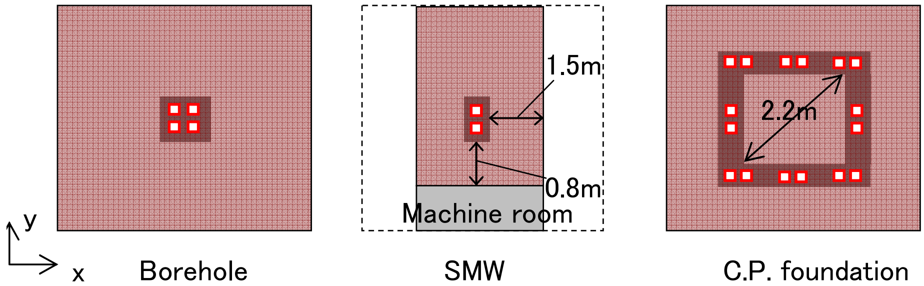


Figure 4: Models of the three types of GHEs

The calculation domain for the ground in the case of the SMW type was assumed to be 3 m wide in x-direction since the distance between the U-shaped tubes was adjusted to 3 m. Also, one side of the calculation domain was assumed to face a facility room at a distance of 0.8 m, where the air temperature inside the facility room was assumed to be 5 ºC higher than the outdoor air temperature at any time.

The boundary condition for all side is adiabatic condition except top and bottom side which are corresponded to ground surface and underground at 100 m deep. The formulas of the heat balance in the calculation domain and at the ground surface are shown below. It is considered that solar radiation and long-wavelength radiation. And the bottom side is assumed being kept at annual mean outdoor air temperature constantly. The effective heat conductivity of the ground at a depth of 100 m is 1.75 W/mK, and the effective heat capacity is 2,366 kJ/m3K.

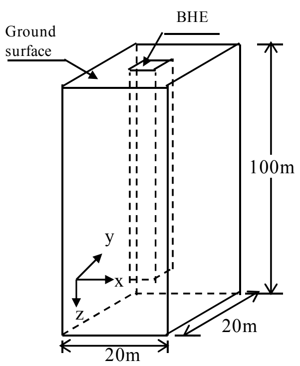


Figure 5: Calculation domain

Heat balance in the ground

$$c_s \rho_s \frac{\partial \theta_s}{\partial t} = \lambda_s \left(\frac{\partial^2 \theta_s}{\partial x^2} + \frac{\partial^2 \theta_s}{\partial y^2} + \frac{\partial^2 \theta_s}{\partial z^2} \right) \quad (1)$$

Heat balance at the ground surface

$$-\lambda_s \frac{\partial \theta_s}{\partial y}\Big|_{z=0} = \alpha_{ss}(\theta_{ss} - \theta_o) + aJ - \varepsilon dn \quad (2)$$

It is assumed that the heat pump equipment is operated in rated output mode with a constant volume of the water (ethylene glycol solution, 20%wt.) heat source and the heated/cooled water. The operation of the HP is simulated by using the approximation equations (3)-(6) as shown below which derived from performance curves in Figure 3. By computing the output and the power of the HP with the temperature of the water heat source at the outlet of the GHEs, the change in operating efficiency caused by the water heat source flowing from GHEs into the HP can be considered.

Operation in heating mode

Output : $Q = 4.79 * Tw + 170.44$ (3)

Power : $W = 0.22 * Tw + 49.89$ (4)

Operation in cooling mode

Output : $Q = - 1.47 * Tw + 208.58$ (5)

Power : $W = 0.95 * Tw + 7.48$ (6)

Here, Tw is the heat source watertemperature at the outlet of the GHEs

4 THERMAL PERPORMANCE OF THE DESIGNED SYSTEM

4.1 Thermal Performance

Figure 6 shows the yearly change of heat source water. The average temperature of heat source water was 37.2˚C in the cooling operation, and 3.2˚C in the heating operation. At the same time, during the same periods, the average outside air temperature was 33.5˚C during the cooling period and 3.16˚C during the heating period.

Table 3 shows the accumulated and the averaged amounts of heat release and heat extraction for the three types of ground heat exchangers. The total amount of heat emitted to the ground through the heat exchangers was 167.5 MWh per year and the total amount of extracted heat was 127.9 MWh per year. The ratio between heat release and heat extraction is 1.3:1 where the heat release is 30% greater than the heat release. There is a difference between the heat rate of injection into the ground and extraction from the ground; however, we could confirm the previous study's finding that the periodic steady state was achieved after three years of operation for this type of system.
The amount of released and extracted heat per length of a heat exchanger is 33 W/m for borehole, 22 W/m for SMW, and 914 W/m for pile foundation, indicating that the largest value is found in pile foundation, which is characterized by a large heat-transfer area and a large circulating flow rate.

Figure 7 shows the yearly change of the output of a heat source water HP and the COP. The graph shows that, although the output falls after July during the cooling operation of HP, the rated output values of 169.5 kW during the cooling operation and 196.4 kW during the heating operation are virtually satisfied in the course of a year. The mean COP was 4.05 for the cooling season and 3.67 for the heating season. The results show that the designed combined system of GHEs satisfies the target COP.

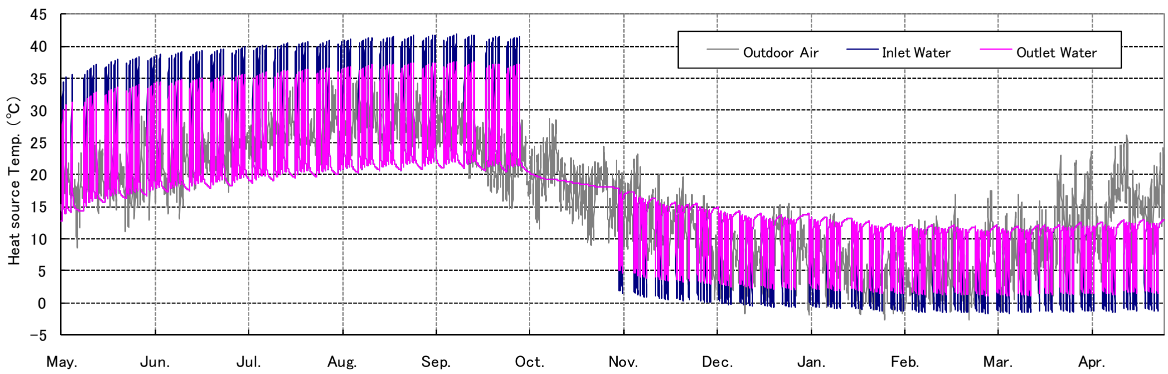


Figure 6: Heat source water temperature

Table 3: Thermal performance for each GHEs

		Borehole	SMW	C.P. pile
Cooling season (Heat release)	Total	106,455 kWh	30,930 kWh	30,133 kWh
	Average	99.5 kW	28.9 kW	28.2 kW
	Average per meter	41 W/m	24 W/m	1,126 W/m
Heat extraction (Heating season)	Total	76,786 kWh	28,674 kWh	22,412 kWh
	Average	62.4 kW	23.3 kW	18.2 kW
	Average per meter	26 W/m	19 W/m	729 W/m
Annual heat transfer	Total	183,241 kWh	59,604 kWh	52,545 kWh
	Average	79.7 kW	25.9 kW	22.8 kW
	Average per meter	33 W/m	22 W/m	914 W/m

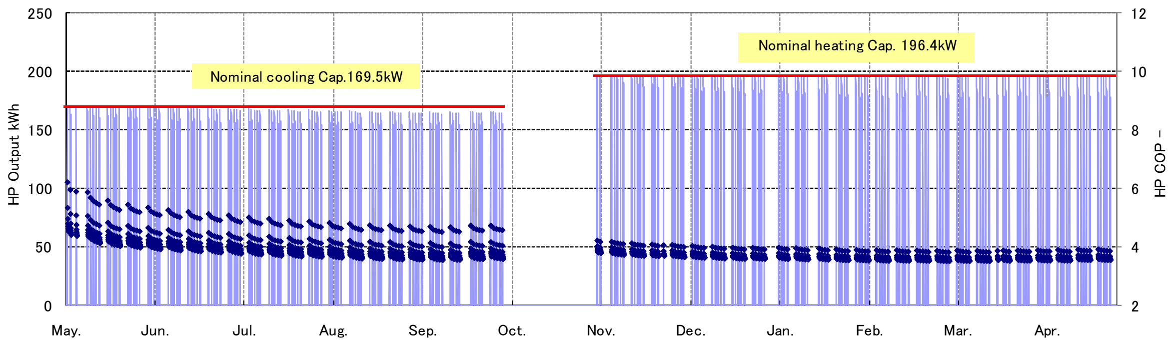


Figure 7: Output and COP of heat pump

4.2 Sensitive study for operation schedule

Here, we modify the time schedule of the HP system operation to examine the operating efficiency of the system. Table 4 shows the five cases of operating time schedule tested. Case 1 is the standard one discussed in the previous section. In Case 2 and Case 3, the operating hours are increased to 10 hrs and 12 hrs while other conditions are in common with Case 1. Case 4 is the same with Case 1 except that the operation is shut down on every Wednesday. In Case 5, the cooling operation is from July to August, and the heating operation is from December to February.

Figure 8 shows the simulation result. It is shown that, compared with Case 1, the year's accumulated output grows as the operating hours per day are increased; in contrast, the COP of HP decreases. The yearly COP of Case 3, 3.68, is smaller than that of Case 1, 3.82. In Case 4 where the operation of HP is shut down on every Wednesday and the yearly operating time is small, the output of HP is as low as 254.6 MWh. However, the annual COP of HP is as good as 3.87. A probable reason is that the temperature increase of surrounding soil during the cooling operation (the temperature decrease during the heating operation) is relieved through one break day a week.

In contrast, in Case 5 where the operating period of HP is short, the year's accumulated output is as small as 146.1 MWh. However, the yearly COP of HP, 3.9, is small compared with Case 1, not at all improving despite the decrease of operating time. This is probably because, in Case 5, the soil temperature around the ground heat exchangers goes back to the natural soil temperature during the 5-month shutdown period following the heating operation period of HP. In other words, in Case 1, the exhaust heat emitted during the heat operation is recovered during the cooling operation following the heating operation. As shown in Figure. 9, in Case 1 as compared with Case 5, the underground temperature is lower at the beginning of cooling operation and higher at the start-up of heating operation.

Table 4: Case study for operation schedule

CASE	Descriptions	Operation time on year
CASE-1	8 hours operate per day 10:00~17:59 except weekend and holiday Cooling operation May to Sep. Heating operation Nov. to April next year	230 days 1,840 hours
CASE-2	10 hours operate per day 8:00~17:59 except weekend and holiday Other conditions are same with CASE-1	230 days 2,300 hours
CASE-3	12 hours operate per day 8:00~19:59 except weekend and holiday Other conditions are same with CASE-1	230 days 2,760 hours
CASE-4	8 hours operate per day 10:00~17:59 except weekend and holiday, also every Wed. Other conditions are same with CASE-1	183 days 1,464 hours
CASE-5	Cooling operation July to Aug. Heating operation Dec. to Feb. next year Other conditions are same with CASE-1	105 days 840hours

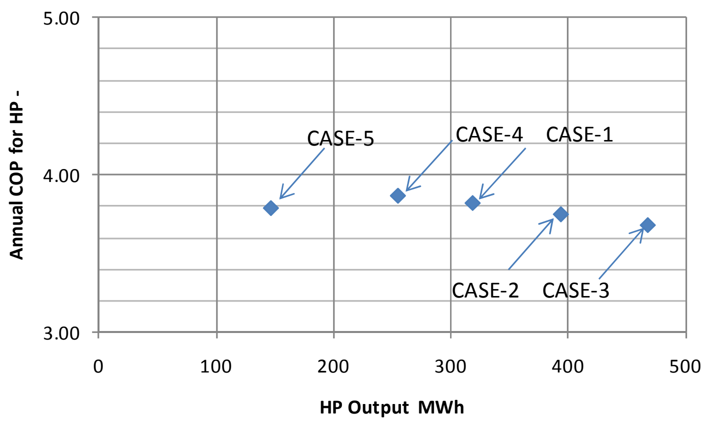


Figure 8: Annual COP for HP according to HP output

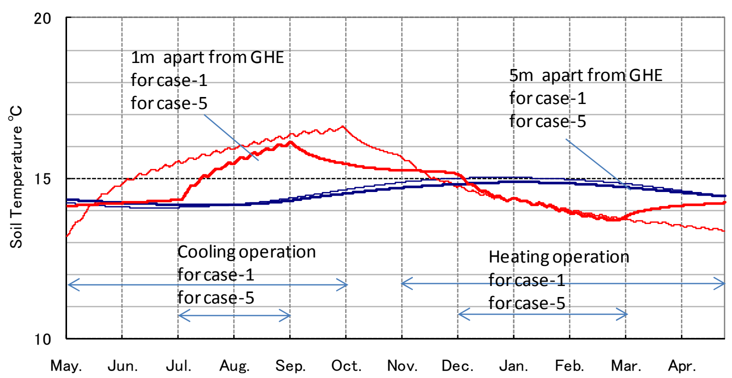


Figure 9: Fluctuation of soil temperature

4.3 Comparison with air source heat pump

Here, the comparison for operation performance with air source heat pump (AHP) is shown. The energy simulation was conducted with the ground source heat pump system assuming in this paper and AHP. The AHP has the similar capacity and performance with ground source heat pump. The cooling capacity of AHP is 170kW, and heating capacity is 195kW. The COP curve according to outdoor air is shown in Figure 10.

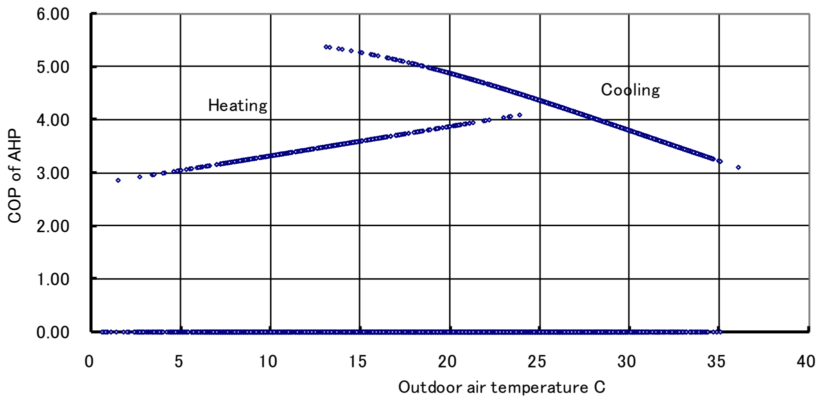


Figure 10:COP curve for AHP (Made by simulation results)

The five cases of energy simulation were conducted based on the operation schedules as shown in Table 4, can be obtained the output heat rate and COP for AHP for each cases. The simulations were done by using the Life Cycle Energy Management Tool Ver. 3.00 (Ito et al., 2007) which had been developed by Ministry of Land, Infrastructure, Transport and Tourism in Japan, were done by input the same conditions and input data with ground source heat pump system.

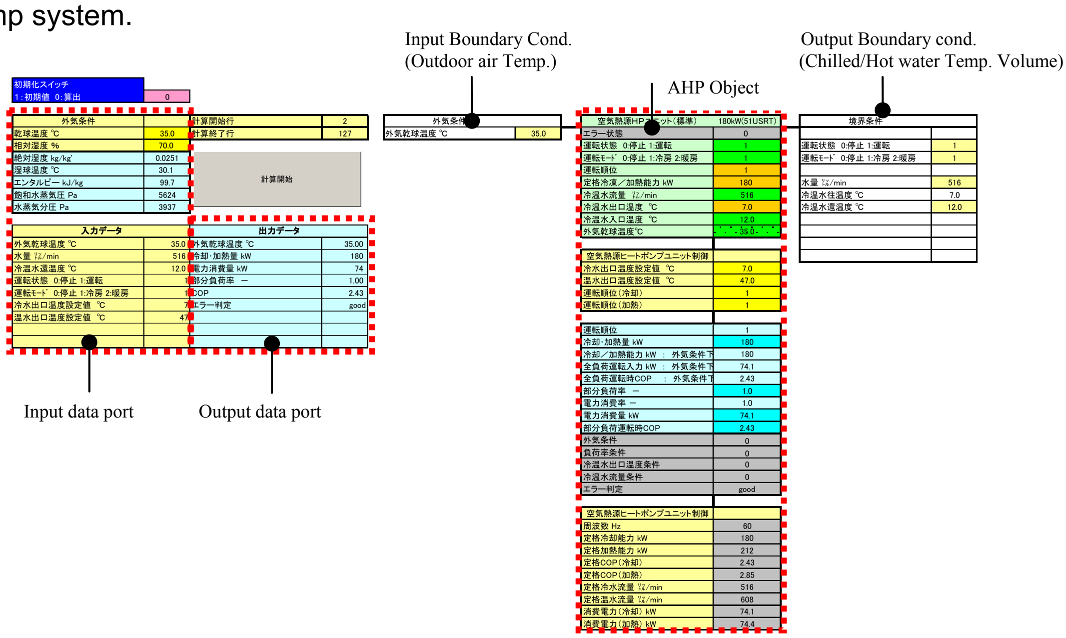


Figure 11: Skelton of subject system in LCEM Tool ver. 3.00
(Developed by Ministry of Land, Infrastructure, Transport and Tourism in Japan)

In figure 12, the fluctuation of COP for case 1 is shown. The mean COP in cooling season is 4.05, that in heating season is 3.4. The minimum COP in cooling season is 3.1, it occurred in Aug. which is hot season. In heating season, the minimum COP is 2.8, it was Jan. to Feb. It shows that the COP of AHP is well affected on the outdoor air temperature.

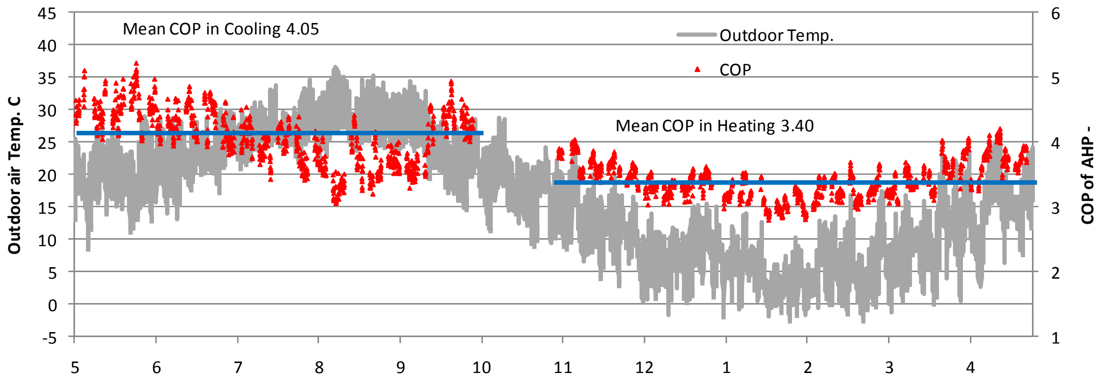
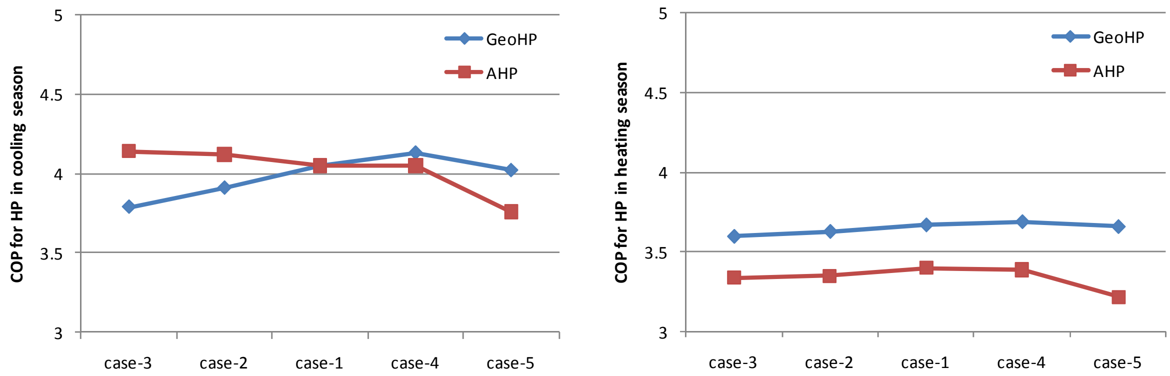


Figure 12: The annual operation performance for AHP in case-1

The comparison for mean COP at each case is shown in Figure13. And, it is shown in long case order of system operation time from the left. The COP of ground source heat pump rise, according to the system operation time shortens. - In case 5, COP of ground source heat pump is smaller than that of case 4, since there is no thermal storage heat induced by the system operation in previous season.-

In contrast, by shortening operation time, the COP of AHP deteriorates in a cooling period and it rises in a heating period. In case 5, the COP of AHP is smallest both in cooling season and in heating season since the operation time of HP concentrates when the outdoor air temperature is high (low) for a cooling period (a heating period).



a) Cooling season **b) Heating season**

Figure 13: Comparison for seasonal mean COP in each case

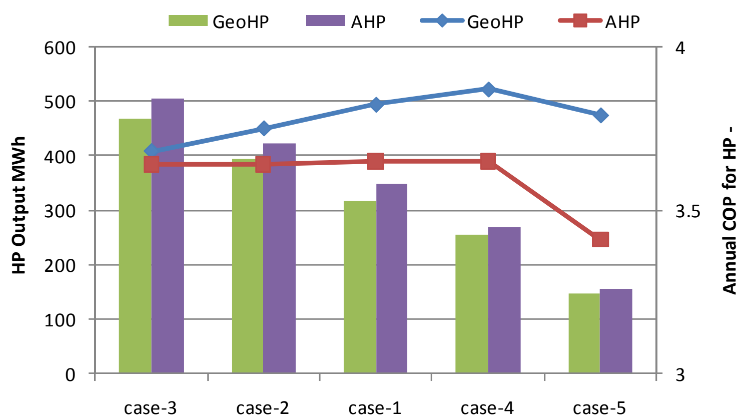


Figure 14: Comparison for annual COP and heat pump output in each case

The comparison for annual COP and heat pump output are shown in Figure 14. The COP differential between ground source HP and AHP become large by shorten operation time, the difference became 0.38 with 0.22, case 5 with case 4. And, by shortening operation time, the reduction for output of ground source HP became small, the output of GHP is 164MWH per year and that of AHP is 155MWh per year.

5 CONCLUSION

In this paper, an HP system incorporating three types of ground heat exchangers was discussed. The system was designed to cover part of the equipment load of a model building. The designed system was analyzed using a numerical analysis model to examine if the target performance was achieved. In addition, we examined the influence of the operating time schedule of HP on the operating performance. As a result, it was confirmed that the output of HP increases while the operating efficiency decreases if the operating time of the HP system is increased. It was also confirmed that, although the HP output decreases, the operating efficiency improves if the operating time for the HP system is decreased. It was shown that high efficiency of operation is brought about by the heat recovery after the switching between cooling and heating operations, and therefore we must be careful when decreasing the operating time.
In addition, the operation performance of ground source heat pump was compared with that of air source heat pump. The improvement of operation performance for ground source heat pump is can be obtained by HP system shortened driving time, and centralizing the operation time in hot season or cold season when the COP of air heat source heat pump be reduced by affecting outdoor air temperature.

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NOMENCLATURE
c : special heat [kJ/kgK], ρ : density [kg/m3], θ : temperature [K], λ : thermal conductivity [W/mK], t : second [Sec.], J : intensity of solar radiation [W/m2], a : solar absorptivity [-], dn : nocturnal radiation [W/m2], α : heat transfer coefficient [W/m2K], ε:emmisivity[-] -Subscript s : soil, ss : ground surface