12th IEA Heat Pump Conference 2017

Development of Optimum Design Method for the Heat Recovery Ground Source Heat Pump System

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Abstract

A method for the design and operation of a heat-recovery ground-source heat pump (HR-GSHP) system has been investigated. In this paper, an optimum design method for the HR-GSHP system was first introduced. By applying the optimum design method, the total heating and cooling loads of each ground-source heat pump (GSHP) unit in the HR-GSHP system were maximized in response to an arbitrarily set total length of the ground heat exchanger (GHEX). This means that the HR-GSHP system designed with the optimum method could yield the maximum energy saving effect for a given GHEX total length. Next, it was assumed that the HR-GSHP system with a 7,200-m total GHEX borehole length was installed in a large scale complex building, which required both heating and cooling at the same time throughout the year, and the hourly heating and cooling loads of each GSHP unit was determined using the optimum design method. As a result, it was confirmed that the HR-GSHP could cover approximately 4.3 times the heat load of a conventional GSHP system. In addition, the simulation of annual HR-GSHP system operation was performed using the design and performance prediction tool for the GSHP system. The hourly heat load determined by the optimum design method was given in the simulation. The average coefficients of performance (COP) for the HR-GSHP system were 4.6 for heating and 10.3 for cooling. Thus, the HR-GSHP system was advantageous in not only the amount of heat load that could be covered but also the COP compared to the conventional GSHP system.

Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

"Keywords: Heat Recovery Ground Source Heat Pump System, Design Method, Optimization method;"

1. Introduction

Ground-source heat pump (GSHP) systems have gained attention in Japan since ground thermal energy was defined as one of the top renewable energies in 2009. However, the number of GSHPs installed in Japan is much smaller than the number in other countries such as the USA, China, and Sweden due to the expensive installation cost of ground heat exchangers (GHEXs) [1]. There are few examples of large GSHP systems in Japan with a total heating or cooling capacity of more than 500 kW.

The advantages of the heat-recovery ground-source heat pump (HR-GSHP) system could potentially promote the installation of large GSHP systems. The HR-GSHP system has several types of GSHPs for different uses connected in the GHEXs in order to yield two types of heat recovery effects. The first type of heat recovery effect is the direct heat recovery effect obtained by operating several types of GSHPs, such as cooling and hot water supply, at the same time; this effect is the same as that of the conventional heat recovery heat pump system. The other type of heat recovery effect is the indirect heat recovery effect that utilizes underground thermal storage effects and is obtained by short-term alternate operation of several types of GSHPs. By utilizing these two effects, the HR-GSHP can yield both energy saving effects and drastic reduction of the total GHEX length. Therefore, the HR-GSHP system has a large potential for saving energy in large-scale complex buildings and industrial plant, which require both heating and cooling at the same time. Although the HR-GSHP system has already been installed and commissioned in the dormitory in Kitakyushu City [2], [3], the design and operation method of the HR-GSHP system have not yet established.

The design and operation method of the HR-GSHP system was investigated. In this paper, the optimum design method for the HR-GSHP system is introduced. By applying the optimum design method, the total heating and cooling loads of each GSHP unit in the HR-GSHP system are maximized in response to an arbitrarily set total length of the GHEX. This means that the HR-GSHP system designed with the optimum method could yield the maximum energy saving effect for a given GHEX total length.

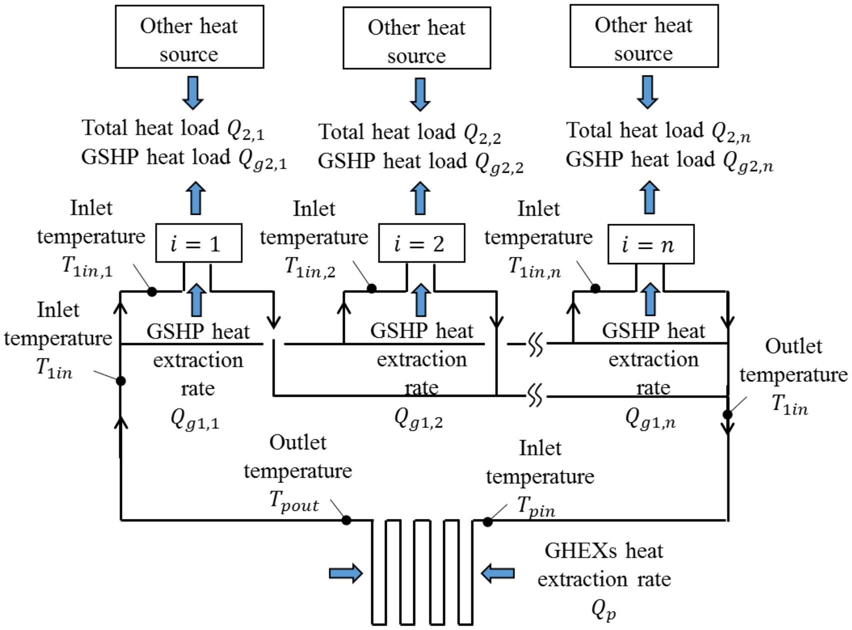
Next, assuming that the HR-GSHP system was installed in a large-scale complex building, which requires both heating and cooling at the same time throughout the year, the hourly heating and cooling loads of each GSHP unit was determined using the optimum design method. Additionally, by using the hourly heating and cooling loads of each GSHP unit, the simulation of annual HR-GSHP system operation was performed, and the results were compared with the those of the annual conventional GSHP system operation with the same GHEX length.

2. Optimum design method of the HR-GSHP

Figure 1 shows the concept diagram of the HR-GSHP system. In this system, the total heat load $Q_{2,i}$ was covered not only by the GSHP in HR-GSHP system but also by other heat source systems such as the air source heat pump (ASHP), the adsorption chiller, and the boiler. (The detailed example is shown in **Chapter 3**.) Here, the heat load for GSHP Q_{g2} ($Q_{g2,i}$) in Figure 1 included both the heating load and the cooling load. On the other hand, the heating load for GSHP Q_{g2h} ($Q_{g2h,i}$) and the cooling load for GSHP Q_{g2c} ($Q_{g2c,\,i}$) considered only the heating load and the cooling load, respectively. Thus, if a heating load at GSHP1 was generated ($Q_{g2,\,1} > 0$), the heating load at GSHP1 would be equal to $Q_{g2,1}$ ($Q_{g2h,1} = Q_{g2,1}$). Similarly, if a cooling load at GSHP1 was generated ($Q_{g2,1} < 0$), the cooling load at GSHP1 would be equal to $-Q_{g2,1}$ ($Q_{g2c,\,1} = -Q_{g2,\,1}$). As shown in Figure 1, the relation between Q_{g1} and Q_{g1e}, Q_{g1i} and the relation between Q_p and Q_{pe}, Q_{pi} are similar to the relation between Q_{g2} *and* Q_{g2h}, Q_{g2c}.

Figure 2 shows the flow of the optimum design method. By designing the HR-GSHP system with balance between heat extraction and heat injection in the short term (e.g., range of 1 month), it was possible to obtain a larger thermal storage effect than the seasonal thermal storage effect, which was further combined with the direct heat recovery effect obtained by operating several types of GSHPs at the same time. Consequently, the total length of the GHEX according to the total heating and cooling loads from the GSHPs could be drastically reduced. The detail of the optimum design method is described below.

First, the calculation conditions were given. The main calculation conditions were the GHEX total length L_p, initial ground temperature T_{s0}, effective thermal conductivity of ground λ_s, and allowable maximum and minimum heat carrier fluid temperature at the inlet of GSHPs T_{1inmax} and T_{1inmin}, respectively. Next, the rated capacities of the GSHPs in the HR-GSHP system, Q_{g2cri} and Q_{g2hri}, and the COP of the GSHPs, COP_{ci} and COP_{hi}, were assumed.



Relation between
Q_{g2} and Q_{g2h}, Q_{g2c}
If $Q_{g2} > 0$ (Heating)
$Q_{g2h} = Q_{g2}$
$Q_{g2c} = 0$
If $Q_{g2} < 0$ (Cooling)
$Q_{g2h} = 0$
$Q_{g2c} = -Q_{g2}$

Relation between
Q_{g1} and Q_{g1e}, Q_{g1i}
If $Q_{g1} > 0$ (Heat extraction)
$Q_{g1e} = Q_{g1}$
$Q_{g1i} = 0$
If $Q_{g1} < 0$ (Heat injection)
$Q_{g1e} = 0$
$Q_{g1i} = -Q_{g1}$

Relation between
Q_p and Q_{pe}, Q_{pi}
If $Q_p > 0$ (Heat extraction)
$Q_{pe} = Q_p$
$Q_{pi} = 0$
If $Q_p < 0$ (Heat injection)
$Q_{pe} = 0$
$Q_{pi} = -Q_p$

Figure 1 Concept diagram of HR-GSHP system

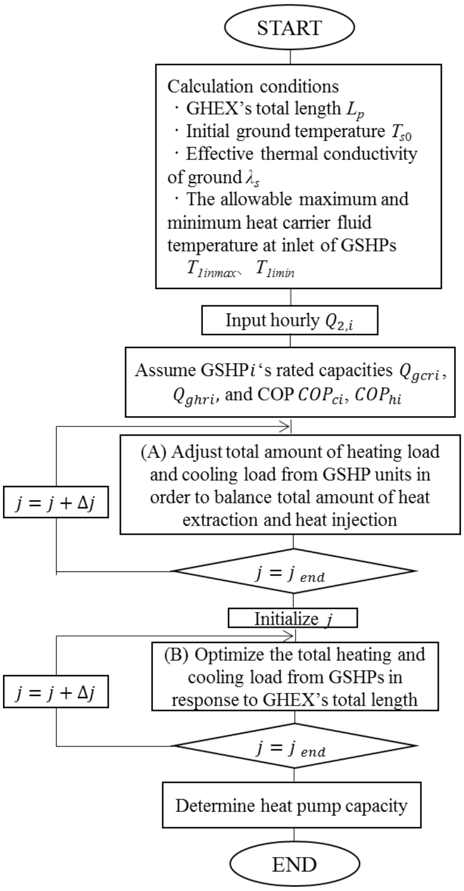


Figure 2 Flow of optimum design method for HR-GSHP system

The total amount of heat extraction and injection in the arbitrary period (1 month) were adjusted and balanced by changing the maximum heating (or cooling) output from the GSHP unit (part (A) in Figure 2). An example of adjusting the total amount of heat extraction and injection was shown. Figure 3 shows an example of hourly heating and cooling load variation in the complex building. Here, GSHP1 and ASHP1 were assumed to correspond to the heating load, while GSHP2 and ASHP2 corresponded to the cooling load. Next, the rated heating capacity of GSHP1 Q_{g2hr1} and the rated cooling capacity of GSHP2 Q_{g2cr2} were given as 1,500 kW and 1,500 kW, respectively. Figure 4 shows the hourly heating load covered by GSHP1 Q_{g2h1} and the cooling load covered by GSHP2 Q_{g2c2} in the period identified by the frame in Figure 3. In addition, the hourly heat extraction generated by GSHP1 Q_{g1e1} and heat injection generated by GSHP2 Q_{g1i2} in the period are shown in Figure 5 for hourly Q_{g1e1} and Q_{g1i2} calculated using the following equations given $COP_{h1} = 4$, $COP_{c2} = 6$, respectively:

$$Q_{g1e,i} = Q_{g2h,i} - Q_{g2h,i}/COP_{h,i} \tag{1}$$

$$Q_{g1i,i} = Q_{g2c,i} + Q_{g2c,i}/COP_{c,i} \tag{2}$$

Here, the total amount of $Q_{g1e,1}$($\sum Q_{g1e,1}$) is larger than the total amount of $Q_{g1i,2}$ ($\sum Q_{g1i,2}$) in Figure 5. Therefore, $\sum Q_{g1e,1}$ was reduced by changing the maximum heating output of GSHP2 from $Q_{g2hr,1}$ to $Q_{g2h\max,1}$, as shown in Figure 4. As a result, $\sum Q_{g1e,1}$, which is surrounded by frame in Figure 5, is almost the same as $\sum Q_{g1i,2}$.

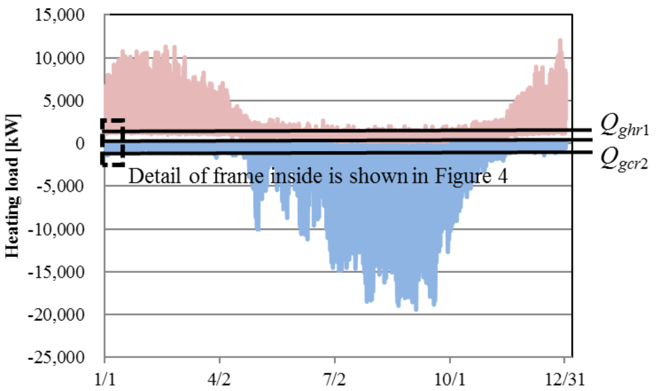


Figure 3 Example of hourly heating and cooling load variation in the complex building

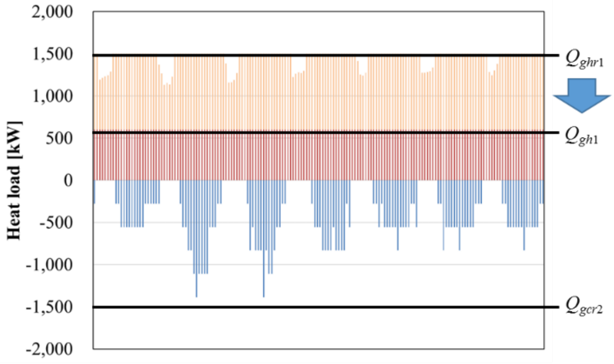


Figure 4 Example of hourly heating and cooling load for GSHP1 and GSHP2

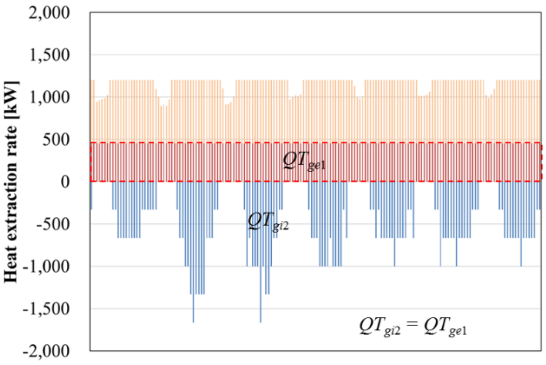


Figure 5 Example of hourly heat extraction from GSHP1 and heat injection from GSHP2

In addition, the total heating load from GSHPs $\sum Q_{g2\mathrm{h}}$ and the total cooling load from GSHPs $\sum Q_{g2\mathrm{c}}$ in response to an arbitrarily set total GHEX length L_p were maximized using the optimization method (part (B) in Figure 2). The objective function, evaluation variables, and constraints are shown below.

Objective function: $\left|\sum Q_{g2\mathrm{h}}\right| + \left|\sum Q_{g2\mathrm{c}}\right|$
Evaluation variables: Q_{pemax}, Q_{pimax}
Constraints:
(A) $0 \leq Q_{pemaxv} \leq Q_{pemax}$
(B) $0 \leq Q_{pimaxv} \leq Q_{pimax}$
(C) $\dfrac{9}{10} \leq \dfrac{\left|\sum \sum_{i=1}^{n} Q_{g1e,i}\right|}{\left|\sum \sum_{i=1}^{n} Q_{g1i,i}\right|} \leq \dfrac{10}{9}$

Here, a genetic algorithm (GA) was applied for the optimization method because the objective function lacked smoothness and was nonlinear according to the evaluation variables [4]. The values $Q_{g2\mathrm{h}}$ and $Q_{g2\mathrm{c}}$ in the objective function were expressed as follows:

$$Q_{g2h} = \sum_{i=1}^{n} Q_{g2h,i} - Q_{pse}/[(COP_{have} - 1)/COP_{have}] \tag{3}$$

$$Q_{g2c} = \sum_{i=1}^{n} Q_{g2c,i} - Q_{psi}/[(COP_{cave} + 1)/COP_{cave}] \tag{4}$$

The values COP_{have} and COP_{cave} are the average COPs of whole GSHPs for heating and cooling, respectively. Moreover, the values Q_{pse} and Q_{psi} can be obtained by the following equations:

$$\begin{aligned} &Q_{pse} = 0 \quad \left(\sum_{i=1}^{n} Q_{g1,i} \leq Q_{pemaxv}\right) \\ &Q_{pse} = \sum_{i=1}^{n} Q_{g1,i} - Q_{pemaxv} \quad \left(\sum_{i=1}^{n} Q_{g1,i} > Q_{pemaxv}\right) \end{aligned} \tag{5}$$

$$\begin{aligned} &Q_{psi} = 0 \quad \left(\sum_{i=1}^{n} Q_{g1,i} \geq -Q_{pimaxv}\right) \\ &Q_{psi} = \sum_{i=1}^{n} Q_{g1,i} + Q_{pemaxv} \quad \left(\sum_{i=1}^{n} Q_{g1,i} < -Q_{pemaxv}\right) \end{aligned} \tag{6}$$

In addition, Q_{pemax} and Q_{pimax} indicate the maximum heat extraction and injection of the GHEXs, respectively. The values are calculated by the following equations:

$$Q_{pemax} = q'_{pe} L_p \left(T_{s0} - T_{pmmin}\right)/1000 \tag{7}$$

$$Q_{gimax} = q'_{pi} L_p \left(T_{pmmax} - T_{s0}\right)/1000 \tag{8}$$

The temperatures T_{pmmin} and T_{pmmax} are the minimum and maximum temperature of the heat carrier fluid in the GHEXs, respectively. The temperature T_{pm} was regarded as the mean temperature of T_{pin} and T_{pout} in Figure 1. In addition, if it was assumed that $T_{pin} = T_{1out}$ and $T_{pout} = T_{1in}$ in Figure1, T_{pmmin} and T_{pmmax} could be derived by using the calculated conditions T_{1inmax} and T_{1inmin}.

$$T_{pmmin} = T_{1inmin} - \Delta T_1/2 \tag{9}$$

$$T_{pmmax} = T_{1inmax} + \Delta T_1/2 \tag{10}$$

Here, ΔT_1 is the temperature difference between T1in and T1out.

The values q'_{pe} and q'_{pi} were the heat extraction rate and heat injection rate per the GHEX length, respectively, and the temperature difference between T_{pm} and T_{s0}. The values q'_{pe} and q'_{pi} are estimated by using the following function expressions:

$$q'_{pe} = f(t_c, \lambda_e, t_{ce}/t_{ci}) \tag{11}$$

$$q'_{pi} = f(t_c, \lambda_e, t_{ce}/t_{ci}) \tag{12}$$

The time t_c was the repeat cycle span of the GHEXs heat extraction and injection, while the time t_{ce} and t_{ci} were the span of the GHEXs heat extraction and injection, respectively. The detail of t_c, t_{ce}, and t_{ci} are explained in Figure 8. The function expressions were the approximate equations that were previously calculated using the simulation result. The simulation was performed using the design and performance prediction tool for the GSHP system [5]–[7] by assuming a simple repeat cycle of the GHEXs heat extraction and injection. Examples of q'_{pe} and q'_{pi} according to t_c, λ_s, and t_{ce} / t_{ci} obtained by the function expressions are shown in Figure 6.

To estimate q'_{pe} and q'_{pi} using equation (11) and equation (12), respectively, the repeat cycle of the GHEXs heat extraction and injection was simplified. An example of the simplified repeat cycle of the GHEXs heat extraction and injection was shown. Figure 7 shows the hourly variation of the GHEXs heat extraction rate Q_p. The value Q_p is equal to $\sum_{i=1}^{n} Q_{g1,i}$. For example, Q_p in Figure 7 is the sum of $Q_{g1e,1}(\leq Q_{g2hmax,1})$ and $Q_{g1i,2}$ in Figure 5. Then, the hourly variation of Q_p in Figure 7 is translated to the hourly variation of Q_p in Figure 8, and the times t_c, t_{ce}, and t_{ci} are shown in Figure 8.

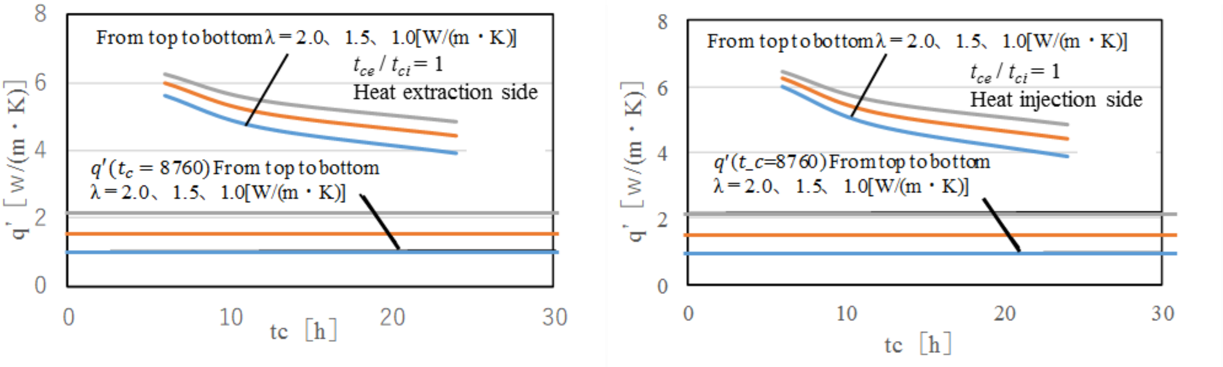


Figure 6 Examples of q'_{pe} and q'_{pi} according to t_c, λ_s, and t_{ce} / t_{ci} obtained by the function expressions

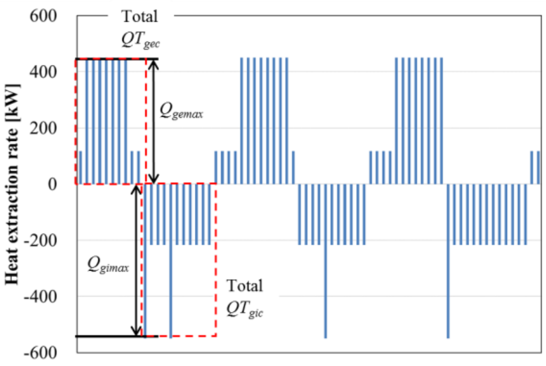


Figure 7 Example of hourly variation of Q_p

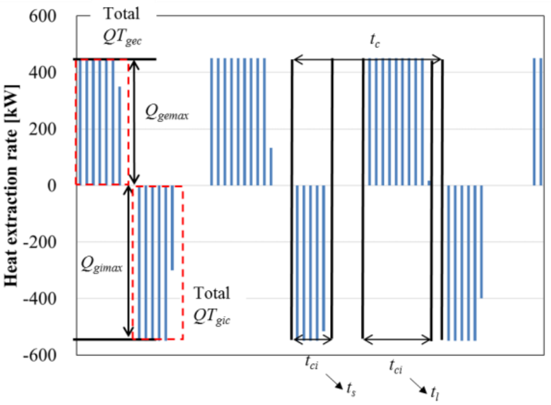


Figure 8 Example of translating hourly variation of Q_p

3. Feasibility study of installing the HR-GSHP system using optimum design method

Assuming that the HR-GSHP system was installed in a large-scale complex building, which required both heating and cooling at the same time throughout the year, the hourly heating and cooling loads of each GSHP unit was determined using the optimum design method. It was also assumed that a conventional GSHP system of the same length of GHEX was installed the building.

Figure 9 shows the concept diagram of the installed HR-GSHP system, and Table 1 shows the calculated conditions. The applied GHEX borehole had single U-tube, and the total length of the GHEX was set at 7,200 m (100 m × 72 boreholes). In addition, the general underground temperature at a moderate climate area in Japan such as Tokyo and the general soil conditions were given.

The resulting hourly variations of the heat load for the HR-GSHP system and the conventional GSHP system are shown in Figure10. The HR-GSHP system could cover 5,442 MWh of the heating load and 3,955 MWh of the cooling load. In addition, the total of heating and cooling load was 9,387 MWh, which occupies 21% of the total heat load. On the other hand, the conventional GSHP could cover 1,303 MWh of the heating load and 883 MWh of the cooling load. Therefore, the HR-GSHP could cover approximately 4.3 times the heat load of the conventional GSHP system.

In addition, the simulation of annual HR-GSHP system operation was performed using the design and performance prediction tool for the GSHP system [5]–[7]. The hourly heat load, shown in Figure 10, was given in the simulation. The hourly variations of T_{1in} for the HR-GSHP system and the conventional GSHP system are shown in Figure 11. The annual heat loads and average COPs for the HR-GSHP system and the conventional GSHP system are also demonstrated in Figure 12. The variation of T_{1in} for the HR-GSHP system was smaller than the variation of T_{1in} for the conventional GSHP system. This variation of T_{1in} yielded the additional increase of average COPs for the HR-GSHP system compared to the conventional GSHP system. The average COPs for the HR-GSHP system were 4.6 for heating and 10.3 for cooling. On the other hand, the average COPs for the conventional GSHP system were 4.1 for heating and 8.0 for cooling. Therefore, the HR-GSHP system was advantageous in not only the amount of heat load that could be covered but also the COP compared to the conventional GSHP system.

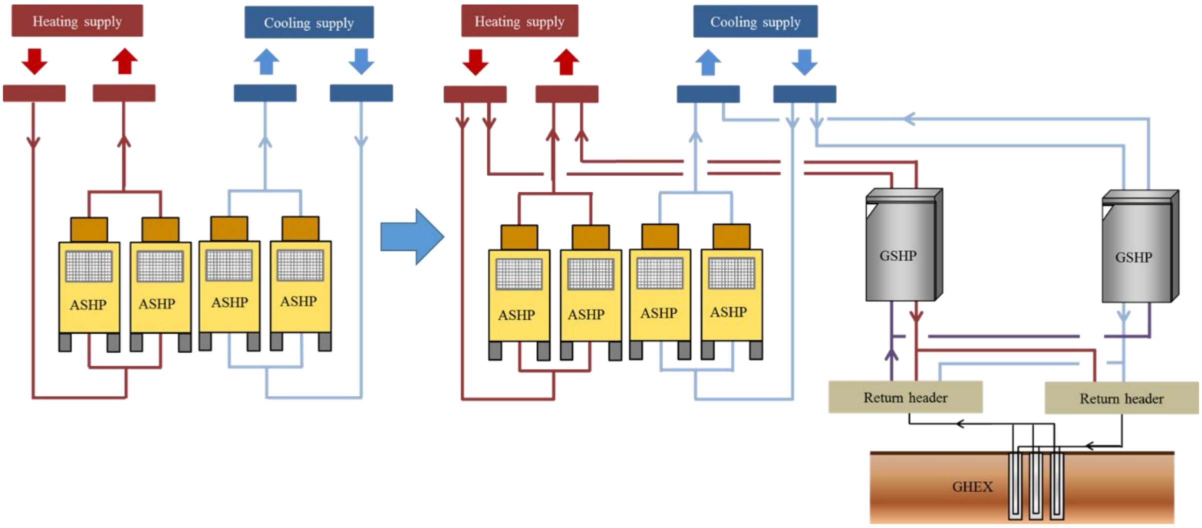


Figure 9 Concept diagram of installing the HR-GSHP system in a large-scale complex building

Table 1 Calculated condition

		HR-GSHP System	GSHP system
Heat pump	Heating capacity	2000 kW	300 kW
	Heating rated power consumption	500 kWh	75 kWh
	Cooling capacity	1200 kW	200 kW
	Cooling rated power consumption	240 kWh	40 kWh
	Supply water temperature of a secondary side(summer)	10 °C	10 °C
	Supply water temperature of a secondary side(winter)	40 °C	40 °C
Circulation pump	Rated flow volume of a primary pump	5000 L/min	1800 L/min
	Power consumption of a primary pump	15 kWh	5 kWh
	Rated flow volume of a secondary pump	5000 L/min	1800 L/min
	Power consumption of a secondary pump	15 kWh	5 kWh

Soil condition	Soil density	1500 kg/m^3
	Underground temperature	16.5 °C
	Soil specific heat	1.5 kJ/(kg·K)
	Soil effective thermal conductivity	1.8 W/(m·K)
Heat exchanger		Borehole single U-tube
	Inside diameter(single U-tube)	0.025 m
	Outside diameter(single U-tube)	0.032 m
	Borehole diameter	0.12 m
	Grout thermal conductivity	1.8 W/(m·K)
	Length	72*100 m

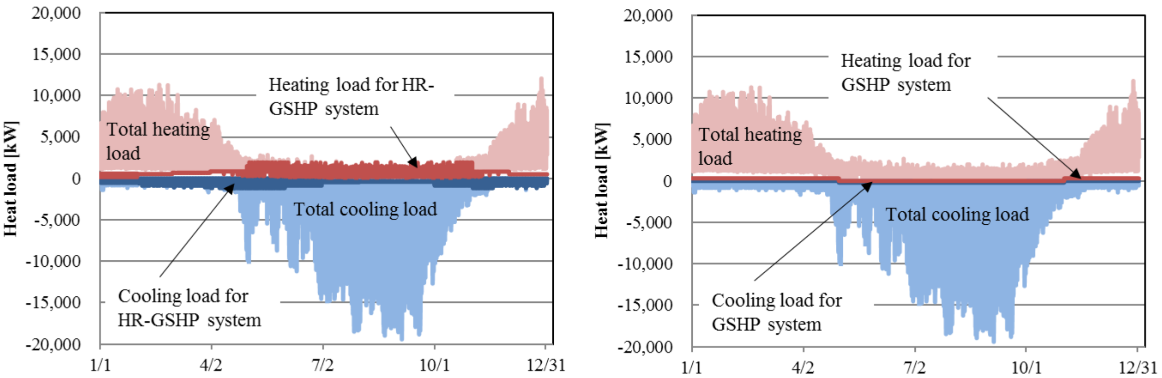


Figure 10 Hourly variations of heat load for the HR-GSHP system (left) and the conventional GSHP system (right)

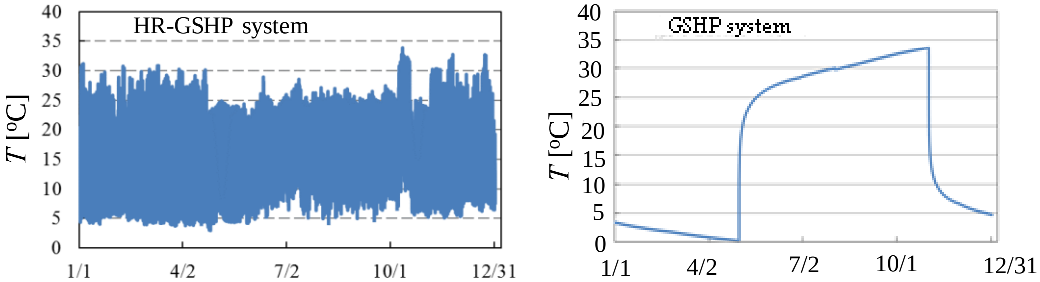


Figure 11 Hourly variations of T_{1in} in the HR-GSHP system (left) and the conventional GSHP system (right)

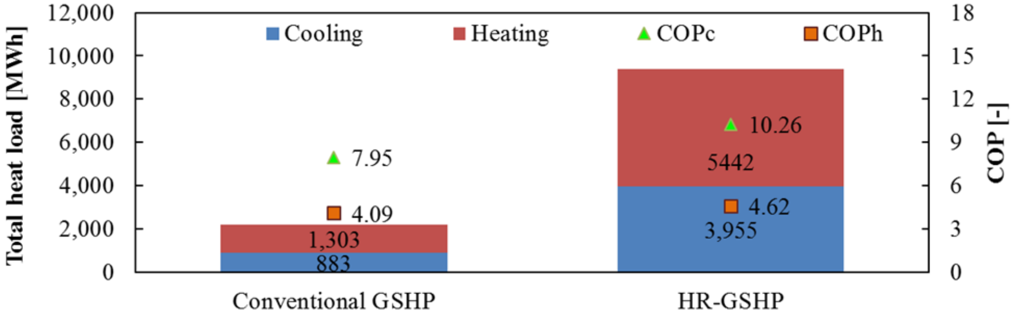


Figure 12 Annual heat loads and average COPs for the HR-GSHP system and the conventional GSHP system

4. Conclusion

1) An optimum design method for the HR-GSHP system was introduced. By applying the proposed design method, the total heating and cooling loads of each GSHP unit in the HR-GSHP system were maximized in response to an arbitrarily set GHEX total length.

2) Assuming that an HR-GSHP system with a 7,200-m total GHEX borehole length is installed in a large scale complex building, which requires both heating and cooling at the same time throughout the year, the hourly heating and cooling loads of each GSHP unit were determined using the optimum design method. The results

showed that the HR-GSHP could cover approximately 4.3 times of the heat load compared to a conventional GSHP system.
3) Simulation of annual HR-GSHP system operation was performed using the design and performance prediction tool for the GSHP system. The hourly heat load determined by the optimum design method was given in the simulation. The average COPs for the HR-GSHP system were 4.6 for heating and 10.3 for cooling. Therefore, the HR-GSHP system was advantageous in not only the amount of heat load that could be covered but also the COP compared to a conventional GSHP system.

Acknowledgements

This study is based on results obtained from the project “Renewable energy heat utilization technology development,” commissioned by the Japan national agency New Energy and Industrial Technology Development Organization (NEDO).

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NOMENCLATURE

L: Length [m]; Q: Heat load, heat extraction [kW]; q': Heat extraction rate per length and temperature difference [W/m/K]; T: Temperature [^{o}C]; t: Time [h]; λ: Effective thermal conductivity [W/m/K]

Subscript abbreviations

ave: Average; *c*: Cooling operation in cycle; *ce*: Heat extraction in cycle; *ci*: Heat injection in cycle; *g*1: Primary side of GSHP; *g*1*e*: Heat extraction in the primary side of GHSP; *g*1*i*: Heat injection in the primary side of GHSP; *g*2: Secondary side of GSHP; *g*2*c*: Cooling operation in the secondary side of GSHP; *g*2*h*: Heating operation in the secondary side of GSHP; *h*: Heating operation; *max*: Maximum; *min*: Minimum; *p*: Ground heat exchanger; *pe*: Heat extraction at ground heat exchanger from the ground; *pi*: Heat injection at ground heat exchanger to the ground; *pin*: Inlet of ground heat exchanger; *pm*: Mean; *pout*: Outlet of ground heat exchanger; *s*: soil; *s*0: Soil initial; 1: Primary side; 1*in*: Inlet in the primary side; 1*out*: Outlet in the primary side