NUMERICAL SIMULATION OF VERTICAL GROUND HEAT EXCHANGERS FOR GROUND SOURCE HEAT PUMPS

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Abstract: This paper presents the numerical simulation of several types of vertical ground heat exchangers. The ground heat exchangers (GHEs) such as U-tube, double-tube and multi-tube were simulated using the commercial CFD software FLUENT. Water flows through the heat exchangers and exchanges the heat to the ground. The inlet and outlet water temperatures, flow rate, and heat exchange rate are presented. The heat exchange rates in discontinuous short-time period of operation namely 2 h operation-time and 2 h off-time and continuous operation are investigated and compared with that of the experimental results. Comparing numerical results with experimental results shows that the numerical models are capable to determine the GHE performances. The heat exchange rate in discontinuous operation increased compared with that of in continuous operation. As an example, the heat exchange rate of the discontinuous operation at 22 h increases of 17.1 % for U-tube, 22.5 % for double-tube, and 16.5 % for multi-tube compare with that of the continuous operation at the same time. In addition, heat exchange process in the off-time increases the heat exchange rate of GHEs.

Key Words: vertical ground heat exchanger, numerical simulation, discontinuous and continuous operation, heat exchange rate

1 INTRODUCTION

Ground source heat pump (GSHP) system is used for space heating and cooling in residential and commercial building. Recently, the vertical type of ground heat exchanger (GHE) has widely used in the GSHP system. The GHE is used in this system to exchange heat with the ground. The relatively high initial cost to build this system due to the installation obstruct to the spread of the system in applications particularly in residential building. The research and developments of GSHP technology with the various models and design/simulation techniques was described in a detailed review of models and systems of vertical GSHPs (Yang et al. 2010). Numerical methods are widely used to consider the complex problem due to simplification of these methods. A numerical model for vertical U-tube GHEs based on a transient two-dimensional finite volume method (Yavuzturk et al. 1999), three-dimensional unstructured finite volume numerical model of vertical U-tube GHE (Li and Zheng 2009) were developed. Also, numerical simulation using commercial computational fluid dynamics (CFD) software FLUENT was used in the ground source energy system (Sharqawy et al. 2009, Li et al. 2009 and Gustafsson et al. 2010).The heat transfer behaviour in alternative operation modes (heating and cooling modes) was investigated in short-time scale and the temperature distribution of borehole field was analyzed using finite element method (Cui et al. 2008). Cooling/heating alternative operation modes in short-time scales improve the performance of the GSHP system. The thermal performance of three types of GHEs with different flow rate in 24 h continuous operation was experimentally investigated (Jalaluddin et al. 2011). The performance of the GHEs descends gradually due to the heat buildup in the surrounding ground with operating time in continuous operation. Operation of GHE such as discontinuous and continuous modes brings the different characteristic of their performance.

The present research investigated numerically the thermal performance of three types of GHEs in discontinuous short-time period of operation and continuous operation. Three-dimensional unsteady-state models for the three types of GHEs were built and simulated in the CFD software FLUENT. The thermal performances in discontinuous short-time period of operation and continuous operation are investigated and compared with that of the experimental results. The experimental results were presented in our published paper (Jalaluddin et al. 2010) with recorded data in April 9th 2010 for continuous operation and in April 11th 2010 for discontinuous operation (experimental condition for three types of GHEs were 4 l/min of flow rate and 27 ^{o}C of inlet water temperature). Heat exchange behaviour in the discontinuous short-time operation is also presented.

2 SIMULATION MODEL

2.1 Three Dimension Model

Three-dimensional unsteady-state models were built and simulated to investigate heat exchange from GHEs to the ground around the borehole. The CFD-software FLUENT uses a finite volume method to convert the governing equations to numerically solvable algebraic equations [FUG 2006]. The schematic diagram of the three types of GHE models are shown in Figure 1. The GHE models consist of three types of GHEs namely U-tube, double-tube and multi-tube inserted to the boreholes. The ground around the GHEs is modelled of 5 m in radius and 22.5 m in depth. The models were simulated in the cooling mode for discontinuous short-time period of operation (2 hours operation-time and 2 hours off-time) and for continuous 24 h operation. The flow rate and inlet temperature were set to 4 l/min and 27 ^{o}C (300 K), respectively.

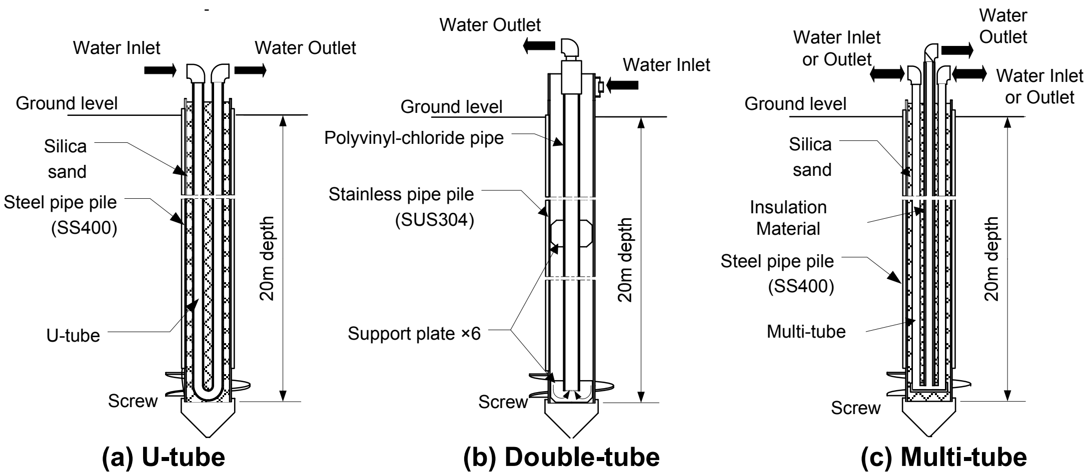
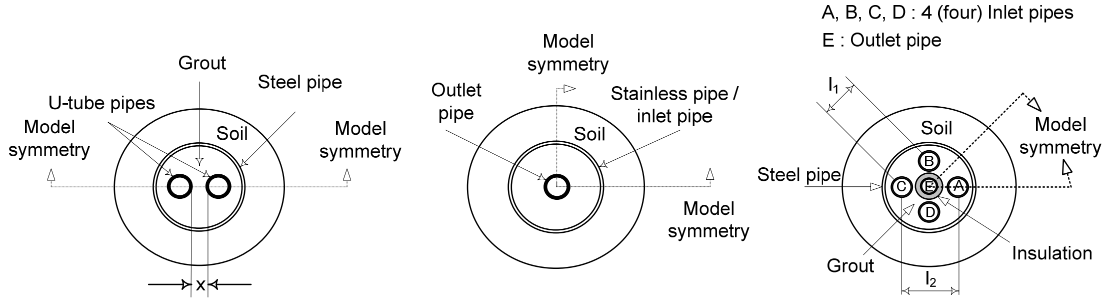


Figure 1: The schematic diagram of the three types of GHEs



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

Figure 2: The schematic diagram of horizontal cross-section of the three types of GHE models

Table 1: Related parameters and properties (Bejan 2003) of the U-tube model

Parameters	Value	Unit
Inlet and outlet pipes (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)
Specific heat, C_P	2300	J/kg K
Density, ρ	920	kg/m^3
Leg spacing, x	0.02	m
Pile foundation (material: Steel)		
Outer diameter, d_o	0.1398	m
Inner diameter, d_i	0.1298	m
Thermal conductivity, k_{Steel}	54	W/(m K)
Specific heat, C_P	465	J/kg K
Density, ρ	7833	kg/m^3
Grout (material: Silica sand)		
Thermal conductivity, k_{grout}	1.4	W/(m K)
Specific heat, C_P	750	J/kg K
Density, ρ	2210	kg/m^3

Table 2: Related parameters and properties (Bejan 2003) of the double-tube model

Parameters	Value	Unit
Inlet pipe / pile foundation (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)
Specific heat, C_P	460	J/kg K
Density, ρ	7817	kg/m^3
Outlet pipe (material: Polyvinyl chloride)		
Outer diameter, d_o	0.048	m
Inner diameter, d_i	0.04	m
Thermal conductivity, k_{pipe}	0.15	W/(m K)
Specific heat, C_P	960	J/kg K
Density, ρ	1380	kg/m^3

Steel pipes buried in the ground in 20 m depth. The steel pipes were used as pile foundation of the GHEs. U-tube and multi-tube were inserted in a steel pile respectively, and the gaps between the steel pile and tubes were backfilled with silica-sand. U-tube is made of polyethylene pipe. Multi-tube consists of a polyvinyl chloride pipe as central pipe and 4 polyvinyl chloride pipes around the central pipe. The central pipe is outlet tube and 4 pipes around the central pipe are inlet tubes. The outlet tube was insulated to protect heat exchange process from the inlet tubes. In the case of double-tube, the stainless steel pipe was used as an inlet tube of GHE and a small diameter polyvinyl chloride pipe was installed inside the stainless steel pipe as an outlet tube. Figure 2 shows the horizontal cross-sectional of the three types of GHE models. The models of simulation are taken of the symmetry of the heat transfer with a vertical plane of borehole as shown in this figure. The related parameters and properties of GHEs are presented in Tables 1 – 3. Ground profile up to 15 m in depth is Clay and below 15 m is Sandy-clay. The properties of ground are presented in Table 4.

Table 3: Related parameters and properties (Bejan 2003) of the multi-tube model

Parameters	Value	Unit
Inlet pipe (material: Polyvinyl chloride)		
Outer diameter, d_o	0.025	m
Inner diameter, d_i	0.02	m
Thermal conductivity, k_{pipe}	0.15	W/(m K)
Specific heat, C_P	960	J/kg K
Density, ρ	1380	kg/m^3
Outlet pipe (material: Polyvinyl chloride)		
Outer diameter, d_o	0.02	m
Inner diameter, d_i	0.016	m
Thermal conductivity, k_{pipe}	0.15	W/(m K)
Specific heat, C_P	960	J/kg K
Density, ρ	1380	kg/m^3
Adjacent pipe distance, l_1	0.05	m
Opposite pipe distance, l_2	0.07	m
Pile foundation (material: Steel)		
Outer diameter, d_o	0.1398	m
Inner diameter, d_i	0.1298	m
Thermal conductivity, k_{Steel}	54	W/(m K)
Specific heat, C_P	465	J/kg K
Density, ρ	7833	kg/m^3
Grout (material: Silica sand)		
Thermal conductivity, k_{grout}	1.4	W/(m K)
Specific heat, C_P	750	J/kg K
Density, ρ	2210	kg/m^3

Table 4: The Properties of Ground (JSME Data book 2009)

Parameters	Value	Unit
Clay (temperature: 293 K: water content: 27.7%)		
Density, ρ	1700	kg/m^3
Specific heat, C_P	1800	J/kg K
Thermal conductivity, k_{Clay}	1.2	W/m K
Sandy-Clay (temperature: 293 K: water content: 21.6%)		
Density, ρ	1960	kg/m^3
Specific heat, C_P	1200	J/kg K
Thermal conductivity, $k_{Sandy\text{-}Clay}$	2.1	W/m K

2.2 Boundary Condition

Constant temperature was applied to the top and bottom surfaces of the model. The initial ground temperature around the three types of GHEs are set to be constant and similar with the initial ground temperature of experimental data as shown in Figure 3. The temperature in the experimental data was recorded before starting the operation. Ground temperatures up to 5 m in depth were strongly influenced by ambient climate. In the simulation model, the ground temperatures below 5 m in depth are assumed to be constant as initial condition.

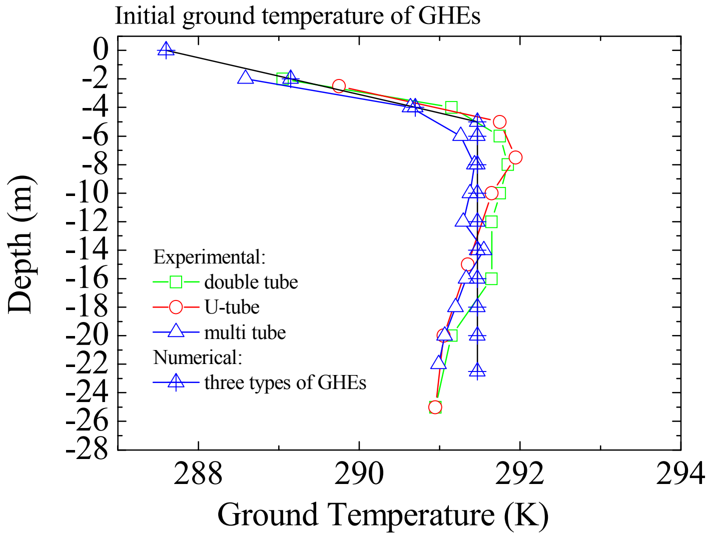
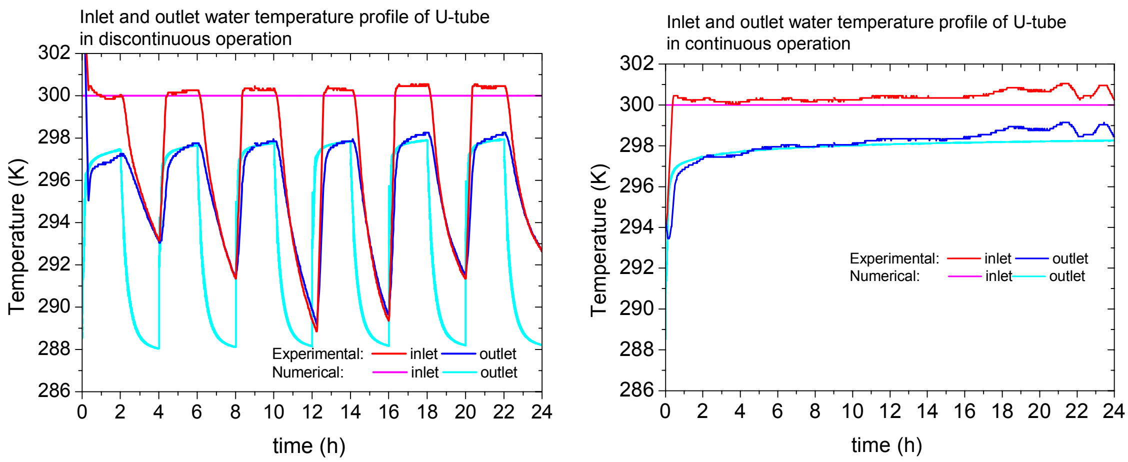


Figure 3: Initial ground temperature profile around the three types of GHEs

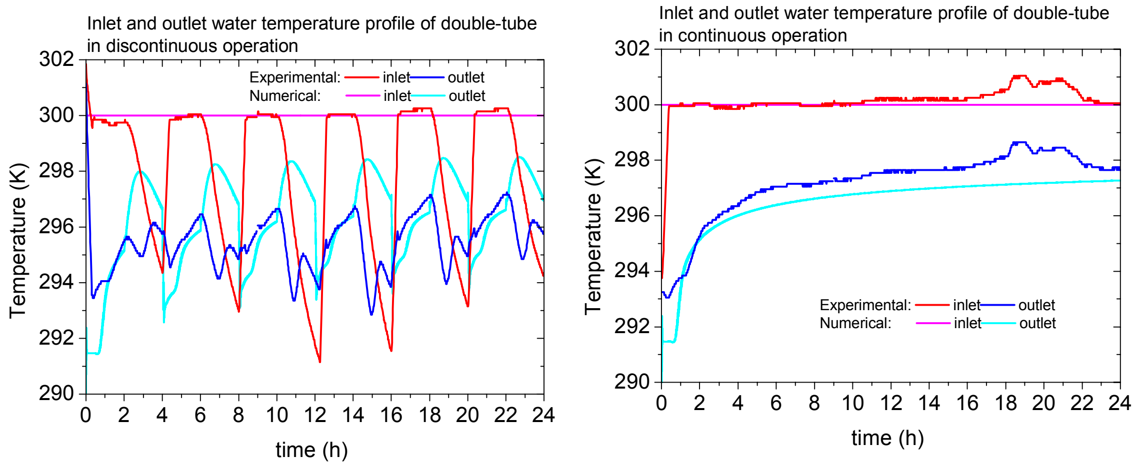
3 RESULTS AND DISCUSSION

3.1 Inlet and Outlet Water Temperature Distributions

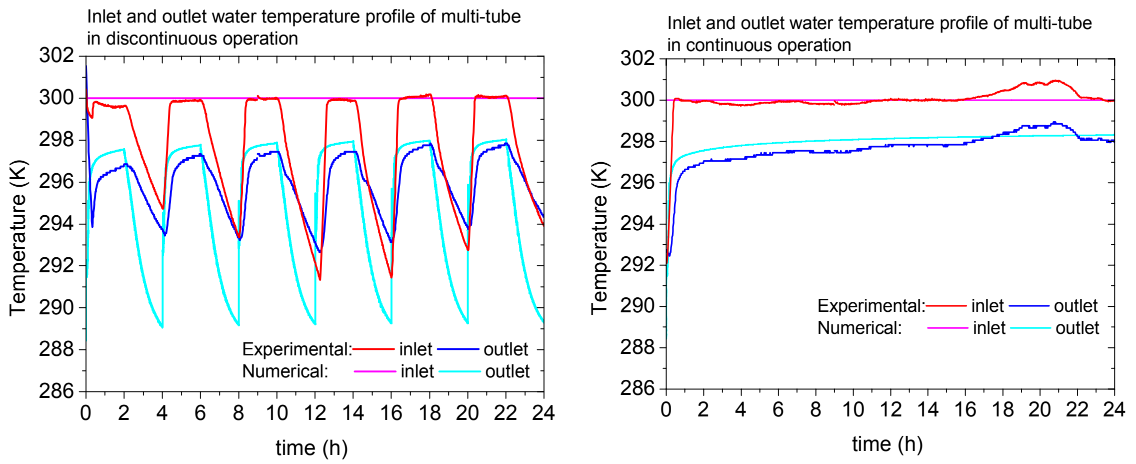
In the simulation model, inlet water temperatures for the three types of GHEs were set to be constant of 27 °C (300 K). The inlet and outlet water temperature distributions in discontinuous and continuous operation are shown in Figure 4 (a) for U-tube, Figure 4 (b) for double-tube, and Figure 4 (c) for multi-tube, respectively. The profiles of inlet and outlet water temperatures of the GHEs tend to be similar with experimental data.



(a) U-tube



(b) Double-tube



(c) Multi-tube

Figure 4: Inlet and outlet water temperature profiles in discontinuous and continuous operation

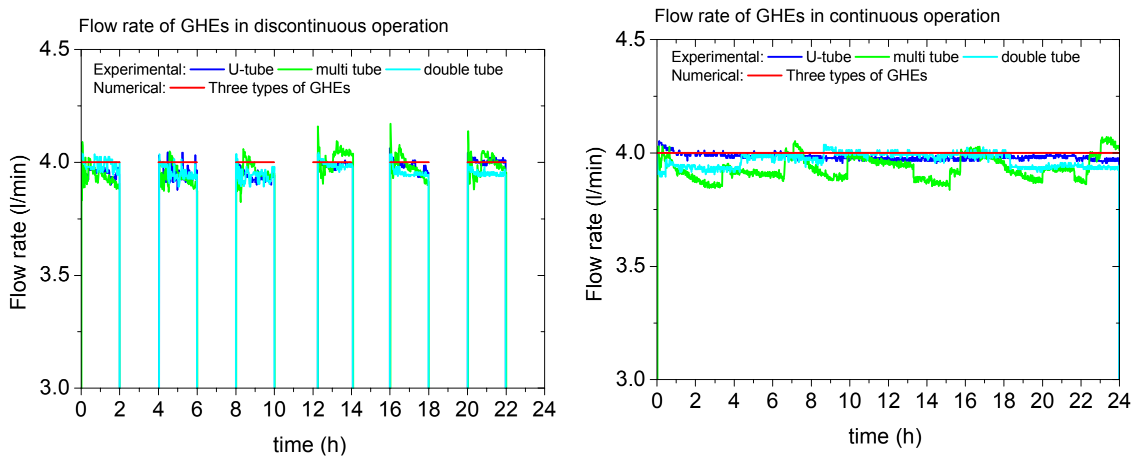


Figure 5: Flow rate variation of ground heat exchangers

In discontinuous operation, inlet water temperature of experimental is higher than 300 K after 2 h operation-time for U-tube and after 16 h operation-time for double-tube. The inlet water temperature is close to 300 K in the multi-tube. The water temperature in off-time were recorded at inlet and outlet points without water flowing. The lowest temperature exist in 12 h operation (it is equal to 03:00 am) as shown in Figure 4 (a), (b), and (c). Those temperatures are influenced by the ground temperature near the surface. In continuous operation, the fluctuation of inlet water temperature in experimental was appeared after 18 h operation.

Flow rates were set to 4 l/min in simulation model as shown in Figure 5. In the off-time of discontinuous operation, flow rate was set to 0 l/min (water flowing was stopped in experimental). Also, the variations of flow rate in experimental for both discontinuous and continuous operation are shown in this figure. In the case of multi-tube type, the flow rate is the total flow rate of four inlet pipes.

3.2 Heat Exchange Rates

To investigate the thermal performances of the GHEs, the heat exchange rate is calculated based on the flow rate and the temperature difference between inlet and outlet of circulated water. The heat exchange rate, Q, is calculated by the following equation;

$$Q = \dot{m} c_p \Delta T \quad (1)$$

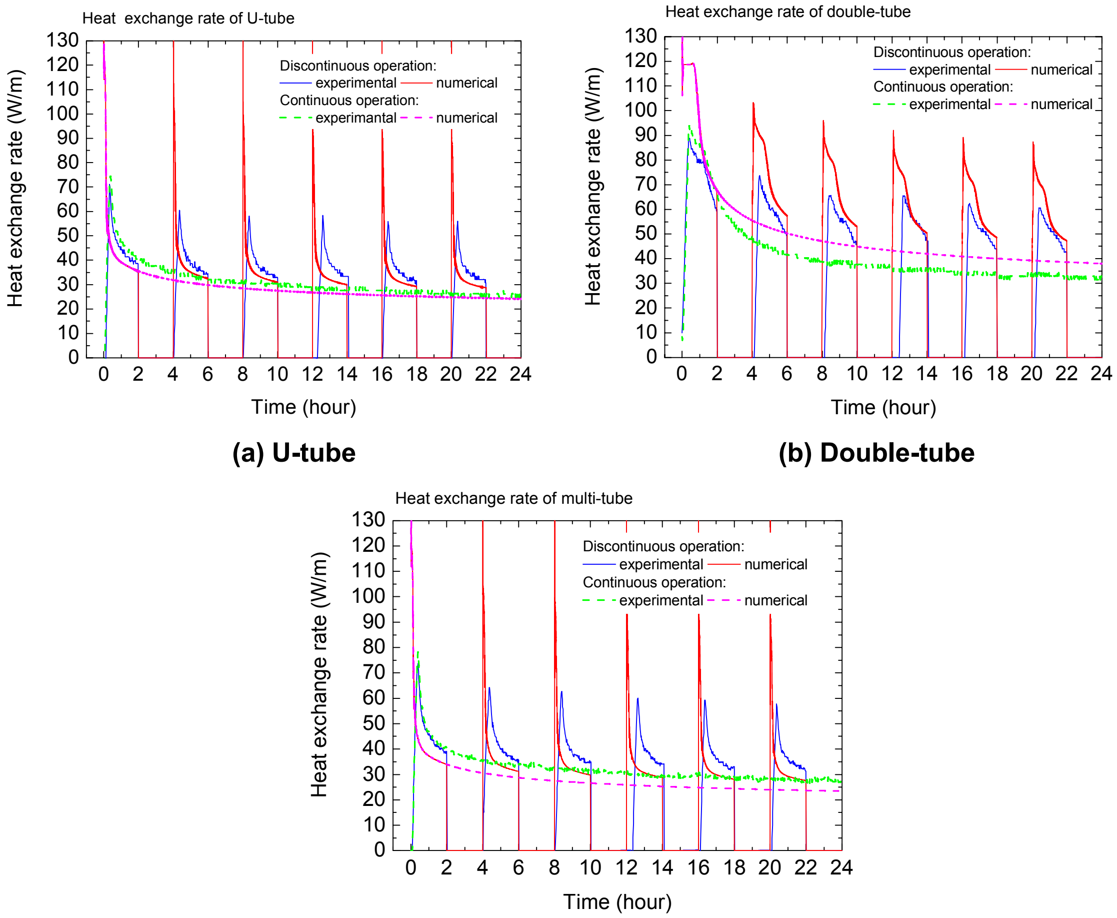
where $\dot{m}$ is flow rate, c_p is specific heat, and ΔT is the temperature difference between inlet and outlet of circulated water. For simplicity, the heat exchange rate per meter of borehole depth, $\overline{Q}$, is defined,

$$\overline{Q} = Q / L \quad (2)$$

where L is depth of each GHEs.

The heat exchange rate of the three types GHEs in discontinuous short-time period of operation and continuous operation are shown in Figure 6 (a), (b), and (c). The off-time period in discontinuous short-time period of operation contributes in increasing the heat exchange rate compared with that of in continuous operation. In continuous operation, the heat exchange rates are high in the beginning of operation and then, decline slightly. The performance of the GHEs descends gradually due to the heat buildup in the surrounding ground with operating time. Comparing numerical results with experimental results shows that the numerical models are capable to determine the performances of the GHEs. The heat exchange rates in discontinuous and continuous operation at 2, 6, 10, 14, 18, and 22 hours are presented in Table 5. In discontinuous operation, it is the minimum value of the heat exchange rate. The heat exchange rates in discontinuous operation are higher than that of in continuous operation. The off-time gives the time to the ground to stabilize its temperature.

Using the GHEs in short-time period of operation in discontinuous operation increases the heat exchange rate. As an example, the minimum heat exchange rate of the discontinuous short-time period of operation at 22 h operation time increases of 17.1 % for U-tube, 22.5 % for double-tube, and 16.5 % for multi-tube compared with that of in continuous operation at the same time of operation. This fact indicated that operating the GHEs in the short-time period with discontinuous operation improve their thermal performances. Alternative operation modes (cooling, heating, and hot water heating) over a short-time period of operation for GSHP system can be alternative solution to increase the performance.



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

(c) Multi-tube

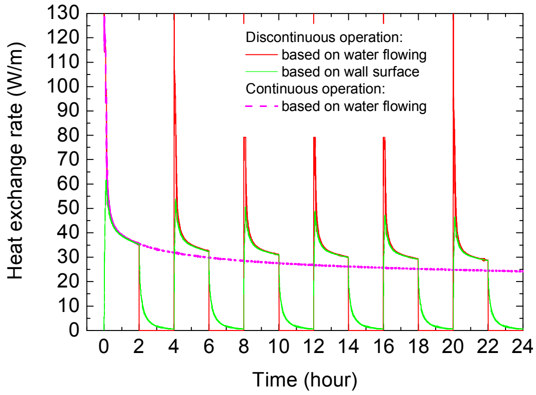
Figure 6: Heat exchange rate of the three types GHEs

Table 5: Heat exchange rates

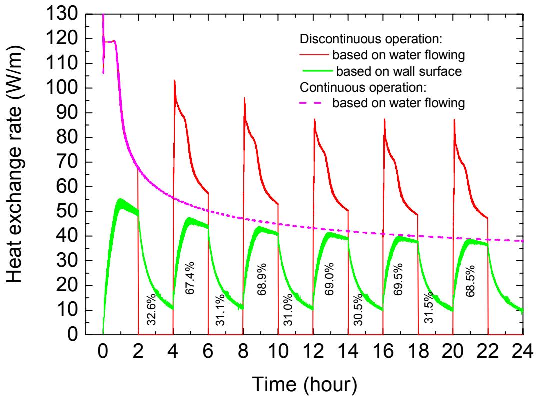
	Heat exchange rate (W/m)					
	2 h	*6 h*	*10 h*	*14 h*	*18 h*	*22 h*
Minimum heat exchange rate in discontinuous 2h operation						
U-tube	35.6	32.7	31.0	30.0	29.3	28.7
Double-tube	67.9	57.6	53.1	50.5	48.6	47.3
Multi-tube	34.0	31.2	29.8	28.8	28.2	27.6
Heat exchange rate continuous operation at the same time						
U-tube	35.6	29.9	27.6	26.2	25.3	24.5
Double-tube	67.9	50.3	44.9	42.0	40.0	38.6
Multi-tube	34.0	28.7	26.6	25.3	24.4	23.7

3.3 Heat Exchange Process in the Off-time

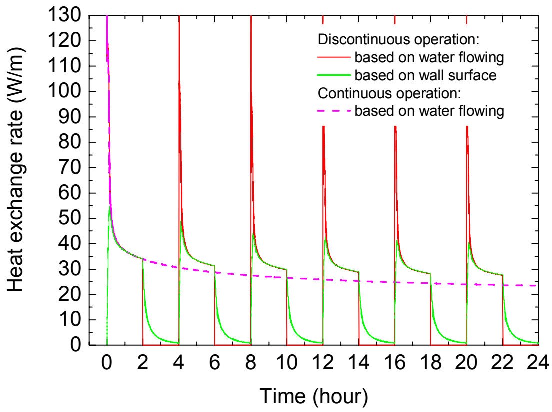
Heat exchange process to the ground exists in the off-time as shown in the Figure 7 (a), (b), and (c). This process increased the heat exchange rate of GHEs in the operation-time. Another factor in increasing the heat exchange rate is stabilizing the ground temperature in the off-time. This heat exchange rate is determined based on the rejected heat through the surface wall of GHE. A small amount of heat was rejected to the ground in the U-tube and multi-tube types in the off-time. In the double-tube type, the rejected heat is high due to the large quantity of water storage. Heat was rejected to the ground about 31.3 % in average in the off-time. This fact shows that the heat exchange process in the off-time increased the heat exchange rate in the double-tube type significantly.



(a) U-tube



(b) Double-tube



(c) Multi-tube

Figure 7: Heat exchange rate in the off-time of discontinuous operation

4 CONCLUSIONS

The thermal performances of the three types of GHEs are investigated numerically using the commercial CFD software FLUENT. Comparing numerical results with experimental results, the numerical models are capable to determine the performances of the GHEs.

The heat exchange rate in discontinuous short-time period of operation increased compared with that of in continuous operation. As an example, the minimum heat exchange rate of the discontinuous short-time period of operation at 22 h operation time increases of 17.1 % for U-tube, 22.5 % for double-tube, and 16.5 % for multi-tube compared with that of in continuous operation at the same time of operation.

The heat exchange process in the off-time increased the heat exchange rate significantly in the double-tube due to the large quantity of water storage. Heat exchanges to the ground about 31.3 % in average in the off-time.

Finally, operating the GHEs in the short-time period in discontinuous short-time period of operation improves their thermal performances.

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