

## Development of the building integrated geothermal system with the horizontal heat exchanger

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**Abstract:** Ground source heat pump systems can achieve the energy saving of building and the reduction of CO<sub>2</sub> emission by utilizing annually stable ground temperature. However, they have barriers for wide-spread such as high cost of installation, incompleteness of design tool, lack of recognition as heating and cooling systems, so on. In order to solve the problems, the building integrated geothermal system (BIGS) has been developed by several researches which use building foundation as heat exchanger. In the study, in order to establish the optimum design tool of BIGS with the horizontal heat exchanger, the prediction method of ground heat exchange rate was developed with numerical simulation model. The developed model was coupled with ground heat transfer model, ground surface heat model and ground heat exchanger model. Furthermore, case studies were conducted in the various conditions of design and installation, in which the depth of installation, space between pipes and the diameter of pipe were considered. In the results, it was found that the case of diameter 32 A, piping space 0.3 m and flow rate 9.52 L/min was the best case as 15.0 W/m of heat exchange, rate in case studies. Moreover, the heat exchange rate of all cases according to operation, conditions was calculated by the long-term simulation.

**Key Words:** ground heat source, heat exchanger, simulation, numerical analysis

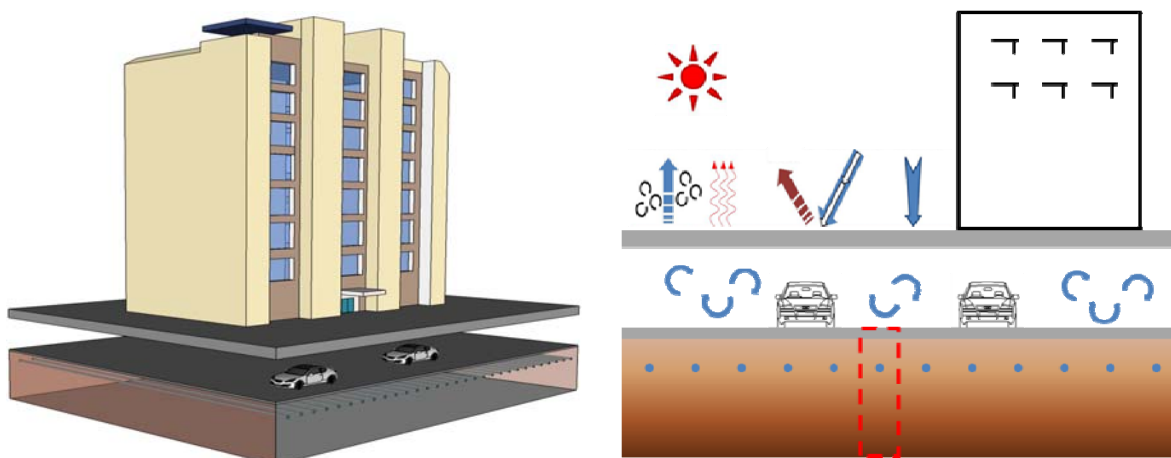
### 1 INTRODUCTION

Recently, the interest in the efficient use of energy and the technology of renewable energy has been increased according to heightening crisis for the environmental pollution and resource depletion. Ground source heat pump (GSHP) systems are becoming more attractive since they can achieve higher system performance than the conventional air source heat pump system. These systems utilize the underground soil of annually stable temperature as a heat sink for cooling or a heat source for heating. Generally, GSHP system can be divided into two types, the open type and the closed type according to the configuration of ground heat exchanger. The closed type is further divided into horizontal and vertical system. In Korea, since 2004, public buildings with up to 3,000m<sup>2</sup> of floor space must invest more than 5% of total construction cost on the renewable energy equipment such as solar, geothermal, wind power energy, biomass so on. As a result of this regulation, the renewable systems including GSHP systems spread, the market of the systems dramatically grew and the market growth of GSHP system among the renewable energy systems was the most remarkable in the last decade [1]. Especially, the vertically closed type and the standing column well type have been mainly applied due to relatively high thermal conductivity, simple design and sufficient experience [2]. However, these types of the systems need to be located at the depth of more than 100m for the installation of ground heat exchanger and they require additional initial cost and construction period than the conventional systems for the application to real buildings. In order to minimize the initial cost, several researches suggested the systems which utilize the building structures as ground heat exchanger. However, the prediction of the system performance was significantly complicated to design

the system by the conventional design tool. Several researches have conducted to estimate the system performance by experimental analysis and simulation method. K. Morino and T. Oka [3] developed a heat exchange system with a steel pile and conducted experimental analysis by circulating water in the pile. They found that the system achieved the heat exchange with the soil of 210 MJ/day as a heat sink, and 113 - 150 MJ/day as a heat source during a short-term experiment. D. Pahud et al. [4] developed PILSIM, a simple simulation tool for the performance of an energy pile in the framework of the Zurich airport project. They approximately predicted the system performance of an energy pile by the modified model of Hellstrom's DST model.

C. K. Lee and H. N. Lam[5] developed a simplified model for a single cylindrical energy pile and analyzed the system performance on the various conditions. The simulation results found that the thermal resistance of the pile region significantly influenced the system performance. J.Gao et al. [6] conducted numerical and experimental analysis for vertical energy piles and it was found that the W-shaped heat exchanger was the most efficient for the system. In Korea, H. Park et al. [7] also evaluated the performance of energy pile with PHC by numerical simulation and field simulation. According to the simulation results, the energy pile with 3U heat exchanger was expected to provide superior performance to that with W heat exchanger in the intermediate operation, but there was negligible difference for continuous operation. In Japan, Yasuhiro et al.[8] studied on the field performance of an 'energy-pile' system for space heating and the seasonal primary energy reduction rate of the system compared with a typical air conditioning system was 23.2%. Moreover, Jalaluddin et al. [9] evaluated the heat exchange rate of several heat exchangers in a steel energy foundation according to the change of the operation condition by experimental study and the heat exchange rate was 49.6W/m for double-tube, 34.8W/m for multi-tube, and 30.4W/m for the U-tube in continuous operation. Nam et al. [10] developed the prediction method for heat exchange rate of GSHP system including the energy pile which can evaluate the system performance in various design conditions. It was found that the heat exchange rate of an energy pile with a cast-in-concrete pile reached 227.7 W/m in the condition of 16 pipes.

Although the previous researches have been conducted for the application to buildings, the standardization for system design and construction method has not been established yet. Furthermore, there are few researches on the horizontal system with the mat foundation, because the prediction for heat exchange rate (HER) is difficult and it depends on various conditions of installation and construction such as the shape of foundation and pipe, the pattern of building loads, and geological condition of the site. Recently, J. Choi [11] conducted experimental approach for the system design of 'energy-slab' which uses the building foundation as horizontal heat exchanger and he found that HER of the system was 13.3W/m in heating and 15.53 W/m in cooling. However, the proper prediction method of the system performance still remains main obstacle to the use of the energy-slab system.



**Figure 1 Horizontal heat exchanger of the energy-foundation system**

The GSHP system for horizontal heat exchanger offers great benefits in the view of the cost-efficiency especially when it is applied to the large site. In recent years, many high-rise residential buildings have been constructed in Korea, and they have mostly underground parking lot as large as total site area. Even though the horizontal GSHP system cannot achieve as high heat exchange rate as vertical GSHP system, it is still available and cost-efficient particularly in the large site area. Therefore, in order to properly design the system using building foundation as heat exchanger, it is necessary to develop a prediction method for HER. In this study, in order to predict the performance of the system using building foundation as horizontal heat exchanger, the coupled simulation with a ground heat transfer model, a heat exchanger circulation model and ground surface heat balance model has been developed. Furthermore, case studies on predication of HER have been conducted at different conditions of design and installation with variables such as pipe space, installation depth, pipe diameter, circulation water temperature, flow rate, and operation condition.

## 2 SYSTEM SUMMARY

Generally, the building foundations, especially the mat foundation, are installed at depth of -3 ~ -10 m under the ground. Although temperature of this zone is influenced by the heat flux of ground surface, its annual fluctuation is relatively stable. This system utilizes building foundation as heat sink or heat source of GSHP system by installing horizontal heat exchanger pipes in concrete foundation. It is possible to reduce initial investment costs and to apply to building structure such as the underground parking lot. In this research, Figure 1 shows the horizontal heat exchanger of the energy-foundation system. If the ground heat exchangers are installed at deeper level, HER would be achieved higher but installation cost can be increased. Pipe space and pipe diameter also are important design factors in this system. In this study, for the optimum design of these horizontal heat exchanges, heat exchange rate between underground and circulation water in the piping has been calculated by the numerical simulation. Figure 2 presents system configuration of GSHP system with the energy-foundation. This heat source system consists of heat pump, circulation pump and horizontal heat exchanger, which can be combined with various secondary systems.

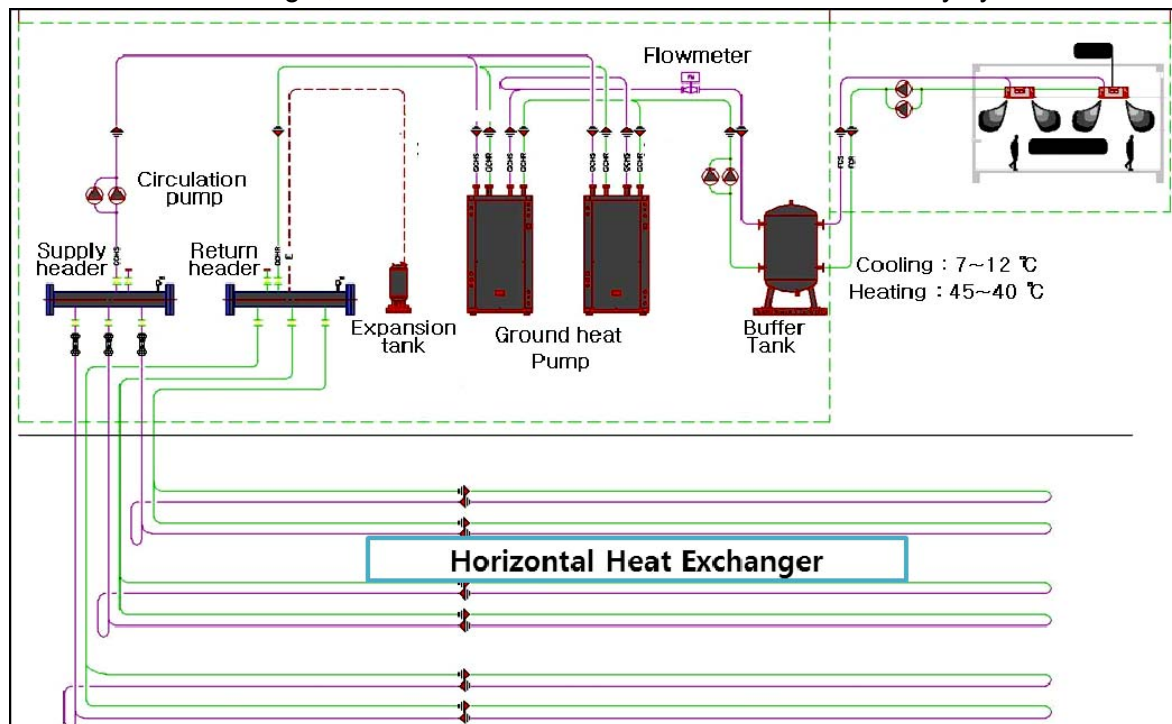


Figure 2 System configuration

### 3 SIMULATION OVERVIEW

#### 3.1. Prediction model of ground heat exchange rate

##### Nomenclature

$\alpha$	: each phase (liquid water, water vapor, and solid soil particles)
$\varepsilon\alpha$	: volume ratio of each phase $\alpha$ ( $0 \leq \varepsilon\alpha \leq 1$ )
$\rho\alpha$	: density of phase $\alpha$ [kg/m <sup>3</sup> ]
$v_i$	: velocity vector [m/s]
$k_{ij}$	: permeability tensor [m <sup>2</sup> ]
$\mu$	: viscosity [kg/ms]
$Q_p$	: mass generation term
$Q_T$	: energy generation term
$\delta_{ij}$	: Kronecker tensor
$V\alpha$	: absolute value of the velocity vector ( $\sqrt{v_i^\alpha v_i^\alpha}$ )
$Pr$	: Prandtl number
$Re$	: Reynolds number
$\lambda$	: heat conductivity [W/mK]
$c$	: specific heat [J/kgK]
$T$	: water temperature [°C]
$\rho$	: density [kg/m <sup>3</sup> ]
$U$	: flow velocity [m/s]
$P$	: rate of discharge [L/s]
$C$	: specific heat [J/kg°C]
$A$	: area [m <sup>2</sup> ]
$h$	: convective heat transfer rate [J/sm <sup>2</sup> °C]
$w$	: water

The heat exchanger rate of GSHP system depends on the design, installation and operation condition of heat exchanger. In order to consider these conditions and optimize the system, it is necessary to develop the simulation tool which can be applied to various conditions of shape and thermal properties. In this study, the simulation method was developed coupled with the ground heat transfer model, the horizontal heat exchanger model and the surface heat balance model.

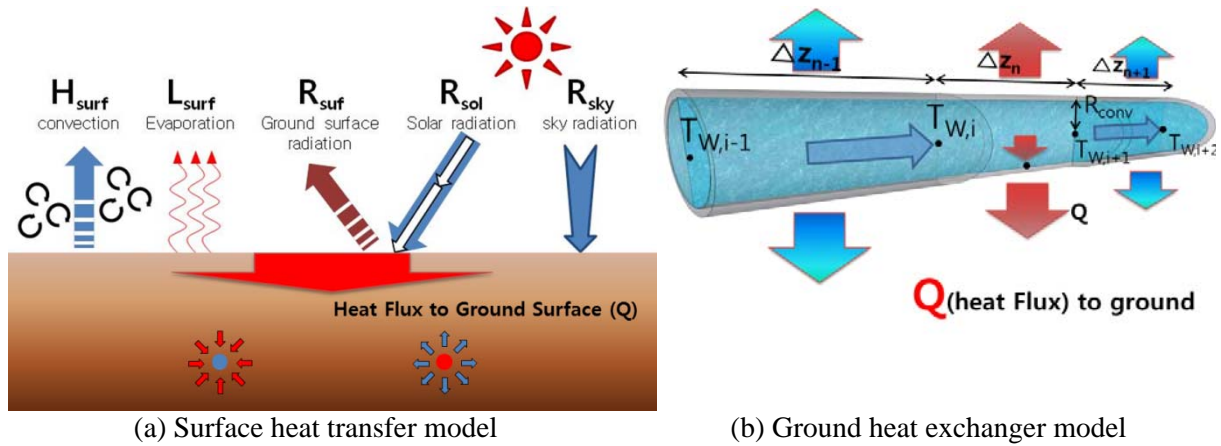
The heat transfer in the soil was calculated by FEFLOW which was based on finite element method and was widely used in fields of groundwater, material and heat transfer analysis. In this model, heat and material transfer in soil was calculated for three phases of gas, liquid and solid, respectively. Equations (1) to (3) present the governed equations of mass conservation, momentum conservation and energy conservation.

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha) = \varepsilon_\alpha \rho^\alpha Q_p^\alpha \quad (1)$$

$$v_i^\alpha + \frac{k_{ij}^\alpha}{\varepsilon_\alpha \mu^\alpha} \left( \frac{\partial p^\alpha}{\partial x_j} - \rho^\alpha g_j \right) = 0 \quad (2)$$

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_i^\alpha E^\alpha) + \frac{\partial}{\partial x_i}(j_{iT}^\alpha) = \varepsilon_\alpha \rho^\alpha Q_T^\alpha \quad (3)$$

Heat flux  $Q$  from the ground surface to underground is given by the following balance equation (4). Figure 3 (a) shows a schematic of the heat transfer on the ground surface. Each detailed equation was explained in previous paper of Nam et al. [11]



**Figure 3 A schematic of the heat exchanger.**

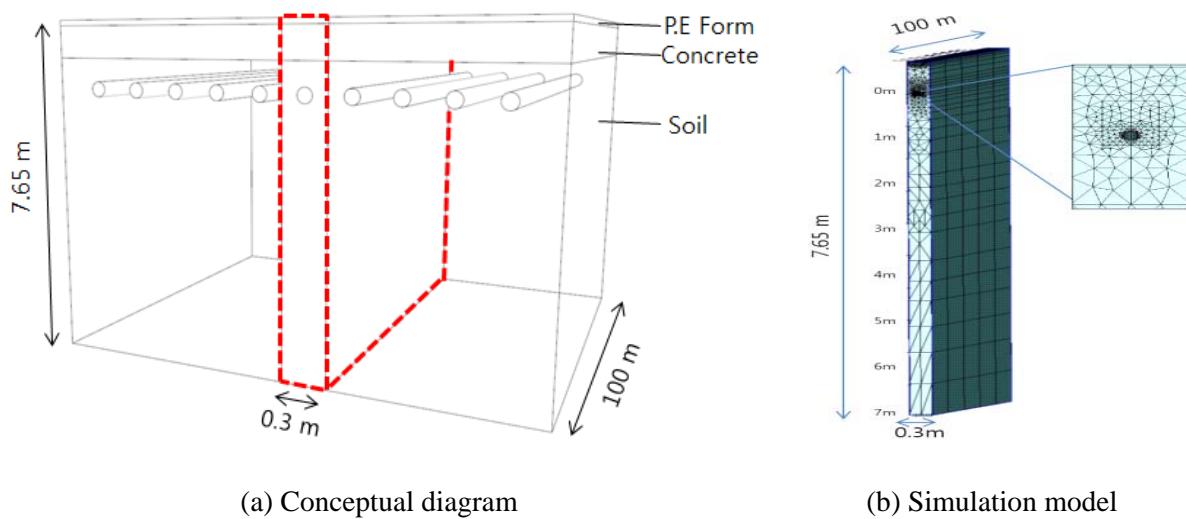
$$Q = R_{sol} + R_{sky} - R_{surf} - H_{surf} - L_{surf} \quad (4)$$

The ground heat exchanger model consists of the circulatory water model with a 1-dimensional advection-diffusion equation to calculate the heat exchange rate between the circulatory water and pipe. The temperature of the circulatory water was given by the following equation (5).

$$\frac{\partial T_w}{\partial t} = -\frac{\lambda_w}{\rho_w C_w} \frac{\partial^2 T_w}{\partial z^2} + U_w \frac{\partial T_w}{\partial z} + \frac{hP_w}{\rho_w C_w A_w} (T_1 - T_w) \quad (5)$$

Figure3 (b) shows a concept of the horizontal ground heat exchanger model. This calculation method which combines three models of the ground heat transfer model, ground heat exchanger model and surface heat balance model was described in previous research and its validity was verified by the comparison analysis with experimental results. [10]

### 3.2 Overview of analysis model

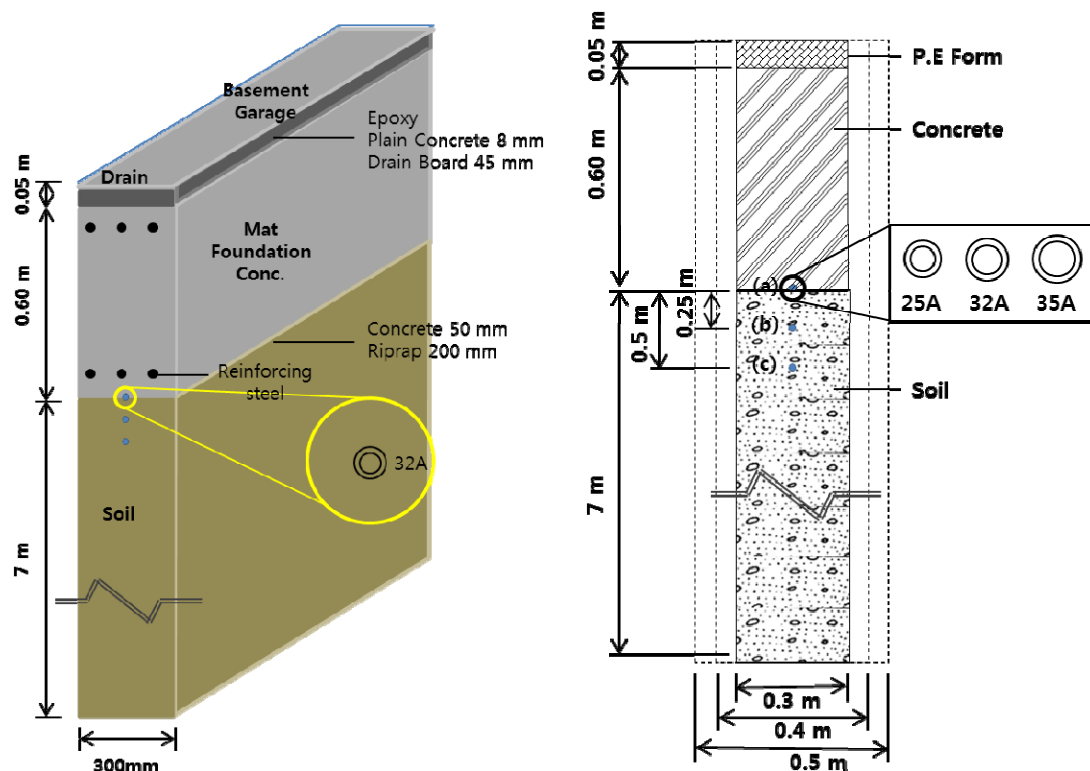


**Figure 4 Simulation model**

In this study, in order to evaluate the heat exchange rate of the proposed system, simulation model was developed as shown in Figure 4. Horizontal heat exchange pipes were installed under the parking lot at depth of 0.65 m from the ground surface with pipe space of 0.3 m, since E. Pulat et.al. [12] conducted experimental study of horizontal ground heat pump system and found that 0.3 m of pipe space was adequate to small capacity system.

Simulation model for the prediction of the heat exchange rate was shown in Figure 4-(b). Simulation domain was set to 0.3 m  $\times$  7.65 m  $\times$  100 m which has the cast-in-place concrete layer (depth of 0.65 m) and the soil layer (depth of 0.65 m to 7 m). The simulation model, including the pipe, the concrete and the soil, was computed by detailed finite element method (FEM) for accurate calculation. Table 1 shows the thermal property of each material.

In addition, the boundary condition on the surface was determined from the calculation result of the surface heat balance model, and those sides were set to be adiabatic condition. In this paper, the underground temperature of depth at -3 m was calculated by the surface heat balance equation and surface heat flux of the analysis model was the input considering convective heat transfer between indoor air of basement and floor surface. The base case has the pipe of 32A, pipe space of 0.3m, and installation position between the foundation and the soil shown in Figure 5-(a).



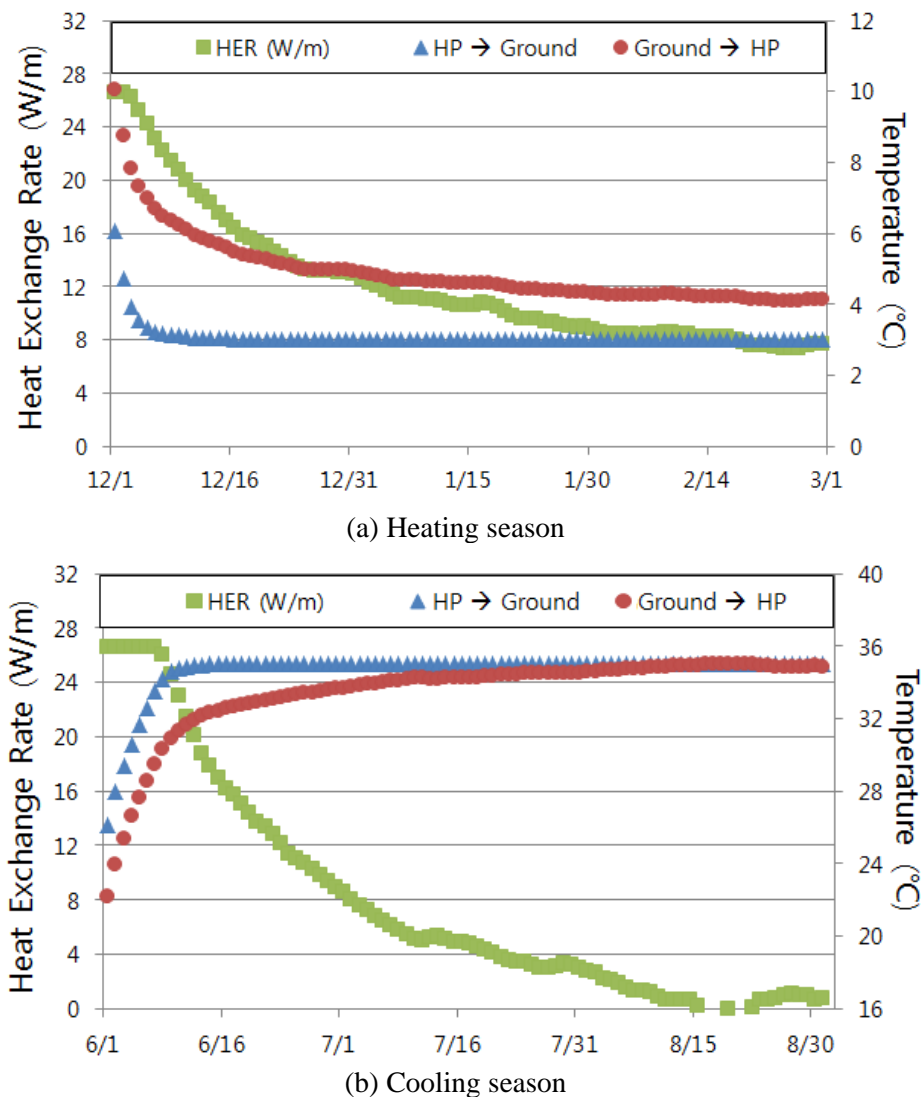
**Figure 5 Conceptual diagram of heat exchanger**

Figure 5 presents the conceptual diagram of the horizontal heat exchanger in the foundation. Tables 2 and 3 show the simulation conditions of the base case and the conditions of all cases for case study, respectively. In this study, the optimum condition of the installation depth, piping space, pipe diameter and operation condition were considered by case study. In order to maintain the superiority of the system compared to the conventional air-source system, the circulation water temperature was controlled to the limited water temperature (LWT). In this study, LWT was set at 3°C during heating season and 30°C during cooling season. Cases 1 to 17 are the condition for heating and Cases 18 to 20 are conditions for cooling with different LWTs, because the design specification of ground heat exchanger could be decided by calculation results in heating operation.



## 4 SIMULATION RESULT

### 4.1 Result of Case 1

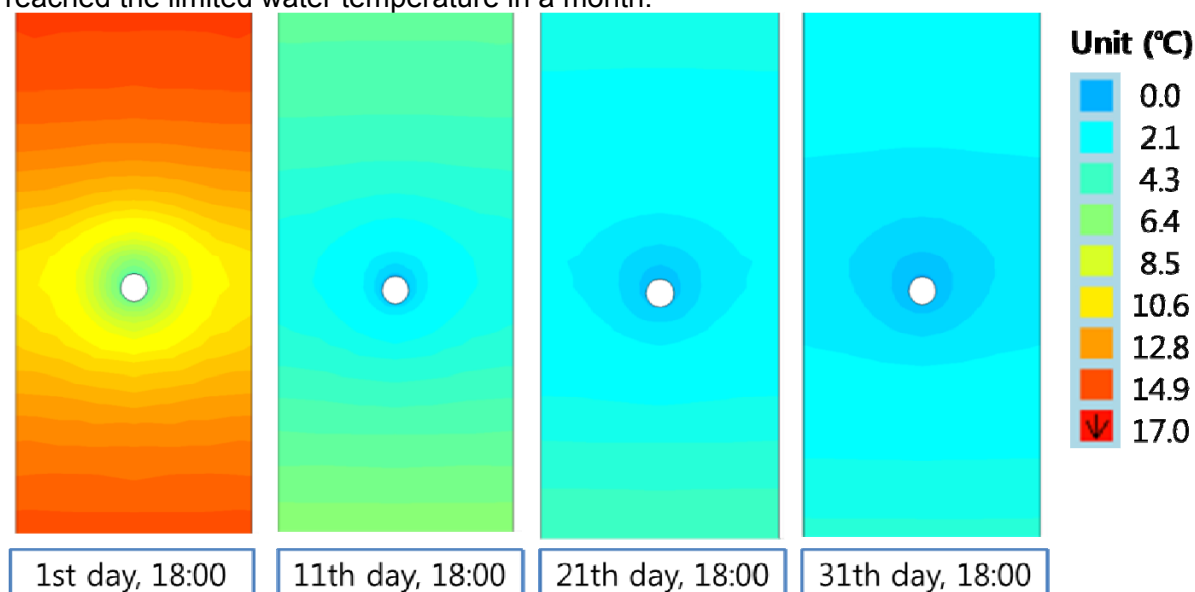


**Figure 6 Change of circulation water temperature and daily heat exchange rate**

Figure 6 shows the simulation result of the heat source temperature and the heat exchange rate during the heating period in Case 1. The temperature difference between the inlet and outlet maintained at 4°C for approximately one week from the start of operation. However, temperature of heat source rapidly decreased due to the drop of ground temperature by heat extraction from the ground. Finally, the average outlet temperature during the heating period was around 4.9°C. The average heat exchange rate during the heating period was calculated to be 12.2 W/m. This figure is similar to experimental result of Choi [11], 13.3W/m, but the verification of the simulation method should be considered by additional comparison analysis. In heating season, this system has possibility of higher HER than calculation results because there is heat emission from car or human, mechanical equipment in underground parking lot.

On the other hand, in cooling season, average outlet temperature was 29.4°C and the average heat exchange rate was 3.6 W/m (Case 19). At the end of cooling season, it was found that heat emission to the underground was difficult due to the rise of underground

temperature. Figure 6 shows the heat distribution around the heat exchanger. It was confirmed that the soil temperature around the heat exchanger gradually decreased and reached the limited water temperature in a month.



**Figure 7 Heat distribution around the heat exchanger**

#### 4.2 Calculation results of all cases

Figures 8 (a) to (h) present the results of case studies, in which the result of base case was compared with the other cases of different conditions, with variables such as pipe space, installation depth, pipe diameter, circulation water temperature, flow rate, and operation condition.

In Figure 8 (a), the wider the piping space was, the higher HER per the length was. However, wide piping space reduces the number of pipes to install at the same space area. Consequently, the best case of HER per unit area was Case 1 in which the piping space was 0.3 m.

Figure 8 (b) shows that the deeper the pipe was installed, the higher HER could be achieved. Generally, the piping at the deeper position makes the efficiency of heat exchange increased, but it causes high installation cost such as the boring cost, the soil covering cost, so on. In this study, Case 5, in which the piping was set to 0.5 m below the base case, can extract 14.0 W/m, which was 15% higher than Case 1, but additional installation period and cost including digging the soil under the foundation were needed.

Figure 8 (d) shows the results of the HER according to pipe diameter at same velocity of circulation water, 0.277 m/s. In general, when the diameter of pipe is large, the HER of the pipe increases due to large surface area of the pipe. However, underground temperature rapidly decreases when the HER between the pipe and underground soil is excessively high. In the calculation results, the outlet temperature of heat exchanger in the case of 25 A pipe was the highest and that in the case of 35A was the lowest. In heating operation of three months, the HER of 32 A was the highest, which was 12.2 W/m with 4.9 °C of average outlet temperature.

Moreover, the HER of ground heat exchanger depends on the operation condition. In heating operation, the heat source condition of the lower limitation temperature makes the HER higher, but it would have lower average temperature of heat source. As shown in Figure (d), when limited water temperature is 5 °C, the HER is 10.4 W/m, which is about 30% lower than that of 0 °C, 15.0 W/m. This indicates that limitation temperature of heat source is a significant performance factor of this system.



Furthermore, Figures 8 (e) and (f) present the results according to flow rate in intermittent and continuous operation. In the results, it was found that the flow rate of 9.52 L/min was the best in the condition of 32A pipe, in which the Reynolds number of circulation water was about 6000. The HER of the continuous operation was about 54% lower than that of the intermittent operation of 9 hours a day, but total extraction heat during the continuous operation was larger than that during the intermittent operation. In addition, in the continuous operation, the effect of the flow rate on the HER was not significant but the effect on the average temperature of circulation water was remarkable.

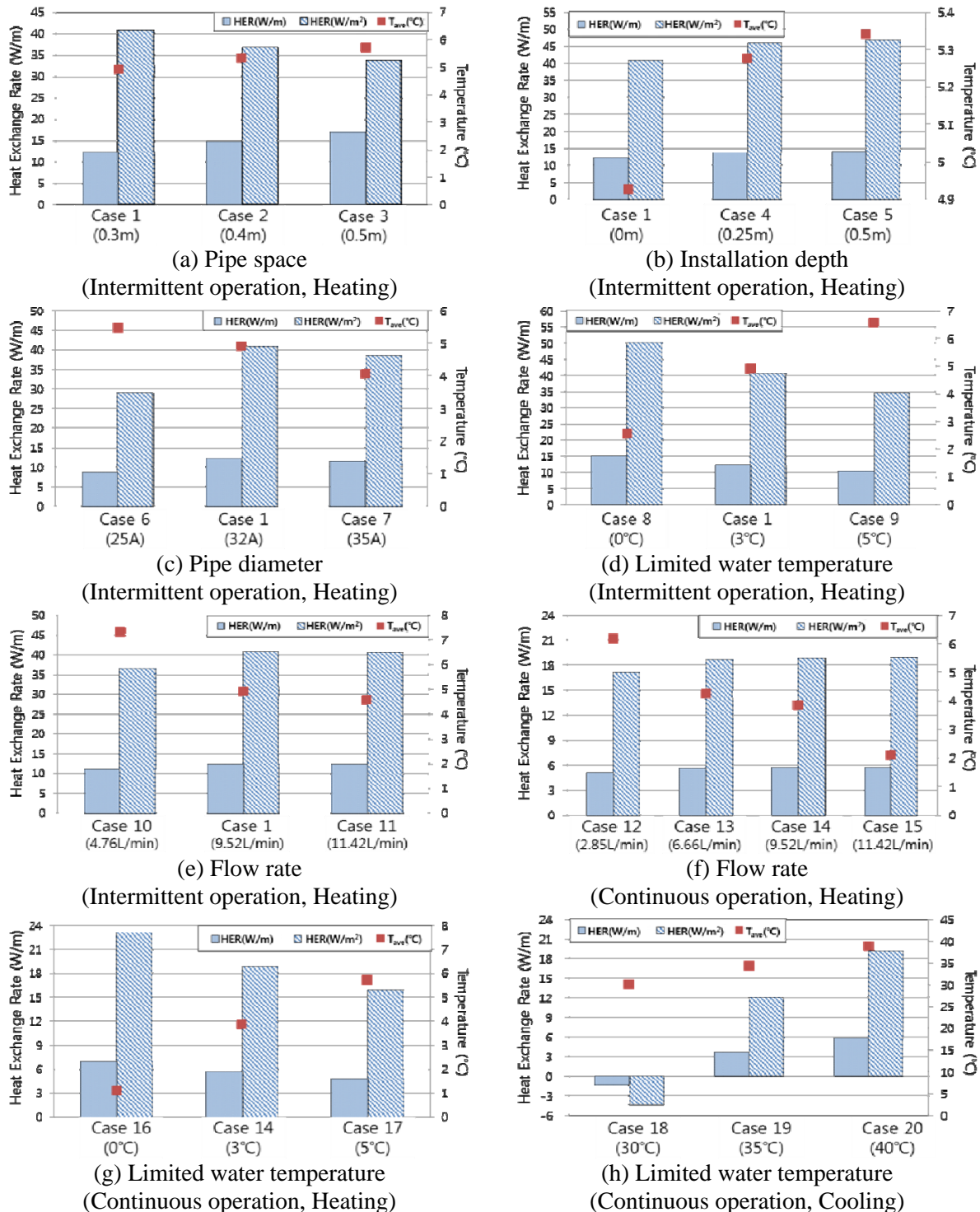


Figure 2 Calculation results of all cases

Figures 8 (g) and (h) show the calculation results according to the limitation temperature of heat source in the continuous operation of heating and continuous operation of cooling, respectively. In continuous operation, the effects of the limitation temperature on the HER were shown as they did in the intermittent operation. Especially, when the limitation temperature was too low (30°C of Case 18) in cooling operation, this system cannot use the underground foundation as the heat sink. In other words, when low limited temperature is set up in cooling operation, heat discharge to the underground does not efficiently perform. Table 4 presents the calculation results of each case including the relative ratio of each case to Case 1.

## 5 CONCLUSIONS

In this study, numerical simulation model is used to develop the method for the prediction of ground heat exchange rate in order to establish the optimum design tool of energy-foundation for horizontal heat exchanger. The simulation model have been developed that couples the models with ground heat transfer, ground surface heat and ground heat exchanger and case studies on predication of HER have been conducted at various conditions of design and installation. The simulation result of HER in heating season is similar to experimental result of Choi [11], but the prediction of HER in cooling season needs additional consideration such as heat emission of cars or mechanical equipment. Through the simulation results, it was confirmed that the energy-foundation system can be energy efficient but its condition can be limited. In more efficient temperature condition compared with the air source heat pump system, the HER of the system was 8.7 ~ 16.9 W/m in continuous operation and 4.8 ~ 6.9 W/m in intermittent operation (9 hour a day). From the calculation results of case studies, it was found that the case of 32 A, piping space 0.3 m, installation between foundation and soil, and flow rate of 9.52 L/min was the best case showing the average heat exchange rate of 14.0 W/m. Furthermore, it is possible for cooling season that this system cannot be energy efficient due to low temperature difference. In other words, energy efficient operation condition of the system can be limited comparing with the conventional system such as air-source heat pump and cooling tower. When the heat exchange pipe is installed at 0.5 m below the foundation, HER can be achieved by 15% higher than the case in which it was installed between the foundation and the soil. However, it is necessary to consider the condition and the situation of installation, because the merit of this system may canceled off due to the increase of cost and period by additional digging construction. In the future, field experiment with real-scale system and comparison analysis with experiment and simulation result will be conducted. Also, construction techniques for the application to real buildings on this study will be developed with Korean construction company.

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