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THERMAL PERFORMANCES OF VERTICAL GROUND HEAT EXCHANGERS IN DIFFERENT CONDITIONS

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Abstract

This study investigates thermal performance of vertical ground heat exchangers (GHEs) with different inlet water temperatures and borehole depths. The performances of three types of GHEs namely U-tube, double-tube and multi-tube GHEs are evaluated by numerical method using a CFD code. The simulation results show that heat exchange rates per unit borehole depth increase in the cooling mode and decrease in the heating mode of 3.4 W/m for U-tube, 5.7 W/m for double-tube, and 3.3 W/m for multi-tube with increasing of 1 ^{o}C of the temperature difference between inlet water and ground. In addition, increasing the depth of vertical GHE lowers the heat exchange with the ground. By comparing with 20 m depth, the heat exchange rates per unit borehole depth lower of 32.5 % in 60 m depth, 47.9 % in 100 m depth for U-tube GHE and 29 % in 60 m depth, 42.7 % in 100 m depth for multi-tube GHE, respectively.

Keywords: Thermal performance, Different inlet water temperatures, Different borehole depths.

1. Introduction

Recently, using environmentally benign energy source such as geothermal energy provides a challenge to make it technologically attractive and cost effective in applying for space heating and cooling in residential and commercial buildings. The geothermal energy source is categorized based on ASHRAE [1] for using in high-temperature electric power production; > 150 ^{o}C, intermediate and low–temperature direct-use applications; < 150 ^{o}C, and Ground-source heat pump (GSHP) system applications; generally < 32 ^{o}C. The GSHP system has been widely used in engineering applications for space heating and cooling.

Nomenclatures

c_p	Specific heat, J/kg K
K	Thermal conductivity, W/m K
L	Borehole depth, m
$\dot{m}$	Mass flow rate, l/min
Q	Heat exchange rate, W
$\overline{Q}$	Heat exchange rate per unit length, W/m
T	Temperature, ^{o}C
x	Leg spacing, m
z	Depth, m
Greek Symbols	
ΔT	Temperature difference, ^{o}C
ρ	Density, kg/m^3
Subscripts	
i	inner
O	outer
PE	Polyethylene
PVC	Polyvinyl chloride

Several factors such as local conditions, ground heat exchanger (GHE) parameters, and operation conditions contribute significantly to the thermal performance of the GHE that used in the GSHP system to exchange heat with the ground. Analyzing the GHE performance in those conditions is needed to provide an accurate prediction of the performance in the GSHP system design. A number of studies have investigated the GHE performance in various backfilled materials, concrete pile foundations, and configuration shapes [2-5]. Experimental study of thermal performance of three types of GHEs including U-tube, double-tube, and multi-tube types installed in a steel pile foundation with 20 m of depth had been carried out [6]. This study reported the heat exchange rates of the GHEs in 24 hours of continuous operation with flow rates of 2, 4, and 8 l/min and the effect of increasing the flow rate. The heat exchange rates increased significantly for flow rate increases from 2 to 4 l/min, but only slightly changed from 4 to 8 l/min. The performance of the GHEs has been also investigated in different operation modes [7]. Operating the GHEs with different operation mode shows the different characteristic in their heat exchange rates. The off-time period in the discontinuous operation and extracting heat from the ground in the heating process in the alternative operation mode contributed significantly to the increasing the heat exchange rate.

Esen et al. [8] investigated temperature distributions in the borehole for different boreholes of 30, 60, and 90 m. Furthermore, heat exchange rate of the GHE with considering the effect of running time, shank spacing, depth of borehole, velocity in the pipe, thermal conductivity of grout, inlet temperature and soil type was evaluated by Jun et al. [9]. Variations of inlet water temperature and borehole depth are important factors to the thermal performance of the GHE. Different conditions of ambient climate, space cooling and heating loads over the year will yield a variation of the inlet water temperature of the GHEs. The thermal performances for single U-tube and double U-tubes GHEs for different inlet water temperature in cooling and heating modes have been reported by Li et al. [2]. The performance of single U-tube and double U-tubes increased with the rise of inlet temperature in the cooling mode. The performance of double U-tubes decreased with the rise of inlet temperature in heating mode. Jun et al. [9] also investigated the thermal performance of the U-tube with different inlet water temperature by using line source theory (LST) and cylindrical source theory (CST). The thermal performance of the GHE increased in the cooling mode and decreased in the heating mode with increasing its inlet water temperature. In addition, heat exchange rate of the GHE is affected by the depth of borehole. Heat exchange rates of the U-tube with different borehole depths from 30 m to 100 m have been investigated by Jun et al. [9]. Increasing the borehole depth leads to the decreasing the heat exchange rate. The heat transfer rates of GHEs for a set of five buried depth (60, 70, 80, 90, and 100 m) under heat rejection and extraction modes were also investigated by Chen et al. [10].

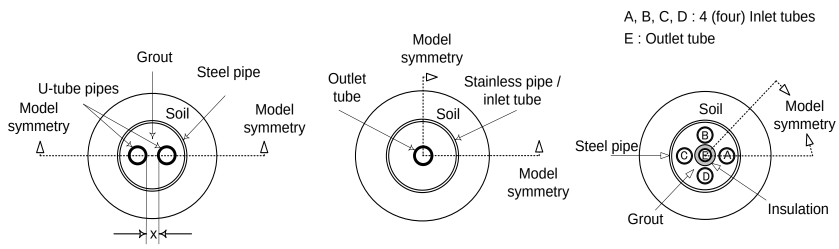
In this work, the performance of the GHEs namely U-tube, double-tube and multi-tube GHEs which were operated with different inlet water temperatures and various borehole depths were investigated. The different inlet water temperatures are set of 30, 27, 25, and 20 ^{o}C in the cooling mode and of 15, 10, 8, and 5 ^{o}C in the heating mode. The various borehole depths are 20, 60, and 100 m.

2. Numerical Method

2.1. GHE models

Three-dimensional unsteady-state models for several types of GHEs were built and simulated by using a commercial CFD code, FLUENT. Steel pipes, which are used as foundation pile for houses, were buried in the ground and used as boreholes for the GHEs. The U-tube and multi-tube were inserted in the steel pile, and the gaps between the steel pile and tubes were grouted with silica-sand. In the double-tube, a stainless steel pipe is used as the inlet tube of the GHE and a small diameter polyvinyl chloride pipe is installed inside the stainless steel pipe as the outlet tube.

The ground around the GHEs is modeled of 5 m in radius. Figure 1 shows the horizontal cross-sections of three types of GHE models including U-tube, double-tube, and multi-tube. The models of simulation are taken of the symmetry of the heat transfer with a vertical plane of borehole as shown in this figure. Three-dimensional hybrid mesh generation was applied in the GHE models. Numerical mesh in a cross-section of the borehole and ground is shown in Fig. 2. Adaptive time stepping method was used in the simulation. All the related geometric parameters and material thermal properties for the GHEs are listed in Table 1.



(a) U-tube **(b) Double-tube** **(c) Multi-tube**

Fig. 1. The horizontal cross-sections of the three types of GHE model.

Table 1. Related geometric parameters and material thermal properties of the GHEs.

Parameters	Value	Unit
Inlet and outlet pipes of the U-tube (material: Polyethylene)		
Outer diameter, d_o	0.033	m
Inner diameter, d_i	0.026	m
Thermal conductivity, k_{PE}	0.35	W/(m K)
Inlet pipe / pile foundation of the double-tube (material: Stainless Steel)		
Outer diameter, d_o	0.1398	m
Inner diameter, d_i	0.1298	m
Thermal conductivity, $k_{Stainless}$	13.8	W/(m K)
Outlet pipe of the double-tube (material: Polyvinyl chloride)		
Outer diameter, d_o	0.048	m
Inner diameter, d_i	0.04	m
Thermal conductivity, k_{PVC}	0.15	W/(m K)
Inlet pipes of the multi-tube (material: Polyvinyl chloride)		
Outer diameter, d_o	0.025	m
Inner diameter, d_i	0.02	m
Thermal conductivity, k_{PVC}	0.15	W/(m K)
Outlet pipe of the multi-tube (material: Polyvinyl chloride)		
Outer diameter, d_o	0.02	m
Inner diameter, d_i	0.016	m
Thermal conductivity, k_{PVC}	0.15	W/(m K)
Pile foundation of the U-tube and multi-tube (material: Steel)		
Outer diameter, d_o	0.1398	m
Inner diameter, d_i	0.1298	m
Thermal conductivity, k_{Steel}	54	W/(m K)
Grout (material: Silica sand)		
Thermal conductivity, k_{grout}	1.4	W/(m K)

2.2. GHE models validation

Three sets of grid for GHEs, including U-tube, double-tube, and multi-tube, are generated using gambit to perform grid independence test. The total cell number of the coarse grid 1, grid 2, and the finest grid 3 are shown in Table 2. The heat exchange rates for the sets of grid after 24 h continuous operation are shown in

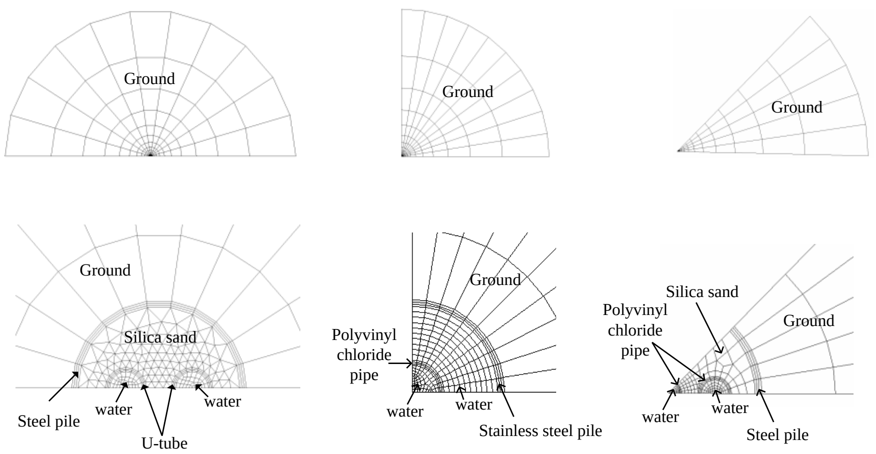
Table 3. The heat exchange rates of the grid 2 of U-tube, double-tube, and multi-tube show the same results as the finest grid 3. Therefore, the grid 2 was employed in simulation of this study and its cross-sectional mesh geometry is shown in the Fig. 2.

Table 2. Total cell number of the grid.

GHE type	Grid 1	Grid 2	Grid 3
U-tube	87246	197581	438346
Double-tube	73800	145530	332880
Multi-tube	88652	107849	226349

Table 3. Heat exchange rates for the sets of grid after 24 h continuous operation.

	Heat exchange rate (W/m)		
	Grid 1	**Grid 2**	**Grid 3**
U-tube	24.75	24.17	24.06
Double-tube	35.7	35.3	35.39
Multi-tube	23.73	23.6	23.5



(a) U-tube **(b) Double-tube** **(c) Multi-tube**

Fig. 2. Numerical mesh in a cross-section of the borehole and ground.

The comparison of simulation results of the heat exchange rate of the GHE models with experimental results shows the reasonable agreement as discussed in our published paper [7]. Small differences between the numerical and experimental were caused by discrepancies of several uncertain factors such as local ground thermal properties, boundary and initial conditions, etc. The deviation of heat exchange rate between the experimental and simulated results is in the range of 2-18 % for U-tube, 3-13 % for double-tube, and 11-17 % for multi tube.

2.3. Boundary conditions

The ground profiles around the borehole consist of Clay, sand, and Sandy-clay. This ground profiles are typical for Saga city, Japan where experimental study was carried out. The ground properties can be estimated using the values for similar ground profiles in simulation.

The thermal characteristic parameters of the ground are:

- Clay (ρ= 1700 kg/m^3, k = 1.2 W/m K, c_p = 1800 J/kg K)
- Sand (ρ= 1510 kg/m^3, k = 1.1 W/m K, c_p = 1100 J/kg K)
- Sandy-clay (ρ= 1960 kg/m^3, k = 2.1 W/m K, c_p = 1200 J/kg K)

A constant and uniform temperature was applied to the top and bottom surfaces of the model. Variation of ground temperature near the surface due to ambient climate effect is negligible. Uniform initial ground temperature is assumed to be equal to the undisturbed ground temperature and constant of 17.7 ^{o}C. The flow rate of circulated water was set to 4 l/min.

3. Heat Transfer Model

Three-dimensional unsteady-state model used in simulation is:

$$k\left(\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}\right)=\rho c\frac{\partial T}{\partial t} \tag{1}$$

Temperature variation distribution of circulated water is simulated and the thermal performances of the GHEs were investigated by calculating their heat exchange rates through the water flow. The heat exchange rate is calculated by the following equation,

$$Q=\dot{m}c_p\,\Delta T \tag{2}$$

The heat exchange rate per unit borehole depth is defined as the following equation and it is used to express the performance of each GHEs.

$$\overline{Q}=Q/L \tag{3}$$

where L is the depth of each GHE.

4. Simulation Results and Discussion

4.1. GHE performance in different inlet water temperature

Temperature of the inlet water temperature contributes to the thermal performance of the GHE. Different conditions of ambient climate, space cooling and heating loads over the year will yield a variation of the inlet water temperature of the GHEs. To investigate the GHE performance in different inlet water temperature, the three types of GHE models (U-tube, double-tube, and multi-tube) with boreholes at a depth of 20 m were simulated in 24 h continuous operation with different inlet water temperatures of 30, 27, 25, and 20 ^{o}C in the cooling mode and of 15, 10, 8, and 5 ^{o}C in the heating mode. In this simulation, the ground profiles around the borehole consist of clay from ground level to 15 m in depth and sandy-clay from 15 m to 20 m in depth. Simulation results of the heat exchange rates are shown in Fig. 3 and the average heat exchange rates within 24 h operation are presented in Table 4.

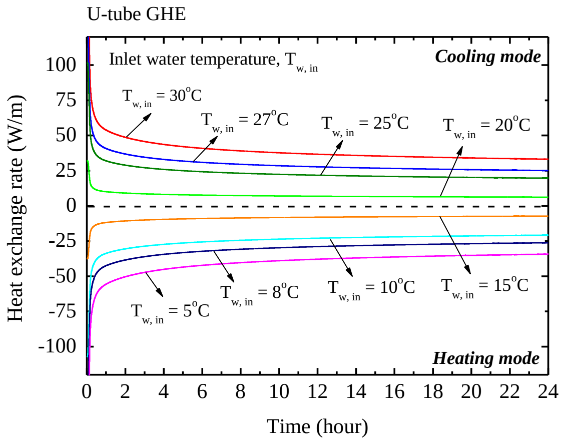
Figure 3(a) shows the heat exchange rates in the cooling and heating modes of the U-tube GHE with different inlet water temperatures. Heat exchange rates of the GHEs increase in the cooling mode and decrease in the heating mode with increasing the temperature difference between inlet water and ground. It shows that high inlet water temperature in the cooling mode and low inlet water temperature in the heating mode provide good heat exchange rate of the GHEs with constant ground temperature. The heat exchange rates of the double-tube and multi-tube GHEs are shown in Figs. 3(b) and 3(c). The heat exchange rates of these GHEs with different inlet water temperatures show similar results with that of the U-tube GHEs. The average value of the heat exchange rates for each GHEs within 24 h operation are shown in Fig. 4. The intersection between cooling and heating modes indicates that no heat is exchanged between circulated water and surrounding ground due to the temperature of inlet water and ground is same. The slope shows the change of the heat exchange rate of each GHEs.

Based on the average value within 24 h operation, the heat exchange rates increase in the cooling mode and decreases in the heating mode of 3.4 W/m for U-tube, 5.7 W/m for double-tube, and 3.3 W/m for multi-tube with increasing of 1 ^{o}C (K) of the temperature difference between inlet water and ground (T_{in}–T_{ground}). These results show that the double-tube GHE provides a better heat exchange rate than the other GHEs. Temperature difference between circulated water and ground surrounding the borehole affects significantly to the heat exchange rate of the GHEs.

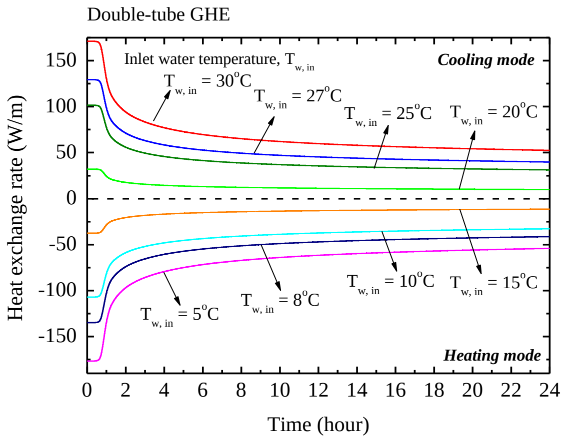
Table 4. Heat exchange rates after operating in 24 h for the different inlet water temperature.

U-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} ^{o}C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground, (T_{in}–T_{ground}) ^{o}C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, ($\overline{Q}_{24h}/L$) (W/m)	41.9	31.7	24.9	7.8	-9.2	-26.3	-33.1	-43.3
Double-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} ^{o}C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground (T_{in}–T_{ground}) ^{o}C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, ($\overline{Q}_{24h}/L$) (W/m)	69.8	52.9	41.5	13.1	-15.3	-43.6	-55	-72
Multi-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} ^{o}C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground (T_{in}–T_{ground}) ^{o}C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, ($\overline{Q}_{24h}/L$) (W/m)	40.6	30.7	24.1	7.6	-8.9	-25.4	-32.1	-42

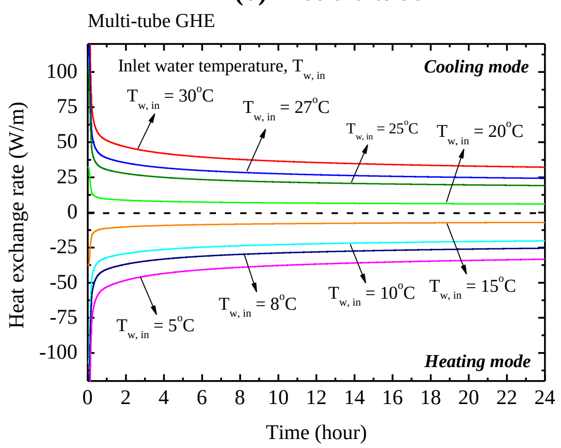
(-) heat is extracted from the ground



(a) U-tube



(b) Double-tube



(c) Multi-tube

Fig. 3. Heat exchange rate of vertical ground heat exchanger with different inlet water temperature.

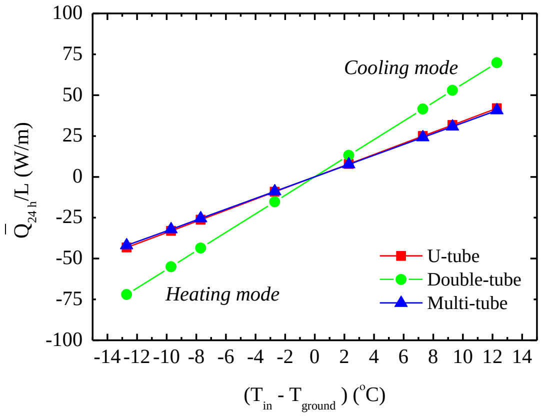


Fig. 4. Average heat exchange rate with temperature difference between inlet water and ground.

Table 4. Heat exchange rates after operating in 24 h for the different inlet water temperature.

U-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} °C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground, $(T_{in}–T_{ground})$ °C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, $(\bar{Q}_{24h}/L)$ (W/m)	41.9	31.7	24.9	7.8	-9.2	-26.3	-33.1	-43.3
Double-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} °C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground $(T_{in}–T_{ground})$ °C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, $(\bar{Q}_{24h}/L)$ (W/m)	69.8	52.9	41.5	13.1	-15.3	-43.6	-55	-72
Multi-tube								
	Cooling mode				***Heating mode***			
Inlet temperature, T_{in} °C	30	27	25	20	15	10	8	5
Temperature difference between inlet water and ground $(T_{in}–T_{ground})$ °C	12.3	9.3	7.3	2.3	-2.7	-7.7	-9.7	-12.7
Average heat exchange rate in 24 h, $(\bar{Q}_{24h}/L)$ (W/m)	40.6	30.7	24.1	7.6	-8.9	-25.4	-32.1	-42

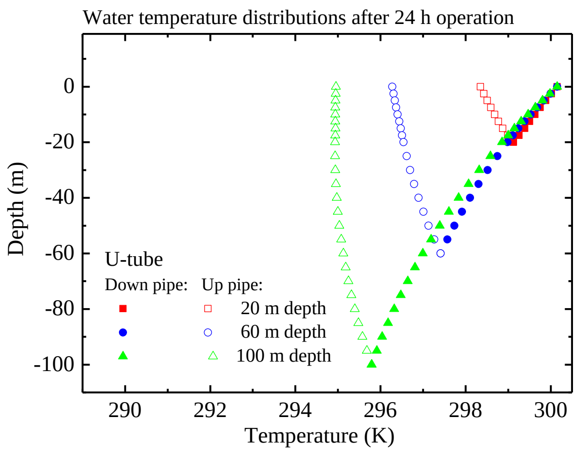
(-) heat is extracted from the ground

4.2. GHE performance in various borehole depths

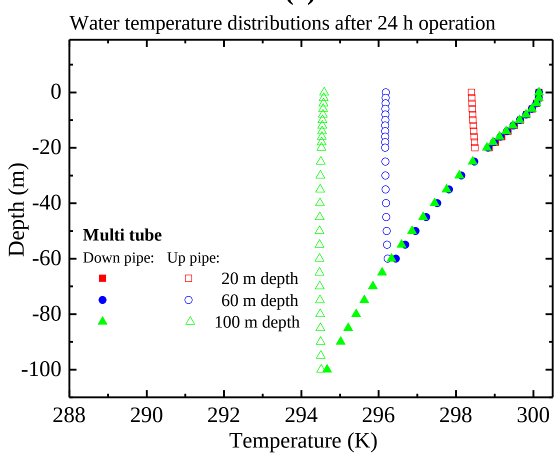
The thermal performances of U-tube and multi-tube GHEs were investigated in 24 h operation with various borehole depths of 20 m, 60 m, and 100 m. Water temperature distributions of the GHEs are also presented. Inlet water temperature was set to be constant of 27 °C. In simulation, the ground profiles around the borehole consist of Clay from ground level to 15 m in depth and below 15 m is

Sand. Regarding to the material and installation costs with increasing borehole depth of the double-tube type in engineering application, the double-tube type was not simulated in this work.

Figure 5 shows the water temperature distributions of the U-tube and multi-tube GHEs. For the both GHEs, the water temperature change between the inlet and outlet does not increase as much as increasing the borehole depth. In the case of U-tube, heat exchange occurs in the inlet and outlet tubes. Therefore, the water temperature changes significantly in the inlet and outlet tubes. However, in the region of 0-45 m of the outlet tube of 100 m borehole depth, the water temperature stays almost constant. In addition, temperature variations of circulated water from the inlet of the U-tube are different in different borehole depth caused by thermal interference of the outlet tube. However, the effect of thermal interference between the tubes in the multi-tube was reduced by insulation the outlet tube.



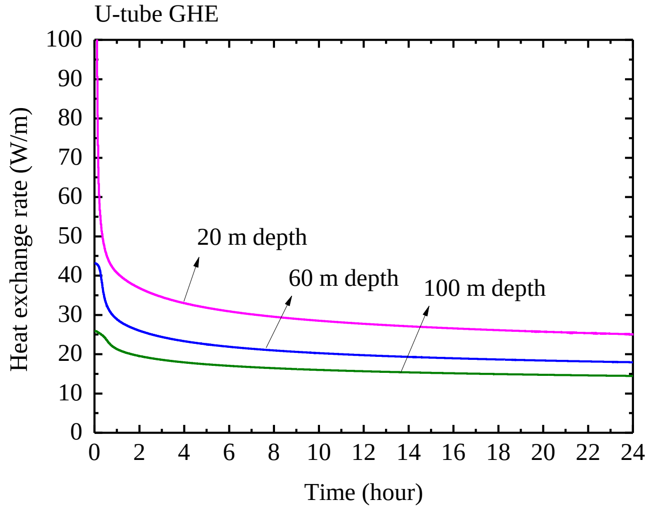
(a) U-tube



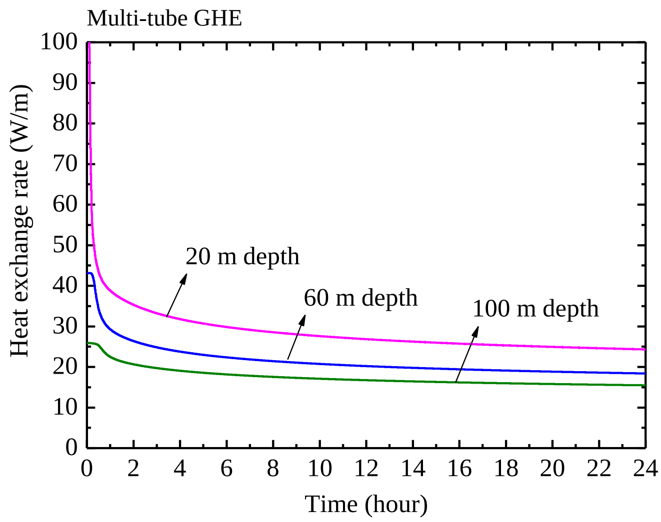
(b) Multi-tube

Fig. 5. Water temperature distribution of GHE with various borehole depths.

The heat exchange rates per unit borehole depth of the U-tube and multi-tube GHEs decrease with increasing the borehole depth as shown in Fig. 6. The average values within 24 h operation of the heat exchange rate with borehole depths of 20 m, 60 m, and 100 m are shown in Fig. 7. By comparing with 20 m depth, the heat exchange rates lower of 32.5 % in 60 m depth, 47.9 % in 100 m depth for U-tube GHE and 29 % in 60 m depth, 42.7 % in 100 m depth for multi-tube GHE, respectively. Increasing the depth lowers temperature difference between circulated water and surrounding ground and then lowers the heat exchange with the ground. In the case of 20 m depth, the heat exchange rate of U-tube is higher than multi-tube and from a certain depth, it becomes worse than the multi-tube when depth increases as shown in Fig. 7. This result is caused by lowering the heat exchange in the outlet tube when the water temperature stays almost constant as explain in Fig. 5(a).



(a) U-tube



(b) Multi-tube

Fig. 6. Heat exchange rate of GHE with various borehole depths.

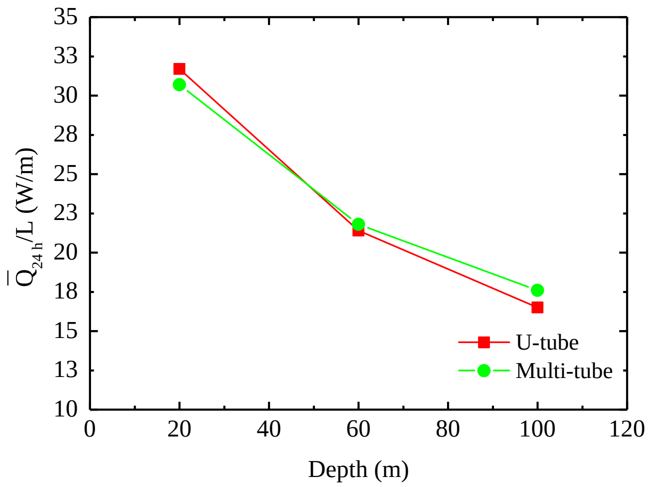


Fig. 7. Average heat exchange rate with various borehole depths.

5. Conclusions

Heat exchange rates of the several types of vertical GHEs were investigated with different inlet water temperatures and various borehole depths. Following conclusions could be drawn from this work:

- Temperature difference between the circulated water and the ground surrounding the borehole affects significantly to the heat exchange rate of the GHEs. The heat exchange rates proportionally increase in the cooling mode and decrease in the heating mode with the temperature difference between inlet water and ground. The variation rates per unit temperature difference are 3.4 W/m for U-tube, 5.7 W/m for double tube, and 3.3 W/m for multi-tube.
- The water temperature change between the inlet and outlet does not increase as much as increasing the borehole depth.
- Increasing the depth lowers temperature difference between circulated water and surrounding ground and then lowers the heat exchange rate. By comparing with 20 m depth, the heat exchange rates per unit borehole depth lower of 32.5 % in 60 m depth, 47.9 % in 100 m depth for U-tube GHE and 29 % in 60 m depth, 42.7 % in 100 m depth for multi-tube GHE, respectively.

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