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Thermal Performances of Three Types of Ground Heat Exchangers in Short-Time Period of Operation

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ABSTRACT

The thermal performances of three types of ground heat exchangers (GHEs) installed in a steel pile foundation including double-tube, U-tube and multi-tube have been investigated in short-time period of operation. The performance of the GHEs descends gradually due to the heat buildup in the surrounding ground with operating time in continuous operation. Alternative operation modes (cooling, heating, and hot water heating) over a short-time period of operation for ground source heat pump (GSHP) system can be alternative solution to increase its performance. Experimental study was carried out in discontinuous operation in 2 hours operation with constant interval of off-time. As a result, the heat exchange rate in the short-time period of operation in discontinuous operation increases of 53.1 % for double-tube, 33.3 % for U-tube, and 29.1 % for multi-tube compare with in continuous operation.

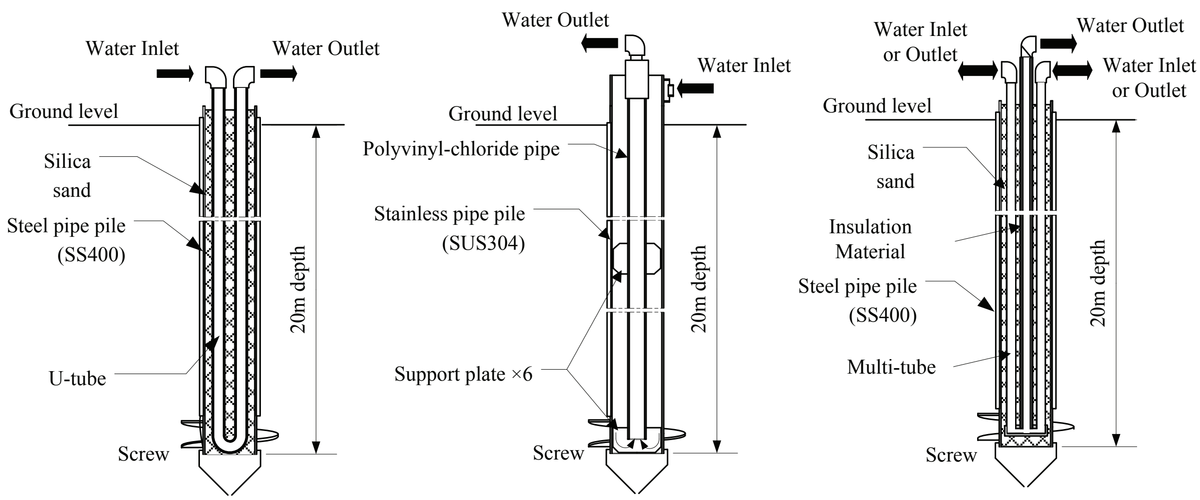
1. INTRODUCTION

Geothermal energy system is receiving interest as environmentally friendly energy source with wide range of applicability such as space heating and cooling, hot water heating and applications in the agricultural field. The well-known application is for space heating and cooling in residential and commercial building with using ground source heat pump (GSHP) systems. Ground heat exchanger (GHE) is used in this system to exchange heat with the ground. The vertical type of GHE is widely used in the GSHP system due to the higher thermal performance than the horizontal type. The thermal performance of the GHE is an important subject in GSHP system design. A number of research have investigated the thermal performance of GSHP system with many design and simulation techniques using experimental, detailed analytical or numerical methods. The performance of the GHEs descends gradually due to the heat buildup in the surrounding ground with operating time in continuous operation. Cooling/heating alternative operation modes in short-time scales improve the performance of the GSHP system. The heat transfer behavior in alternative operation modes (heating and cooling modes) investigated in short-time scale and the temperature distribution of borehole field was analyzed using finite element method (Cui *et al*., 2008). Short-time analysis of the GSHP system was discussed in many researches. Yavuzturk and Spitler (1999) use numerical heat diffusion problem in this analysis, Sutton *et al*. (2002) and Lamarche and Beauchamp (2007) proposed analytical solutions. In applying the GSHP system in alternative operation modes, it is crucial to investigate the thermal performance in short-time period of operation.

The present research investigated the thermal performance of three types GHEs installed in a steel pile foundation in short-time period of operation. The temperature distribution of borehole field is shown from the experimental data. The thermal performances of the GHEs in short-time period of operation in discontinuous operation are compared with that of in continuous operation.

2. OVERVIEW OF THE THREE TYPES OF GHE

Three types of GHEs including U-tube, double-tube, and multi-tube are shown in Fig. 1. 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 with 33 mm in outer diameter. Multi-tube consists of a polyvinyl chloride pipe with 20 mm in outer diameter as central pipe and 4 polyvinyl chloride pipes with 25 mm in outer diameter 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 with 139.8 mm in outer diameter was used as an inlet tube of GHE and a small diameter polyvinyl chloride pipe with 48 mm in outer diameter was installed inside the stainless steel pipe as an outlet tube. The detailed ground heat exchangers configuration and properties are shown in table 1.



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

Figure 1: The schematic diagrams of geothermal heat exchangers

Table 1: Configuration and properties of double-tube

Double-tube:	
Inlet pipe (pile foundation)	
Material	Stainless (SUS304)
Length	20 m
Outer diameter	0.1398 m
Inner diameter	0.1298 m
Thermal conductivity	13.8 W/(m K)
Outlet pipe	
Material	Polyvinyl chloride
Outer diameter	0.048 m
Inner diameter	0.04 m
Thermal conductivity	0.15 W/(m K)

Table 2: Configuration and properties of U-tube

U-tube:	
Inlet and outlet pipes	
Material	Cross-linked Polyethylene
Outer diameter	0.033 m
Inner diameter	0.026 m
Thermal conductivity	0.35 W/(m K)
U-tube distance	0.02 m
Pile foundation	
Material	Steel (SS400)
Outer diameter	0.1398 m
Inner diameter	0.1298 m
Thermal conductivity	52 W/(m K)

Table 3: Configuration and properties of multi-tube

Multi-tube:	
Inlet pipes	
Material	Polyvinyl chloride
Outer diameter	0.025 m
Inner diameter	0.02 m
Thermal conductivity	0.15 W/(m K)
Outlet pipe	
Material	Polyvinyl chloride
Outer diameter	0.02 m
Inner diameter	0.016 m
Thermal conductivity	0.15 W/(m K)
Pile foundation:	
Material	Steel (SS400)
Outer diameter	0.1398 m
Inner diameter	0.1298 m
Thermal conductivity	52 W/(m K)

Table 4: Grout thermal conductivity

Grout thermal conductivity	
Material	Silica sand
Thermal conductivity	1.4 W/(m K)

3. SOIL CHARACTERISTICS

The heat transfer between the GHE and adjoining soil depends strongly on the soil type, temperature and moisture gradients (Khamahchiyan and Iwao, 1994). This research was conducted at Saga University, Saga city, Japan. The soil sample at Fukudomi area, Saga city consist of clay from 0 to 15 m, sand and sandy clay from 15 m to 20 m with water content of 30 – 150 % vary with the depth (Hino *et al*., 2007). The soil properties can be estimated using values for similar soil type. The soil properties of clay, sand and sandy clay are shown in table 2 (JSME Data book, 2009).

Table 5: Soil properties

Soil Profile	**Temperature [K]**	**Density [kg/m^3]**	**Specific Heat [kJ/kg.K]**	**Conductivity [W/m.K]**	**Thermal Diffusivity [mm^2/s]**	**Water Content [%]**
Clay	293	1700	1.8	1.2	0.39	27.7
Sand	293	1510	1.1	1.1	0.68	7.9
Sandy Clay	293	1960	1.2	2.1	0.93	21.6

4. EXPERIMENTAL SET-UP

Experimental study over a short-time period of operation has been carried out under the same condition of the three types of GHEs. Water was circulated through the GHEs and the heat exchange with the ground. The experiments were held in discontinuous operation in 2 hours operation with constant interval of off-time. The experimental conditions are presented in Table 3. The flow rate of the multi-tube is the flow rate of the 4 inlet pipes. The temperature distribution of borehole field, inlet and outlet of circulated water were periodically recorded. The measurement temperature precision is 0.2 °C.

Table 6: Experimental conditions

Date	**Start Time**	**Inlet Water Temperature (^{0}C)**	**Flow Rate (l/min)**
Continuous operation (24 hours)			
09/04/2010	15:00	27	4
Discontinuous operation (2 hours)			
11/04/2010	15:00	27	4

The location of the three types of GHEs is shown in Fig.2. Two types of GHEs (double-tube and U-tube) and other type (multi-tube) are located at opposite ends of laboratory building. The temperature distribution of borehole field and ground along the depth were measured with constant interval using T-type thermocouples. The ground temperatures around the U-tube and double-tube were measured up to 25 m in depth. In the multi-tube, the ground temperatures were measured up to 22 m in depth.

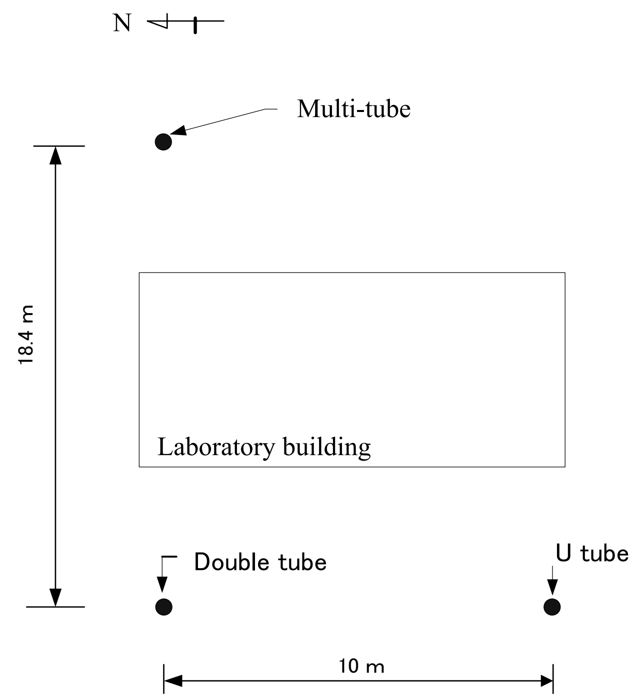


Figure 2: The locations of the three types of GHEs

5. RESULT AND DISCUSSION

5.1 The Temperature Distribution of Borehole Field

The ground temperature profiles around the three types of GHEs are shown in Fig. 3. Temperature distributions of ground before starting the experiments around the GHEs indicated similar characteristic of the three locations. Ground temperatures up to 5 m in depth were strongly influenced by ambient climate. The temperature distribution of the tube wall along the depth, inlet and outlet water temperature after 2 hours operation are shown in fig. 4. Temperatures of the outer side of the inlet tube wall of the double-tube gradually decline to the depth. The heat is rejected to the ground through the inlet tube and water temperature gradually decline. The temperature of the inner side of the outlet tube wall gradually increases upwards to the exit point due to the heat exchange from inlet water. In the U-tube and multi-tube, the wall temperatures of inlet tubes decrease to the depth. The heat is also rejected to the ground through the outlet tube of U-tube since the wall temperature is higher than the ground temperature shown in Fig. 3. In the multi-tube, the heat exchange from inlet tubes to outlet tube was avoided with the insulation of the outlet tube. By the insulation, water temperature rise might be smaller in the outlet tube. Water temperature difference at inlet and outlet points under the same condition are 3.2°C for double-tube, 2.3 °C for U-tube, and 2.4 °C for multi-tube.

Tube wall temperature profile of double-tube indicated that the water temperature profile is close to the values. It is due to the high thermal conductivity of Stainless steel that used as the inlet pipe of double-tube. In the U-tube and multi-tube, the water temperature profiles are quite different with the tube wall temperature profile due to the low thermal conductivity of the tubes. In addition, the thermal conductivity of U-tube pipe is higher than that of multi-tube as shown in table 1.

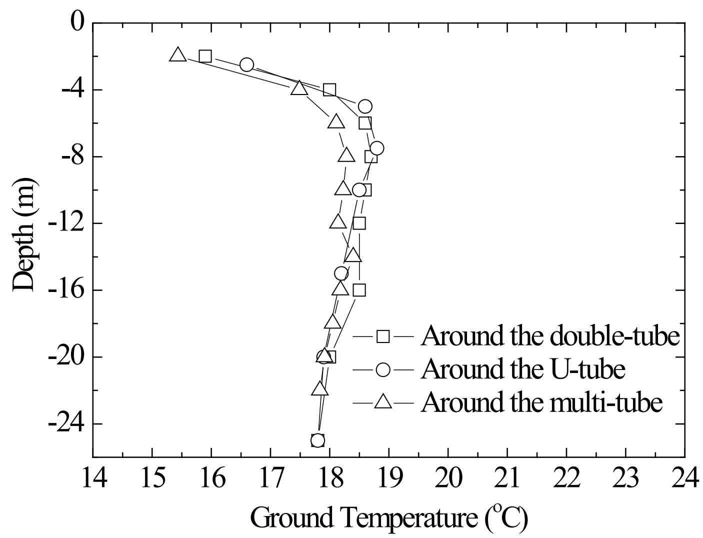


Figure 3: Ground temperature profile around the three types GHEs

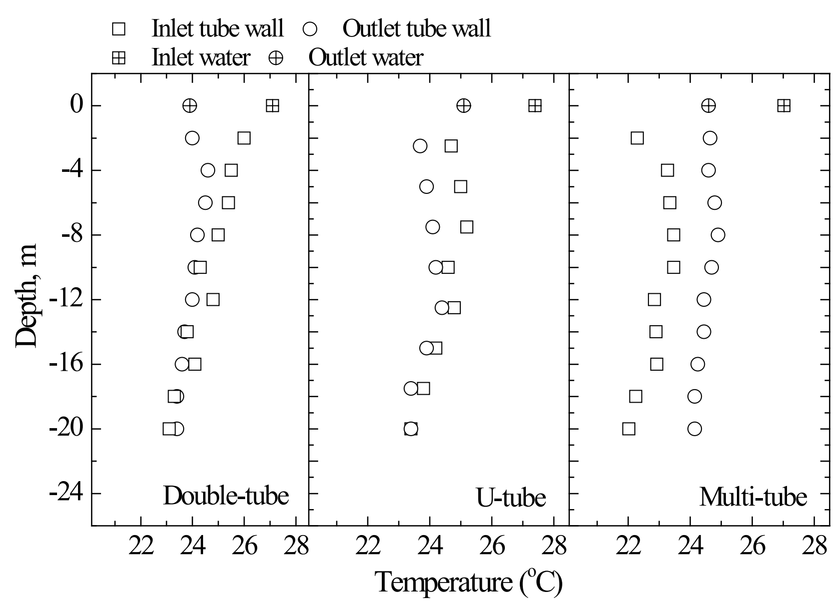


Figure 4: Temperature profiles of borehole field of three types GHEs

5.2 Heat Exchange Rate

To investigate the heat exchange rate of three types of GHEs, temperatures of inlet and outlet of circulated water of each flow rate were measured. The heat exchange rate, Q, is calculated by the following equation.

$$Q = \dot{m} c_p \Delta T \tag{1}$$

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,

$$\overline{Q} = Q / L \tag{2}$$

where L is depth of each GHEs.

The heat exchange rates of the three types of GHEs in discontinuous and continuous operation are shown in fig. 5. In continuous operation, the heat exchange rates are high in the beginning of the running due to the uniform temperature of ground around the borehole. After certain hours of running, the heat exchange from circulated water to the ground increases the temperature of ground around the borehole and then, the heat exchange rates decline slightly and tend to be constant. The double-tube had the highest heat exchange rate, followed by multi-tube and U-tube.

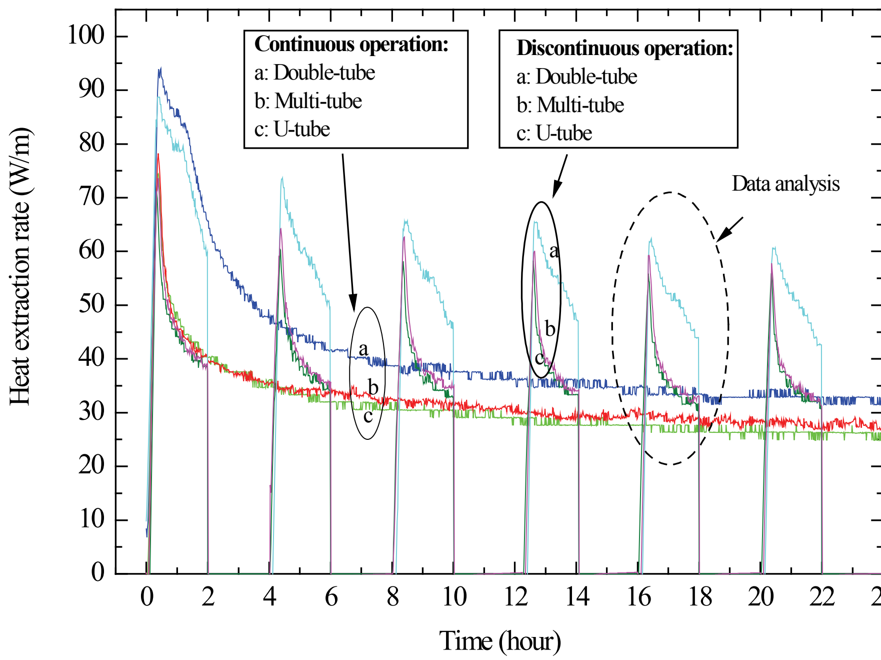


Figure 5: Heat exchange rate of the three types GHEs in discontinuous and continuous operation

In discontinuous operation, the heat exchange rate profile is high in the first 2 hours operation and then, decline. To study the thermal performance of the three types GHEs in short-time period of operation, the heat exchange rate profile in the fifth 2 hours operation is compared with that of in continuous operation as shown in the fig. 6. The average of heat exchange rates in discontinuous and continuous operation are presented in table 4. It is shown that operating the GHEs in short-time period increase the heat exchange rate. The increasing of heat exchange rate is affected by the effectiveness of heat exchange with the ground due to uniform of ground temperature around the GHEs with the undisturbed ground temperature. The off-time gives the time to the ground to stabilize its temperature.

Using the GHEs in short-time period of operation (2 hours operation) in discontinuous operation increases the heat exchange rate of 53.1 % for double-tube, 33.3 % for U-tube, and 29.1 % for multi-tube compare with in continuous 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 ground source heat pump (GSHP) systems can be alternative solution to increase the performances. The operation modes in short-time scales can be implemented through the triple-function GHE systems such as cooling, heating, and hot water heating according to requirements as discussed by Cui *et al*. (2008).

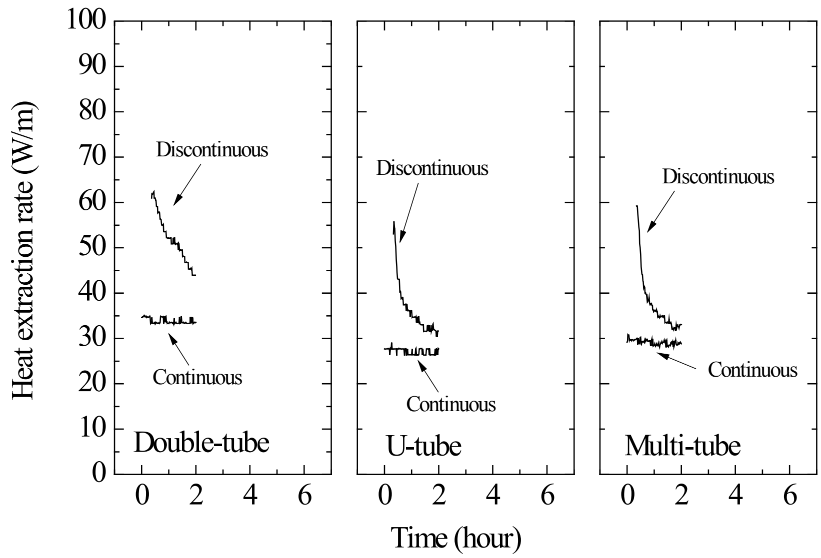


Figure 6: Heat exchange rate of the three types GHEs in discontinuous and continuous running after 16 hours operation time

Table 7: Heat exchange rate

	Heat exchange rate (W/m)		
	Double-tube	U-tube	Multi-tube
Discontinuous operation	51.8	36.2	37.6
Continuous operation	33.8	27.1	29.2

6. CONCLUSIONS

The experimental study of the three types of GHEs in short-time period with discontinuous operation shows their thermal performances. Finally, the conclusions could be drawn:

- The heat exchange rate in the short-time period of operation in discontinuous operation increases of 53.1 % for double-tube, 33.3 % for U-tube, and 29.1 % for multi-tube compare with in continuous operation.
- Operating the GHEs in the short-time period in discontinuous operation improves their thermal performances.

NOMENCLATURE

Q	heat exchange rate	(W)
$\dot{m}$	mass flow rate	(kg/s)
c_p	specific heat	(kJ/kg K)
ΔT	temperature difference	(^{o}C)
$\overline{Q}$	heat exchange rate per meter of borehole depth	(W/m)
L	borehole depth	(m)

REFERENCES

ASHRAE HandbookCD, 2009, *Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA 30329.

Bejan, A., Kraus, A.D., 2003, *Heat transfer handbook*, John Wiley & Sons, Inc., New Jersey.

Bandyopadhyay, G., Gosnold, W., Mann, M., 2008, Analytical and Semi-analytical Solutions for Short-time Transient Response of Ground Heat Exchangers, *Energy and Buildings*, 40: 1816–1824.

Cui P., Yang H., Fang Z., 2008, Numerical Analysis and Experimental Validation of Heat Transfer in Ground Heat Exchangers in Alternative Operation Modes, *Energy and Buildings*, 40: 1060–1066.

Hino, T., Koslanant, S., Onitsuka, K., Negami, T., 2007, Changes in Properties of Holocene Series during Storage in Thin Wall Tube Samplers, *Report of the faculty of science and engineering, Saga University*, vol. 36, No.1.

JSME Data book, 2009, *Heat Transfer 5th Edition*, The Japan Society of Mechanical Engineers (in Japanese).

Khamahchiyan, M., Iwao, Y., 1994, Geotecnical Properties of Ariake Clay in Saga Plain-Japan, *Journal of Geotechnical Engineering*, 505/III-29: 11-18.

Lamarche, L., Beauchamp B., 2007, New Solutions for the Short-time Analysis of Geothermal Vertical Boreholes, *International Journal of Heat and Mass Transfer*, 50: 1408–1419.

Sutton, M.G., Couvillion, R.J., Nutter, D.W., Davis, R.K., 2002, An Algorithm for Approximating the Performance of Vertical Bore Heat Exchangers Installed in a Stratified Geological Regime., *ASHRAE Transactions*, 108 (2): 177–184.

Yavusturk, C., Splitter, J., 1999, A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers, *ASHRAE Transactions*, 105 (2): 475-485.

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