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Study on Heat Exchange Characteristics for PHC Energy Piles

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ABSTRACT

An energy pile encases heat exchange pipes to exchange heat energy with the surrounding ground formation by circulating working fluid through the pipes. In this paper, a PHC energy pile assembled with a coil-shape heat exchange pipe was constructed, and its thermal performance was experimentally and numerically evaluated to develop a preliminary design. In-situ thermal response tests (TRTs) were performed and the TRT results were compared with the solid cylinder source model and a CFD numerical model using FLUNET. The CFD numerical model was adopted to back-analyze the effective thermal conductivity of the ground formation from the TRTs. In addition, the thermal interference between heat exchange pipes in PHC energy piles was parametrically studied to evaluate the sustainability of thermal performance. Finally, an equivalent heat exchange efficiency for the various PHC energy piles was compared with a common multiple U-type PHC energy pile to facilitate a preliminary design by adopting the PILESIM2 program.

1. INTRODUCTION

As one of the promising new and renewable energy sources, geothermal energy is a sustainable and environment-friendly energy system. Geothermal energy can be utilized as a ground source heat pump (GSHP) system which uses the earth as a heat source in heating operation or a heat sink in cooling operation by exchanging thermal energy between the ground heat exchanger (heat exchange pipe) and the surrounding ground. Utilizing geothermal energy as a GSHP system was reported to be the most effective method according to the US Environmental Protection Agency and the Department of Energy.

Preceding researches on the GSHP system have been mainly performed on the closed-loop vertical ground heat exchanger that needs expensive initial construction cost and large construction space. Therefore, it is considerably important to obtain economical alternatives to the conventional closed-loop vertical ground heat exchangers in order to promote the extensive use of geothermal energy. As one of

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the promising options, several attempts have been made to embody heat exchange pipes in structural foundations such as piles, mat foundations, slurry walls, etc. (Pahud et al. 2007, Gao et al. 2008, Jun et al. 2009).

Energy pile is equipped with the heat exchange pipes inside a pile constructed as a structural foundation and allows circulating fluid through the pipes, creating heat exchange with the subsurface ground formation. Since constructed in foundations, the energy pile can function as not only a structural foundation but also a heat exchanger.

In this paper, In-situ thermal response tests (TRTs) were carried out on an energy pile which was constructed in a PHC pile equipped with a coil-shape heat exchange pipe. The TRT results were compared with those from the solid cylinder source model and the computational fluid dynamics (CFD) numerical model. From comparison results, the effective thermal conductivity of the ground formation is back-analyzed. In addition, the thermal interference between heat exchange pipes in the PHC energy pile was parametrically studied to evaluate thermal performance by using the numerical model developed in this paper. Finally, an equivalent heat exchange efficiency for the coil-shape PHC energy piles was compared with that of a typical multiple U-shape PHC energy pile to facilitate a preliminary design by adopting the PILESIM2 program.

2. SIMULATION OF IN-SITU THERMAL RESPONSE TESTS

Mogensen (1983) suggested the TRT as a method to estimate the in-situ thermal properties of the ground formation and the performance of heat exchanger by recording temperature of outlet fluid with applying a constant rate of heat injection. In this paper, a series of TRTs was carried out on the energy pile which was constructed in a PHC pile equipped with a coil-shape heat exchange pipe. The dimensions of the PHC energy pile and heat exchange pipe were shown in Table 1.

Table 1 Dimensions of PHC energy pile and heat exchange pipe

PHC energy	External diameter	400 (mm)
	Internal diameter	245 (mm)
	Total length	10 (m)
Coil-shape Heat exchange pipe	External diameter	20 (mm)
	Internal diameter	16 (mm)
	Coil pitch	50 (mm)
	Coil radius	240 (mm)
	Total length	196 (m)

The field data from TRTs are usually compared with a mathematical model such as a line source model or cylindrical source model (Carslaw and Jaeger 1959, Ingersoll 1954) to estimate thermal properties of the ground formation including a geothermal heat exchanger. These mathematical models assume that the heat source is applied as a shape of an infinite line or infinite cylinder. Since the closed-loop vertical ground heat exchanger forms relatively longer vertical length than the borehole diameter, the configuration of heat source is presumably assumed as an infinite line or an infinite cylinder shape. On the other hand, since an energy pile is much thicker in diameter but shorter in depth, the line source model or cylindrical source model is not appropriate for analyzing the thermal properties of an energy pile. Thereafter, Man et al. (2010) suggested the modified solid cylinder source model applicable to a finite cylinder heat source and Cui et al. (2011) suggested the ring-coil source model suitable for a coil-shape heat source.

In this paper, coil-shape heat exchange pipes were constructed with the tight coil pitch of about 0.05m, thus it is assumed that the heat source forms a finite cylinder shape. Therefore, to estimate thermal properties of the ground formation and to evaluate the heat performance of energy pile, the modified solid cylinder source model was adopted in this study.

2.1. Solid cylinder source model

The cylinder source model was first suggested by Carslaw and Jaeger (1947) as an analytical solution with varying boundary conditions for regions bounded by cylinder geometry. Thereafter, this model was refined by Ingersoll et al. (1954). In this model, the source is assumed as an infinite cylinder surrounded by homogeneous solid medium with constant thermal properties, and heat transfer between the source and medium with perfect contact is pure heat conduction.

Based on the governing equation of the transient heat conduction along with the given boundary and initial conditions, the analytical solution for a constant heat flux (q) is given as follows:

$$\mathrm{T(r,t)} = \frac{\mathrm{q}}{\mathrm{k}}\mathrm{G(z,p)} \quad \begin{cases} \mathrm{z} = \dfrac{\mathrm{at}}{\mathrm{r}^2} \\ \mathrm{p} = \dfrac{\mathrm{r}}{\mathrm{r_0}} \end{cases} \tag{1}$$

where G(z,p) is the cylinder source function as described by Ingersoll et al. (1954). T(r,t) is the temperature (K) at r (distance from the center of a cylinder source) with time (t). k is the thermal conductivity of the medium (W/mK). a is the thermal diffusivity (m^2/s). r_0 is a radius of the cylinder source (m). G(z,p) is only a function of time and radial distance from the center of a cylinder source, and defined as follows:

$$\mathrm{G(z,p)} = \frac{1}{\pi^2}\int_0^\infty \mathrm{f}(\beta)\mathrm{d}\beta \tag{2}$$

$$\mathrm{f}(\beta) = \left(\mathrm{e}^{-\beta^2 \mathrm{z}} - 1\right)\frac{[\mathrm{J_0(p\beta)Y_1(\beta) - Y_0(p\beta)J_1(\beta)}]}{\beta^2\left[\mathrm{J_1^2(\beta) + Y_1^2(\beta)}\right]} \tag{3}$$

where J_0, J_1, Y_0 and Y_1 are the Bessel functions of the first and second kind.

Man et al. (2010) suggested the modified solid cylinder source model to apply for an energy pile which has a relatively short vertical length compared with the borehole diameter. The modified solid cylinder model provides T(r,t) as the following equation.

$$\mathrm{T(r,t)} = \frac{\mathrm{q}}{\rho \mathrm{c}} \int_0^t \int_0^h \frac{1}{8[[\sqrt{\pi k(t-t')}]^3} I_0\left[\frac{r r_0}{2k(t-t')}\right] \exp\left[-\frac{r^2+{r_0}^2+(z'-z)^2}{4k(z'-z)}\right] - \exp\left[-\frac{r^2+{r_0}^2+(z'+z)^2}{4k(z'-z)}\right] dz'dt' \tag{4}$$

$$I_0(x) = \frac{1}{\pi}\int_0^{\pi} \exp(x cos\varphi)\, d\varphi \tag{5}$$

where I_0 is the modified Bessel function.

Average temperature of the inlet and outlet fluid measured by TRTs were compared with temperature calculated at the inner diameter ($r = r_0 = 0.1225$ m) obtained by the modified solid cylinder source model (refer to Fig 1). To estimate the effective thermal conductivity of the ground formation, a back-analysis was performed by inputting varying thermal conductivities of the ground formation into the model and matching the solution with a field TRT data set. From this inverse parameter estimation, the effective thermal conductivity of 2.5 W/mK was evaluated for the constructed site. These results show that it is reasonable to estimate thermal properties with the modified solid cylinder source model for case of the coil-shape PHC energy pile.

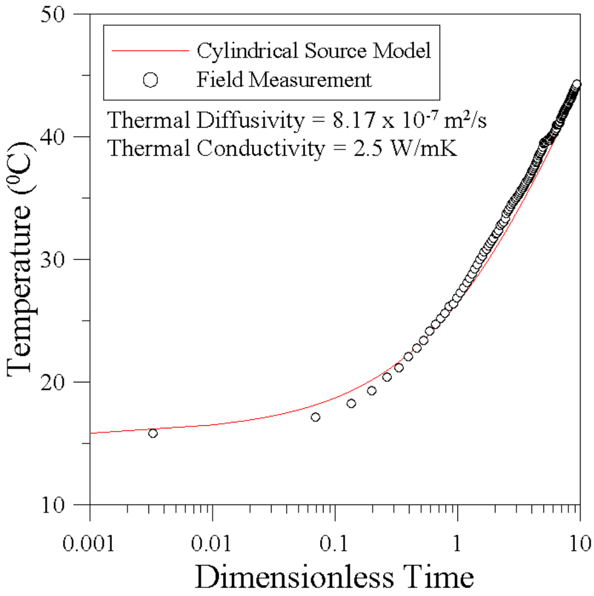


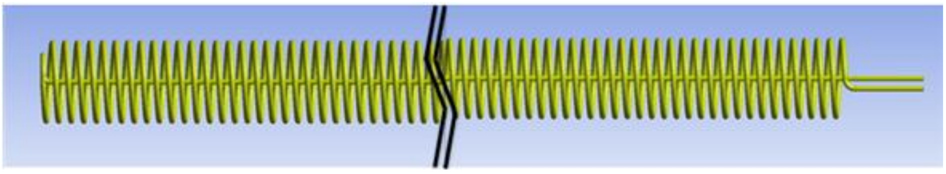
Fig. 1 Comparison of field TRT result and solid cylinder source model

2.2. Numerical simulation

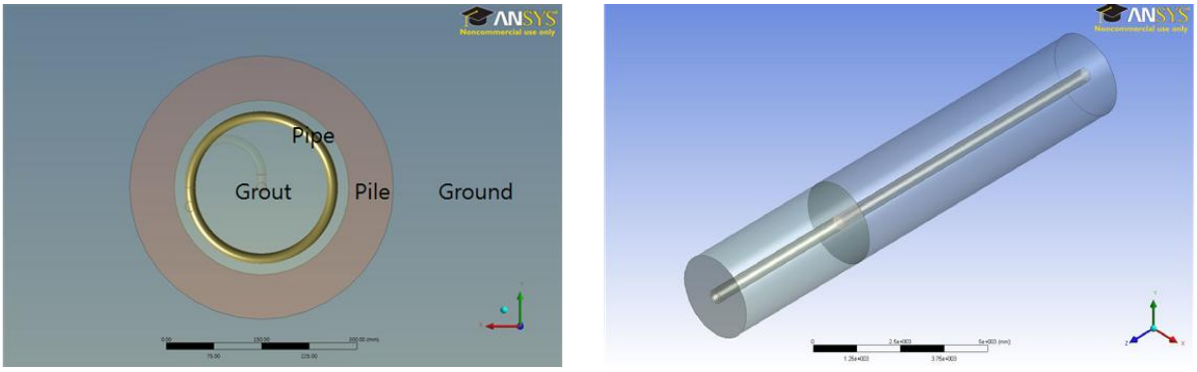
In this section, the TRT results obtained from the coil-shape PHC energy pile were numerically simulated to estimate thermal properties of the field ground formation and to evaluate thermal performance of the energy pile. In a CFD numerical analysis, the heat exchange pipe, PHC pile and surrounding ground formation were modeled using FLUENT, a finite-volume method (FVM) program, to simulate the heat transfer process of the system. For analyzing the solid-fluid coupled heat transfer encountered in ground heat exchangers, the mass, momentum, energy conservation of water flow, and conservation of solid are considered in the model(Jun et al. 2009; Nam et al. 2008). The modeling is based on an implicit finite volume formulation of the transient heat conduction in the three dimensional space (Yavuzturk et al. 1998).

The model dimensions of the energy pile correspond to the actual construction condition as shown in Fig 2. Table 2 summarizes material properties of each component modeled in the numerical analysis that were obtained from the laboratory tests and referred to Engineering toolbox (2005). In case of thermal conductivity, a back-analysis was performed with varying thermal conductivities of the ground formation to match with the field TRT data.

Since a constant rate of heat is continuously supplied to the inlet fluid during the TRT, the fluid temperature entering into the inlet pipe increases according to the flow rate of circulation fluid and power supply. Therefore, in the numerical model, a constant temperature increment was applied on the inlet boundary by using User Define Function (UDF). The temperature was obtained from the recorded outlet fluid temperature and power supply.



(a) Coil-shape model of heat exchange pipe



(b) Cross section of PHC energy pile (c) Modeling form of PHC energy pile

Fig. 2 3-D numerical model of PHC energy pile (FLUENT)

Table 2 Material properties of energy pile components

	Ground	Pile	Grout	Pipe
Density (kg/m3)	2600	1780	2200	1000
Specific heat (J/kgK)	2500	700	900	600
Thermal conductivity (W/mK)	3.0	2.3	2.5	0.5

The inlet and outlet temperature obtained from the TRT and the numerical simulation are compared in Fig. 3. In the inverse parameter estimation, the back-analyzed thermal conductivity of the field ground formation is 3.0 W/mK which allows the numerical simulation to match closely to the field TRT data. This value is slightly larger than that evaluated by the modified solid cylinder source model (i.e., 2.5 W/mK). This difference may be attributable to the assumption accepted in the modified solid cylinder source model which considers the whole domain is regarded as a homogeneous medium except the cylinder-shape heat source. However, the numerical model enables to consider separately all of the components in the energy pile such as the heat exchange pipe, grout, pile, and ground formation.

In summary, the numerical analysis results correspond with the field data of TRT with high accuracy. It indicates that the developed numerical model is appropriate for simulating the coil-shape PHC energy pile. After the 2880 minutes simulation, the temperature distribution of cross and vertical section are rendered in Fig. 4.

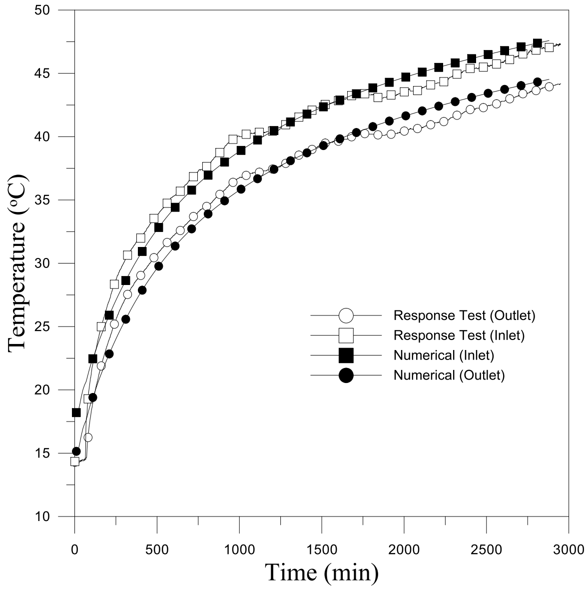


Fig. 3 Comparison of TRT data and numerical analysis

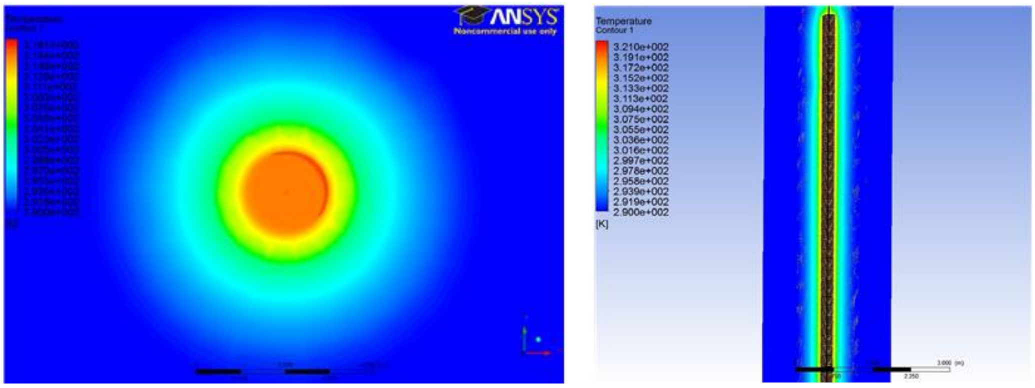


Fig. 4 Temperature contours of PHC energy pile

3. PARAMETERIC STUDY FOR EFFECT OF PIPE LENGTH AND COIL PITCH

When a coil-shape heat exchange pipe is constructed, the designer tries to insert the pipe as long as possible to obtain the maximum heat exchange or thermal performance from the energy pile. However, because the over-lengthened pipe configuration leads to a very tight coil pitch that may cause thermal interference between each loop of the heat exchange pipe, the heat exchange rate will not be directly in proportion to the installed pipe length.

In this section, a parametric study was performed to evaluate any relationships between the heat exchange pipe length (in other words, the coil pitch) and heat exchange rate. Four different heat exchange lengths (i.e., 200m, 150m, 100m and 50m) are considered in a 10m long PHC energy pile. The coil pitch corresponds to 40mm, 54mm, 79mm and 160mm, respectively. A monotonic cooling loading is applied to each energy pile for 50 hours.

The outlet fluid temperature with time is continuously recorded from the output and is shown in Fig. 5. The results indicate that a difference in the outlet fluid temperature between each case is reduced as the pipe length increases. This shows that the thermal interference between each pipe loop is increased as the pipe length is increased (that is the coil pitch is decreased), which lessens efficiency of heat exchange.

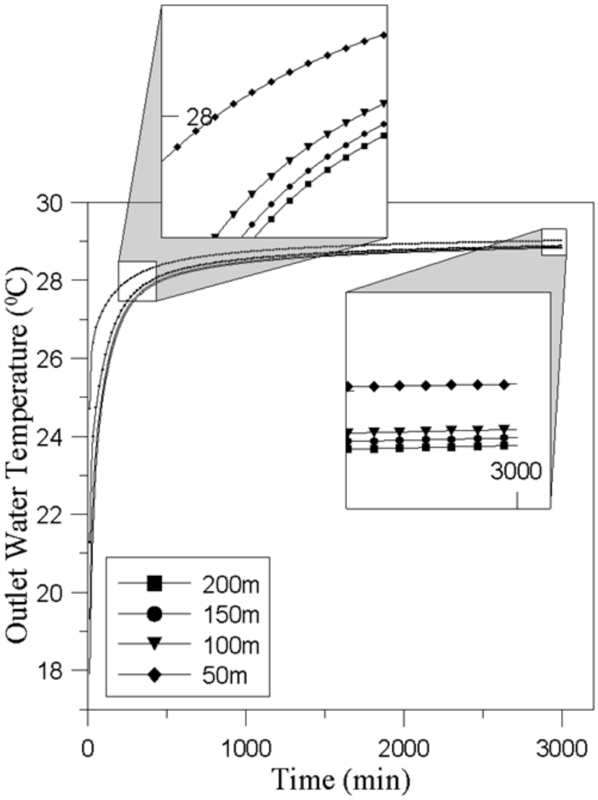


Fig. 5 Change of outlet fluid temperature with various coil pitch

The difference of outlet fluid temperature between each case versus time is shown in Fig 6. The temperature difference in EWT(Entering Water Temperature) between the pipe length of 150m and 200m becomes close to zero as the time elapsed, which means an over-lengthened heat exchange pipe installed a limited space of an energy pile is not economical. Thus, the thermal interference should be considered in designing a heat exchange pipe configuration in respect of economy and efficiency.

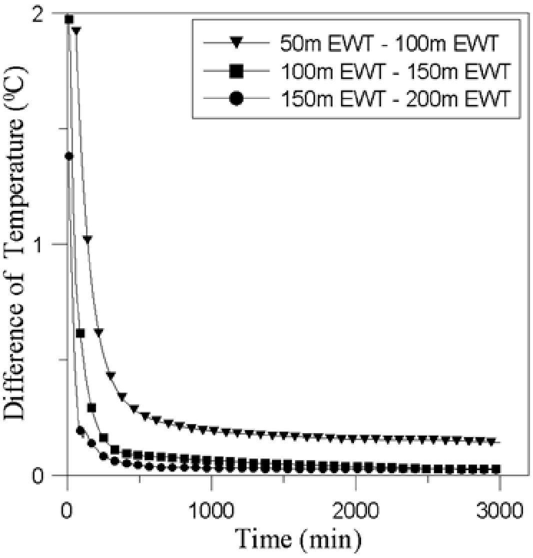


Fig. 6 Difference of outlet fluid temperature between each case

The amount of heat exchange (*Q*) is calculated by the following equation during the monotonic cooling operation.

$$Q = C\dot{m}\Delta T = C\dot{m}(T_{in} - T_{out}) \quad (6)$$

where *C* is the specific heat capacity of working fluid (J/kgºC), $\dot{m}$ is the mass flow rate (kg/s), and ΔT is the difference between the inlet and outlet temperature.

The amount of heat exchange with time is shown in Fig. 7, and each indicative value is summarized in Table 3. The relative heat exchange represents the total heat exchange rate normalized by that of the pipe length of 50m. When the pipe length increases from 50m to 200m, the relative heat exchange increases by only 50%. Furthermore, the amount of heat exchange per pipe length (in other words, the rate of heat exchange) is much higher in case of the pipe length of 50m. The total amount of heat exchange and the rate of heat exchange (amount of heat exchange per pipe length) versus the heat exchange pipe length are compared in Fig. 8. As the pipe length increases (coil pitch decreases), the rate of heat exchange decreases.

According to results of the parametric study for thermal interference, it is presumably concluded that an optimum pipe length is about 100m for the 10m long coil-shape PHC energy pile in this study. In designing an optimum heat exchange pipe length, the designer should consider not only the rate of heat exchange but also workability, material cost and local conditions.

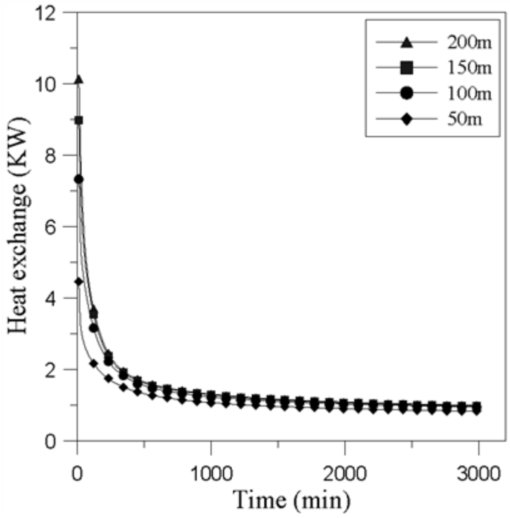


Fig. 7 Amount of heat exchange versus time with various pipe length

Table 3 Heat exchange comparison per pipe length

	50m	100m	150m	200m
Coil picth (mm)	160	79	54	40
Difference of temperature (^{0}C)	0.81	1.53	1.63	1.68
Mass velocity of fluid (kg/s)	0.201	0.201	0.201	0.201
Total amount of heat exchange (KWh)	53.98	73.76	78.06	80.47
Relative heat exchange	1	1.37	1.45	1.49
Amount of heat exchange per pipe length or rate of heat exchange (KWh/m)	1.078	0.74	0.52	0.40

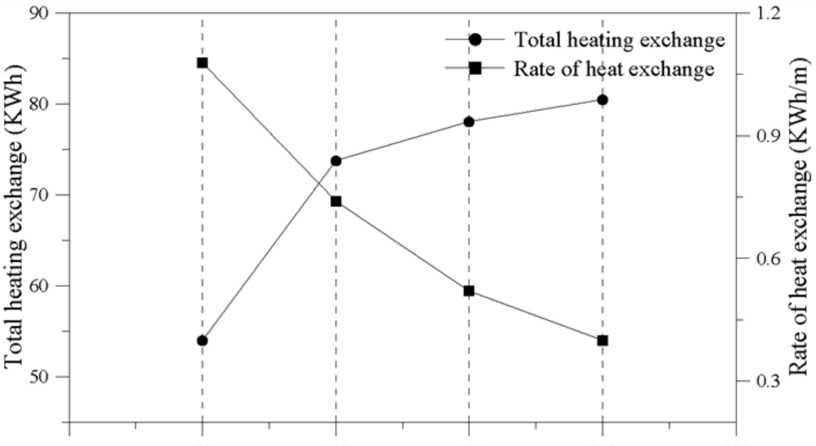


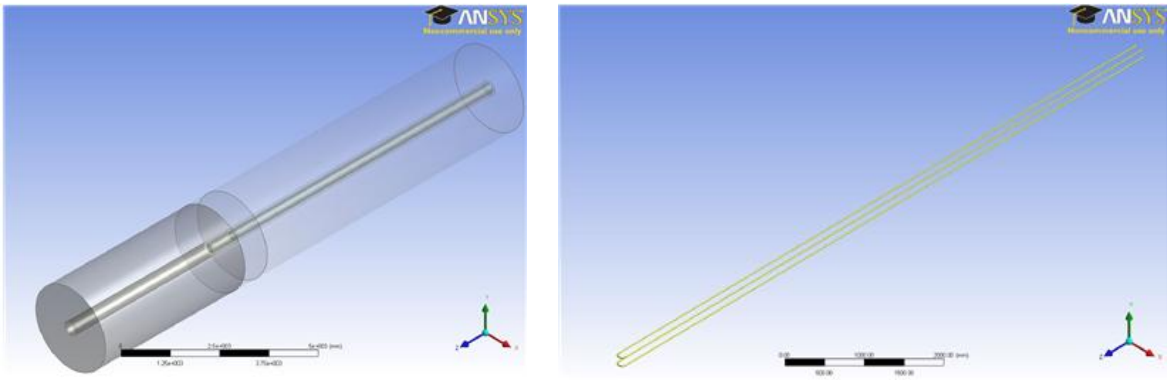
Fig. 8 Total amount of heat exchange and rate of heat exchange versus pipe length

4. PRELIMINARY DESIGN OF PHC ENERGY PILE

A preliminary design of the PHC energy pile was developed by using PILESIM2. The PILESIM2 program was developed by Pahud and Hubbuck(2007) by two-year monitoring thermal performance of energy piles which were constructed in Zurich airport, Switzerland, from October, 2004. The optimum load or dimension of the energy pile can be designed through the PILESIM2 program by simulation of cooling/heating operation considering local conditions, dimensions of pile and pipe, operation conditions, etc. However, only the U-shape heat exchange pipe and double-tube heat exchange pipe can be dealt in PILESIM2, thus other pipe configurations such as coil-shape heat exchange pipe could not be directly designed. Therefore, in this paper, to preliminarily design a coil-shape PHC energy pile using the PILESIM2 program, a new design process was developed as follows: first, a typical multiple U-shape PHC energy pile is designed by the PILESIM2 program, and then, an equivalent heat exchange efficiency factor for the coil-shape configuration is obtained through the CFD numerical model. The procedure compares the heat exchange rate of the multiple U-shape energy pile and the coil-shape energy pile.

4.1. Estimation of equivalent heat exchange efficiency factor

To estimate the equivalent heat exchange efficiency factor, a typical PHC energy pile was modeled, which encases two pairs of U-shape heat exchange pipe in parallel and connected on the ground. The length of modeled U-shape pipe is 40m while the length of a coil-shape pipe is 196m. Except for the configuration and pipe length, other specifications of the pile and heat exchange pipe are identical each other. The numerical model of the U-shape energy pile is shown in Fig. 9.



(a) Modeling of energy pile (b) Modeling of U-shape pipe

Fig. 9 Numerical model of U-shape energy pipe

To compare the amount of heat exchange of the U-shape and the coil-shape energy pile, a monotonic cooling operation for 100 hours was applied in the numerical model. The change of outlet fluid temperature with time for each case is compared in Fig. 10. Since the length of the coil-shape pipe is almost 5 times longer than the U-shape pipe, a large temperature difference is initially observed. However, as the simulation continues, the difference in outlet fluid temperature between the two cases decreases continuously. As mentioned in section 3, since the thermal interference is occurred in the coil-shape energy pile due to a tight coil pitch, it is observed that the superiority of heat exchange in the coil-shape pipe is gradually reduced..

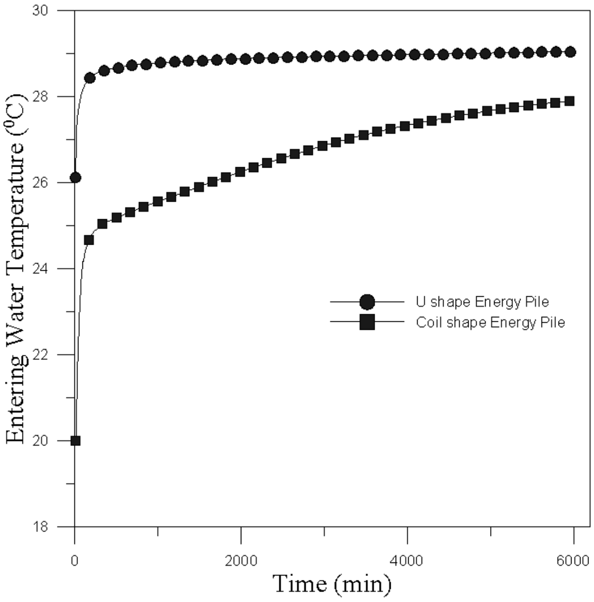


Fig. 10 Outlet temperature with different pipe configurations

The amount of heat exchange is calculated by Eq. 6 and summarized in Table 4 and Fig. 11. Although the coil-shape energy pile shows the total amount of heat exchange and the amount of heat exchange per pile length are larger than the U-shape energy pile, the amount of heat exchange per pipe length (efficiency of heat exchange) is smaller than the U-shape energy pile because of the thermal interference.

The equivalent heat exchange efficiency factor for the coil-shape energy pile against the U-shape energy pile is evaluated as 3.2, base on comparing the total amount of heat exchange.

Table 4 Equivalent heat exchange efficiency factor of energy piles

	U-shape energy pile	Coil-shape energy pile
Temperature difference per unit (℃)	1.25	2.76
Mass flow rate per unit (kg/s)	0.1085	0.2170
Number of unit	2	1
Total length of heat exchange pipe	40	196
Total amount of heat exchange (kWh)	107.08	342.50
Amount of heat exchange per pipe length (kWh/m)	2.68	1.75
Amount of heat exchange per pile length (kWh/m)	10.71	34.25
equivalent heat exchange efficiency factor	1	3.2

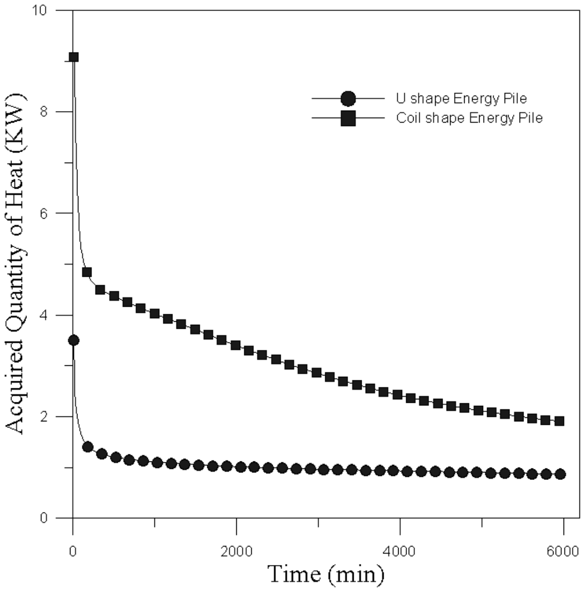


Fig. 11 Comparison of amount of heat exchange of different PHC energy piles

4.2 Preliminary design of PHC energy pile

A preliminary design for a coil-shape energy pile was developed by using PILESIM2. Since the PILESIM2 program is unable to design various heat exchange pipe fattens such as a coil-shape PHC energy pile, the equivalent heat exchange efficiency factor calculated in the preceding section (i.e., 3.2) was adopted for designing the coil-shape energy pile. The climate date for air temperature of Seoul in 2010 (Fig. 12) was used in the design. One hundred U-shape PHC energy piles are designed on the construction purpose. The heat pump EWT was set as 30°C for cooling operation and 5°C for heating operation to maintain the coefficient of performance (COP) of the heat pump as 4.7. The thermal conductivity of the ground formation was assumed as 3 W/mK. The input design paramerters are shown in Table 5 and the expected cooling and heating loading pattern of a year is shown in Fig. 13.

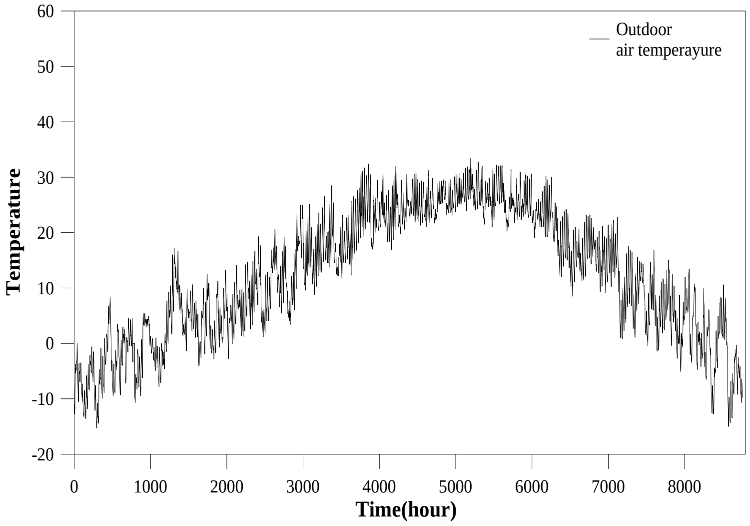


Fig. 12 Atmospheric temperature variation of Seoul in 2010

Table 5 Input design parameter of PILESIM2 (two pairs of U-shape pipe)

Yearly energy load	Cooling	33.07MW·h
	Heating	142.07MW·h
EWT of heat pump	Cooling	30°C
	Heating	5°C
COP of heat pump		4.7
Dimension of energy pile	Diameter: 0.4m, Depth: 10.0m	100 piles
Configuration of pipe		Two pairs of U-shape
Thermal conductivity of ground		3 W/mK

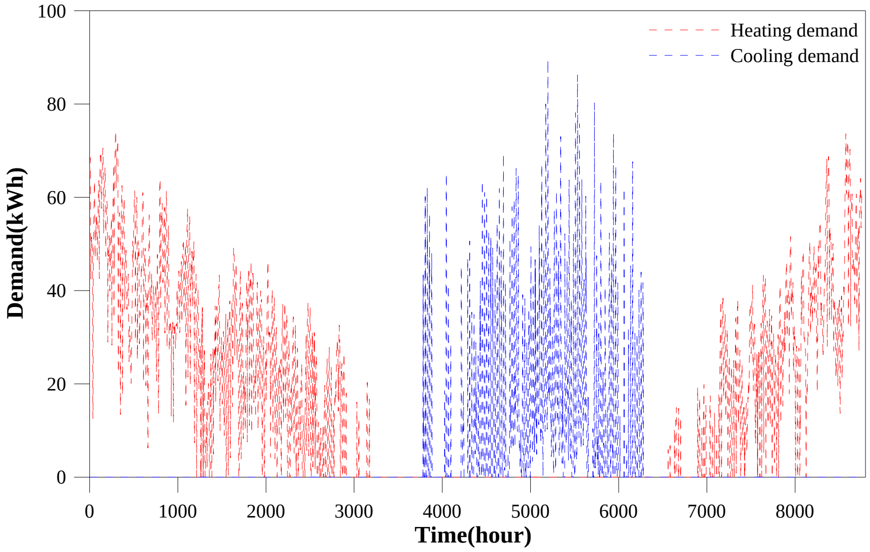


Fig. 13 Applied cooling and heating loading pattern for a year

Considering the design parameters specified in Table 5, the variation of heat pump EWT for 20 years, when one hundred U-shape PHC energy piles are all in use, is shown in Fig. 14. Since the heating load is greater than the cooling load in this design, the ground temperature and the heat pump EWT decrease gradually for 20 years. However, since the heat pump EWT is maintained within the heat pump specification, a reasonable design seems to be made.

Yearly energy loads shown in Table 5 (33.07 MW·h for cooling operation and 147.07 MW·h for heating operation) are obtained when one hundred U-shape PHC energy piles are in use. Now, the cooling and heating loads for one hundred coil-shape PHC energy piles can be designed by adopting the equivalent heat exchange efficiency (i.e., 3.2), and the values are calculated as 105.82 MW·h for cooling operation and 454.62 MW·h for heating operation, respectively. In other words, only 32 coil-shape energy piles are needed to obtain the cooling and heating energy equal to that obtained from one hundred U-shape PHC energy piles. The evaluating design data for the coil-shape energy piles are summarized in Table 6.

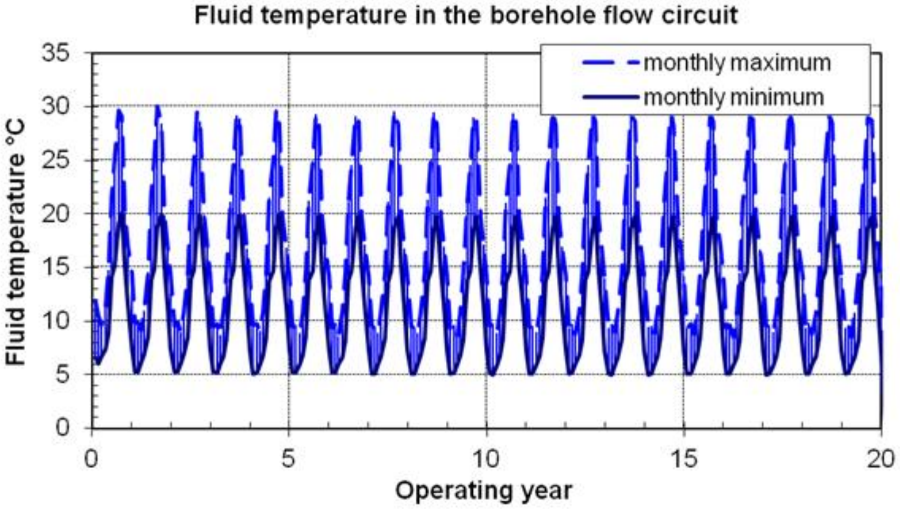


Fig. 14 Variation of heat pump EWT for 20 years

Table 6 Input design parameters of PILESIM2 (coil-shape heat exchange pipe)

Yearly energy load	Cooling	105.82 MW·h
	Heating	454.62 MW·h
EWT of heat pump	Cooling	30°C
	Heating	5°C
COP of heat pump		4.7
Dimension of energy pile	Diameter: 0.4m, Depth: 10.0m	100 piles
Configuration of pipe		Coil-shape
Thermal conductivity of ground		3 W/mK

CONCLUSION

(1) A coil-shape PHC energy pile was constructed at a test bed and a TRT was performed. Simulation and analysis of the TRT were conducted by adopting the modified solid cylinder source model and the CFD numerical model. In the back-analysis to estimate the effective thermal conductivity of the ground formation, the modified solid cylinder source model slightly underestimates this value because this model assumes the whole domain as a homogeneous medium except for the cylinder-shape heat source.

(2) For studying thermal interference between pipe loops of the coil-shape heat exchange pipe, a series of numerical analyses were performed with various coil pitches. It is found that thermal interference between each pipe loop is increased as the pipe length is increased (that is the coil pitch is decreased), which lessens efficiency of heat exchange. In designing an optimum heat exchange pipe length, the designer should consider not only the rate of heat exchange but also workability, material cost and local conditions.

(3) Except for the U-shape heat exchange pipe and double-tube heat exchange pipe, various configurations such as coil-shape heat exchange pipe could not be directly designed in the PILESIM2 program. Therefore, an equivalent heat exchange efficiency factor for the coil-shape configuration is obtained through the CFD numerical model, which can be used for a preliminary design.

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(4) By adapting the equivalent heat exchange efficiency factor at the design process of a multiple U-shape energy pile, a preliminary design for the coil-shape PHC energy pile was successfully performed.

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