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Performance analysis of ground source heat pump system with vertical borehole heat exchangers affected by rapid groundwater flow

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Abstract

The objective of this study is to estimate a cooling and heating performance of the ground source heat pump system with the borehole heat exchangers affected by rapid groundwater flow. The performance prediction is especially performed according to the required length of the borehole heat exchangers. For the evaluation of the performance, the measured data are analyzed in a three-floor building installed on the ground source heat pump system with four borehole heat exchangers (BHE s) in Kazuno City, Japan where the area has the groundwater flow actively. Based on the thermal properties of the soil and the groundwater velocity analyzed by the thermal response test, the measured circulating fluid temperature corresponding with the building load is compared with the calculated circulating fluid. The calculated fluid temperature was in agreement with the measurement data when an effective thermal conductivity of soil and a groundwater velocity were 4.7 W/(m K) and 120 m/y. An average coefficient of performance in a cooling/heating period was 4.5 and 7.8 respectively.

Keywords: Performance analysis, ground source heat pump system, groundwater, borehole heat exchanger;

1. Introduction

Ground source heat pump system (GSHPs) has been used to supply heating and cooling to buildings, using the ground as a heat source or a heat sink. The GSHPs installed in some areas with groundwater flow can achieve high performance. Some areas in Japan have an active groundwater flow owing to a steep slope of the mountains and the coefficient of permeability of the soil. Since the effect of the groundwater flow makes the ground temperature constant, the length of the ground heat exchanger (GHE) and initial cost can decrease. Ingersoll et al. [1] mentioned that the 286 m/y of the groundwater velocity results in the heat exchange rate (HER) to increase by 19 %.

A lot of research has been analyzed a coefficient of performance (COP) of the GSHP system to deliberate the optimal design of the GSHP system under widely divergent conditions. However, there is little research reflecting the effect of the groundwater velocity estimated from the thermal response test to consider the COP of the GSHP system. This study is carried out the calculation of the circulating fluid temperature at inlet and outlet pipes, based on the building load and the soil properties from the TRT results reflecting the effect of the groundwater flow. As a result of the previous study [2], the groundwater velocity and effective thermal conductivity were estimated at 120 m/y and 4.7 W/(m·K)), respectively. The calculated fluid temperatures are compared with the measurement data. The performance prediction is especially performed according to the required length of the borehole heat exchangers.

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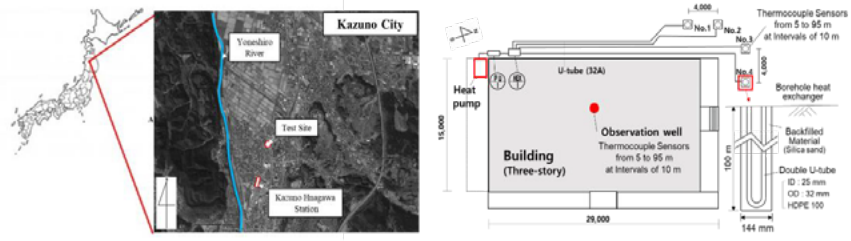
2. Site description

The test site was located in Kazuno city (40°19'N and 140°78'E), Akita Prefecture where the groundwater flow was expected to move actively by surrounding mountains and Yoneshiro River in Figure 1 (a). Figure 1 (b) shows the ground plan of the target building. The target building was a three-floor building, and the floor area was 435 m^2. The four GSHPs were installed for cooling and heating at intervals of 4 m. The diameter and length of the borehole were 144 mm and 100 m. A double U-tube was inserted in the borehole. The U-tube was high-density polyethylene, and an outer and an inner diameter of the U-tube was 32 and 25 mm respectively. A grout material was filled from a ground surface toward a bottom side of the borehole. The soils of the test site were mainly composed of gravel, gravelly sand and sandy gravel, and the effective thermal conductivity of the soil calculated by the thickness-weighted average of the soils was 2.4 W/(m·K). The experiment data was measured from 1st to 14th January 2018 in the heating period and from 1st to 14th July 2018 in the cooling period. Table 1 shows the description of the building in test site.



(a) Location of test site (b) Ground plana of target building

Fig. 1. Location of test site and Ground plana of target building

Table 1. Description of the building in test site

Category	Description
Total floor area	435 m^2 (Three floor building)
Total length of BHEs	400 m (Four BHEs)
Borehole diameter/U-tube size	144 mm / Double U-tube (outer:32 mm, inner:25 mm)
Measurement period	Heating (January 1 - 14th, 2018) / Cooling (July 1 - 14th, 2018)

3. Method

3.1 Analysis method of the measurement data

In the heating period, the heating load of the building is the sum of the HER and the power consumption of the heat pump in Eq (1). on the other hand, in the cooling period, the sum of the HER equals the sum of the cooling load of the building and the power consumption of the heat pump in Eq (2). The HER is calculated in Eq (3) or (4).

$$Q_c \approx Q_{inj} - W_{hp} \quad (1)$$

$$Q_h \approx Q_{ext} + W_{hp} \quad (2)$$

$$Q_{\mathrm{inj}} = \dot{m}_{\mathrm{f}} c_{\mathrm{f}} (LWT - EWT) \quad (3)$$

$$Q_{\mathrm{ext}} = \dot{m}_{\mathrm{f}} c_{\mathrm{f}} (LWT - EWT) \quad (4)$$

Here, Q_{c} and Q_{h} are the cooling/heating load of the building. Q_{inj} and Q_{ext} are the heat injection/extraction rate from/to the ground. W_{hp} is the power consumption of the heat pump. LWT and EWT are the leaving water temperature from the heat pump and the entering water temperature to the heat pump respectively. $\dot{m}_{\mathrm{f}}$ is the flow rate of the circulating fluid and c_{f} is the specific thermal capacity of the circulating fluid.

The coefficient of performance (COP) of the GSHP in the cooling period and the heating period is calculated as follows;

$$COP_c = \frac{Q_c}{W_{hp}} \approx \frac{Q_{inj}-W_{hp}}{W_{hp}} \tag{5}$$

$$COP_\mathrm{h} = \frac{Q_\mathrm{c}}{W_\mathrm{hp}} \approx \frac{Q_\mathrm{ext}+W_\mathrm{hp}}{W_\mathrm{hp}} \tag{6}$$

Here, W_cp is the power consumption of the circulating pump.

3.2 Calculation of the fluid temperature with the groundwater flow

The moving line source theory is applied for calculation of the fluid temperature, considering the groundwater flow. The soil in this method is treated as homogeneous medium which do not change physical properties with the temperature in Eq (7) [3,4].

$$\theta(r,\varphi,\tau) = \frac{q}{4\pi\lambda_\mathrm{S}} \exp\left(\frac{Ur}{4\alpha_\mathrm{s}} cos\varphi\right) \int_0^{\frac{r^2}{4\alpha_S\tau}} \frac{1}{\beta} \exp\left(-\frac{1}{\beta} - \frac{U^2 r^2 \beta}{16\alpha_\mathrm{S}^2}\right) d\beta \tag{7}$$

Here, θ is the temperature rise in medium, $\theta = T - T_0$, T_0 is an initial temperature of the soil, $\boldsymbol{r}$ is radius coordinate, φ is a polar angle, q is a heat flux per meter, λ_S is an effective thermal conductivity of the soil and α_s is a thermal diffusivity, U is a Darcy velocity, β is an integration parameter.

The previous study of the authors [2] analyzed the thermal response test data in the same field and estimated the groundwater velocity and the effective thermal conductivity of the soil. The fluid temperature was calculated by applying superposition of the thermal response with hourly heat extraction and heat injection and the estimated groundwater velocity and the effective thermal conductivity. The calculated results were compared with measured data. The estimated groundwater velocity and the effective thermal conductivity were 120 m/y and 4.7 W/(m K)

4. Results and discussion

4.1 Measurement data of the units

Figure 2 shows the outdoor temperature, the mean ground temperature in the observation wall and the heating/cooling load. During the measurement period, the minimum and maximum temperatures of the outside were -4.5 and 33.9 °C. On the other hand, the average soil temperatures in the observations well, which is 15 m away from the BHEs, were constant to be 11.2 °C. The results indicate that the outdoor temperature and the BHEs injecting/extracting the heat to/from the ground do not affect the temperature of the observation wells due to the effect of the groundwater flow. During the heating period, the GSHPs was operated continuously, and the average heating load was 9.8 kW. On the other hand, in the cooling period, the GSHPs was operated intermittently, and the average cooling load was 2.5 kW.

Figure 3 illustrates the power consumption of the heat pump and the circulating pump and the flow rate. The power consumption of the heat pump of the heating period was higher than that of the cooling period because of the relative high-temperature difference between the outdoor temperature and the indoor temperature. The mean power consumption of the heat pump in the heating period and the cooling period was 3.1 and 0.6 kW respectively. The power consumption of the circulating pump was constant to be 0.2 kW regardless of the period. The mean flow rate in the heating period and cooling period was 48.5 and 40.7 L/min respectively.

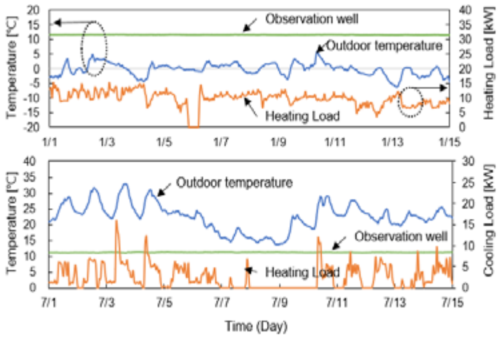


Fig. 2 Outdoor temperature, the mean ground temperature in the observation wall and the heating/cooling load.

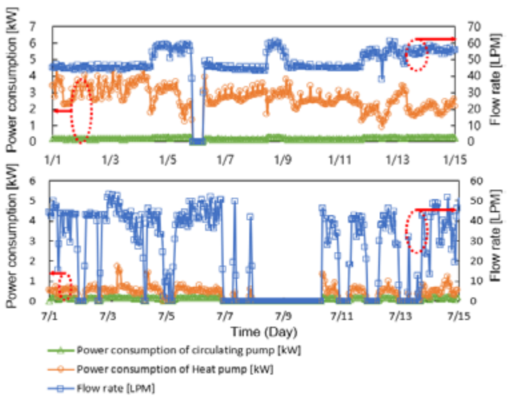


Fig. 3. Power consumption of the heat pump and circulating pump and the flow rate.

4.2 Temperature variation of the circulating fluid

Figure 4 indicates the temperature variation of the LWT and the EWT in the heating/cooling period. The LWT showed large fluctuations due to the ununiform power consumption of the heat pump whereas the fluctuation of the EWT was relatively constant. Especially, the results were regarded that the effect of the groundwater flow makes the EWT constant despite the continuous operating for the heating in the heating period.

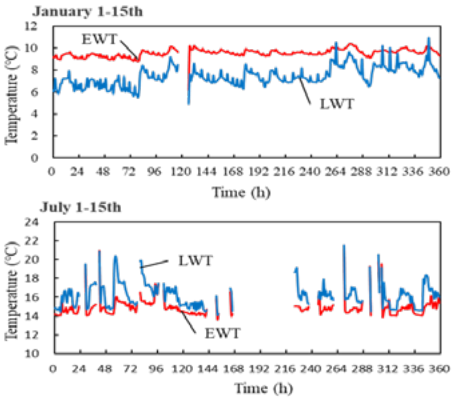


Fig. 4. Temperature variation of the LWT and the EWT

4.3 Performance analysis of ground source heat pump system

Figure 5 shows the variation of the heat exchange rate, the COP. Each result was calculated in Eq (4), (5), (6) and (7). The mean COP during the heating/cooling period was calculated to be 8.4 and 4.0 respectively. The heating load was bigger than the cooling load over 3.9 times, and the heat exchange rate of the heating period was also bigger that of the cooling period over 2 times. On the other hand, the average COP of the heating/cooling period was 3.6 and 6.2 because the power consumption of the heat pump of the heating period was lower than that of the cooling period over 5 times.

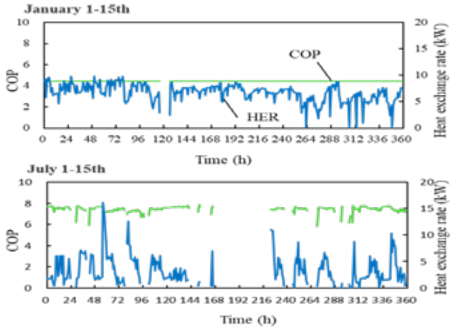


Fig. 5. Variation of the heat exchange rate, the COP

Table 2. The results of COP, Heat exchanger, EWT and LWT

Period	COP	Heat exchange rate [kW]	EWT [°C]	LWT [°C]
Heating period	4.5	6.7	9.5	7.5
Cooling period	7.8	3.3	15.0	16.2

4.4 Variation of EWT and LWT each case

Figure 6 shows the variation of EWT and LWT each case. The Cases were classified by the analysis method of the TRT, and the results of estimated parameter each case show in Table 3. As results, the calculated temperature results of the case 1 reflecting the groundwater velocity were similar to that of the measurement data. The temperature error between the case 1 and measurement data was under 6 % and 1 % during the heating period and cooling period, respectively.

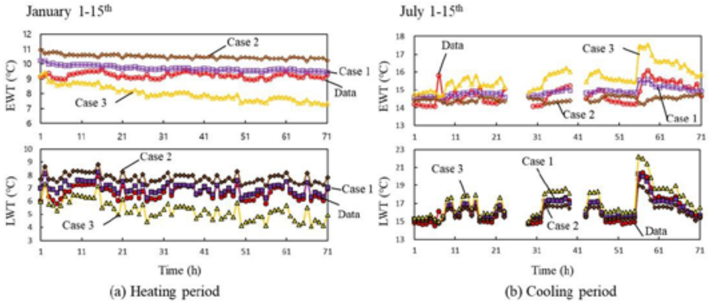


Fig. 6. Variation of EWT and LWT each case.

Table 3. Cases classified by the analysis method of the TRT

Case	λ_{eff} $(W/(m \cdot K))$	v (m/y)
Case 1 (Results calculated by MLS theory)	4.7	120
Case 2 (Results calculated by ILS theory)	8.9	0
Case 3 (Results from the column section)	2.4	0

4.5 Variation of EWT and COP according to total borehole length

Figure 7 shows the variation of EWT and COP according to the required total length of the borehole heat exchanger. Based on the parameters of the case 1, the EWT and COP were calculated according to the total borehole length. The shorter total borehole length resulted in the more significant fluctuation of EWT. In the analysis of the COP according to the total borehole length during the short-term period, the variation of COP during the heating period was insignificant, but the variation of COP during the cooling period was significant. Each COP according to the total borehole length was summarized in Table 4.

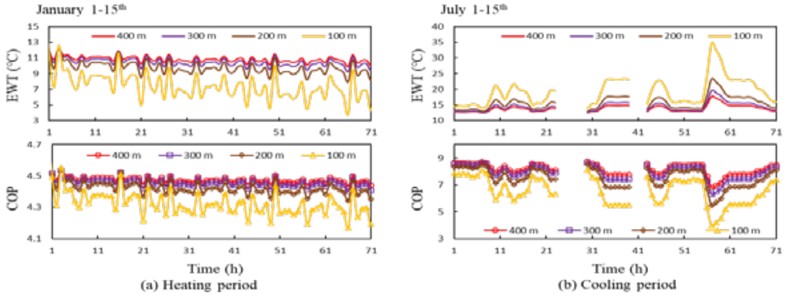


Fig. 7. Variation of EWT and COP according to total borehole length

Table 2. Variation of EWT and COP according to the required total length of the borehole heat exchanger.

Period	COP	Heat exchange rate [kW]	EWT [°C]	LWT [°C]
Heating period	4.5	4.5	4.4	4.3
Cooling period	7.8	7.7	7.5	6.6

5. Conclusion

The main objective of the present study is to investigate the cooling and heating performance of the ground source heat pump system with the borehole heat exchangers affected by groundwater flow. The EWT and LWT calculated by the MLS model based on the thermal properties of the ground (groundwater velocity= 120 m/y, effective thermal conductivity=4.7 W/(m·K)) [2] according to the building loads were compared with that of measurement data. The following is a summary of this study.

1) The performance analysis of the GSHP system was conducted by using the field data which is measured in the three-floor building located in Kazuno City.
2) The COP in measured heating and cooling period was 4.5 and 7.8.
3) The variation of EWT and LWT calculated by the MLS theory with the estimated parameters in the previous study was similar to that of measurement data.
4) In the analysis of the COP according to the total borehole length during the short-term period, the variation of COP during the heating period was insignificant, but the variation of COP during the cooling period was significant.

The decrease in the total length of the BHEs during the short-term period did not affect the COP of the GSHP system significantly when groundwater flows. therefore, the initial cost can be saved by decreasing the total length of the BHEs.

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