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Development of the Performance Prediction Equation for a Modular Ground Heat Exchanger

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Received: 14 September 2020; Accepted: 13 November 2020; Published: 17 November 2020

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Abstract: Although ground source heat pump (GSHP) systems are more efficient than conventional air source heat pump (ASHP) systems, their high initial investment cost makes it difficult to introduce them into small buildings. Therefore, the development of a method for reducing the installation costs of GSHPs for small buildings is essential. This study proposes a modular ground heat exchanger (GHX) for cost reduction and an improved workability of GSHPs. In addition, a numerical model was constructed for the analysis of the performance of the modular GHX. However, to easily introduce the new GHX at the building design stage, the development of a performance prediction method for the introduction of modular GHXs to small buildings is necessary. Therefore, the entering water temperature (EWT) equation was derived from the calculation methods in the heat transfer process, and the ground temperature model was developed in consideration of the operation condition. The numerical results showed that the average values of EWT and ground temperature were 8.11 °C and 8.00 °C, respectively under an average ambient temperature of 0.42 °C. In addition, the performance prediction model was compared with the numerical results. The results showed that the coefficient of variation of the root mean square error (RMSE) of the ground temperature and EWT model were 5.20% and 1.33%, respectively.

Keywords: numerical analysis; ground source heat pump; heat exchange rate; ground heat exchanger; modular heat exchanger

1. Introduction

The performance of ground source heat pump (GSHP) systems is more stable than that of other heat source systems because the former use heat from the ground, which maintains a constant temperature throughout the year. In particular, although GSHP systems exhibit higher efficiency in energy use compared to conventional air source heat pump (ASHP) systems, their high investment cost, which includes the drilling cost and the difficulty in securing sites for system introduction, makes their introduction into small buildings difficult. For a typical closed-loop GSHP system, earthwork and boring account for approximately 40% of the total construction cost (Figure 1). Therefore, for the introduction of GSHP systems into small buildings, ground heat exchangers (GHXs) that can efficiently use the installation area and reduce the initial investment cost are required.

This study proposed a modular GHX for small buildings, and the performance prediction model was investigated to facilitate performance analysis and field application through numerical analysis. As the modular GHX is installed at a depth of 2 to 4 m, it can significantly reduce drilling and installation costs compared to the closed-loop type, which is installed at a depth of 100 m or more. In addition, the design allows for the easy setting of capacity according to the load conditions of the building (Figure 2).

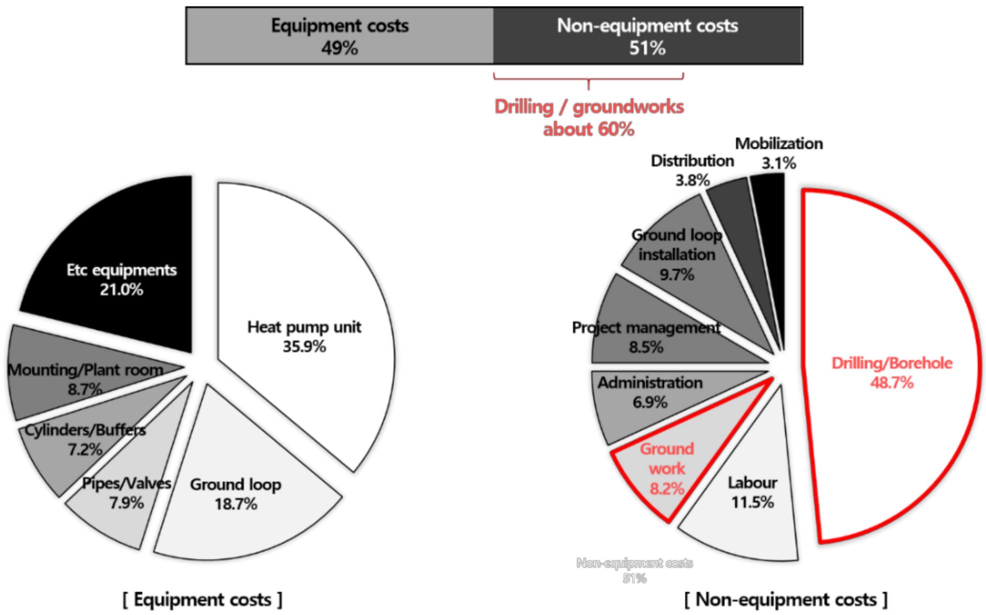

Figure 1. Construction costs of ground source heat pump (GSHP) systems [1].

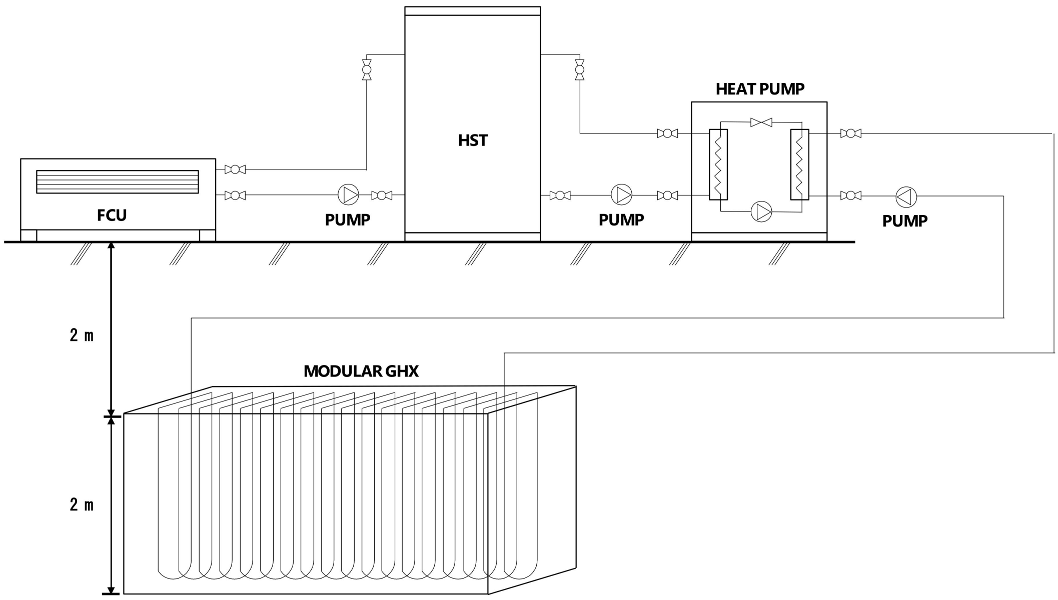

Figure 2. Modular ground heat exchanger (GHX) system.

The high initial investment cost of vertical-type GHXs makes the optimization of ground source systems in small and medium-sized buildings difficult. Therefore, the horizontal GHX with a low initial cost can accelerate the applicability of GSHP systems. In general, to design the proper capacity of a ground heat system, the calculation of the capacity of the heat pump and the length of the ground heat exchanger is important. While the closed-loop type can be designed using tools based on the G-function, the heat-exchange performance of other GHX types, including the horizontal type, can only be identified by conducting a precision analysis using ground heat transfer analysis tools or computational fluid dynamics (CFD). Selamat et al. [2] conducted research on the optimization of a horizontal type GHX using different layouts and pipe materials. According to the results of a numerical study that used an CFD simulation, horizontal GHX in shallow trenches provides a low-cost solution, as it is inexpensive, but it requires a large installation area and a large amount of pipe materials. Yoon et al. [3] conducted experiments on the heat exchange rates of three horizontal GHXs installed in a steel box (slinky, spiral coil, and U-type). Their results showed that the U-type GHX yielded the highest heat exchanger rate per pipe length and a cost-efficiency analysis showed that the U-type GHX was the most economical. To develop a heat transfer model for the horizontal type GHX, Demir et al. [4] carried out a numerical study using MATLAB. In addition, an experimental study was conducted to analyze the validity of the model. The results indicated that the temperature profiles of the numerical data matched the experimental data. To evaluate the parameters of horizontal GHX, Naili et al. [5] experimentally analyzed its performance. The experiment results showed that the coefficient of performance (COP) of the heat pump and system ranged between 3.8–4.5 and 2.3–2.7, respectively. Jeon et al. [6] suggested a scale factor for spiral-coil-type horizontal GHXs to provide an alternative way to design such GHXs. The effects of weather, properties, and configuration were numerically analyzed in their parametric study. The results showed that the scale factor had the main influence, which was validated using an artificial neural network (ANN) and linear regression analysis. Arif et al. [7] analyzed the potential use of a GSHP with horizontal heat exchangers in Thailand and compared it with ASHPs in a two-month experiment. It was found that the GSHP consumed less electricity than the ASHPs. In addition, the CO_2 emission rate could be reduced at a similar rate.

On the other hand, the GSHP system with energy piles and slabs reduces installation and maintenance costs. Moon and Choi [8] presented earth-contact structures that work as heat exchangers, energy piles, and slabs. The structures were filled with a heat carrier fluid and installed under structural elements. According to the experimental data, the COPs of the heat pump with energy piles and slabs were 4.2 and 4.5, respectively. Yu [9] developed a PHC file used to build a foundation as a ground heat exchanger. The performance of the PHC ground heat exchanger was evaluated and the thermal conductivities of each type (sand and gravel) were found to be 32.4 W/m°C and 36.5 W/m°C, respectively. Batini et al. [10] investigated the thermomechanical response of a full-scale energy pile to analyze numerical sensitivity considering pipe configurations, foundation aspect ratios, and fluid conditions. The results showed that the pipe configuration was the major factor influencing the performance of the energy pile. The other factors were similar to the pipe configuration in the analysis.

In general, the evaluation of the effective thermal conductivity of GHX is very important. However, a method of evaluating the effective conductivity of the vertical closed-loop type was presented. Lee et al. [11] evaluated the effective thermal conductivity of vertical closed-loop GHXs in in-situ thermal response tests. The thermal efficiency of GHXs was analyzed under different construction conditions, such as grouting materials and the shape of heat exchange pipe sections. Chang and Kim [12] evaluated the thermal performance of vertical closed-loop GHXs using in-situ thermal response. Four types of GHXs with different borehole configurations were tested, and the thermal conductivity and borehole thermal resistance were derived using the line source method. The results showed that grout thermal resistance had considerable impact on the borehole thermal resistance component (more than 65% of the total borehole resistance). To clarify the effect of groundwater level changes on TRT (Thermal hydraulic Response Test), Luo et al. [13] carried out TRTs with different groundwater levels in a loess deposit area. The effective thermal conductivity of the ground was indicated as 1.64 W/m·K and 2.07 W/m·K at ground levels of 35 m and 10 m, respectively. In addition, the heat transfer rate of the ground heat exchanger increased with increasing groundwater level. In this study, the borehole thermal resistance of the modular GHX was applied in the same way as that of the vertical closed-loop type. There are no methods of calculating the thermal factors of the modular GHX.

Several novel designs for ground heat exchangers have been proposed for several reasons. Pu et al. [14] suggested a novel tree-shaped ground heat exchanger for GSHPs in severely cold regions. In cold regions, thermal load imbalance and fluctuation of soil temperature result in a decrease in thermal efficiency. The numerical study indicated that the performance of the tree-shaped ground heat exchanger was 33.4–38.3% higher than that of the serpentine type. Warner et al. [15] proposed an underground thermal battery to reduce the installation costs in GSHPs. The results showed that the installation costs of the thermal battery could be 39% lower than those of the vertical closed-loop type. Cauret et al. [16] developed a compact collector for the reduction of installation costs of GSHPs. Two field tests were carried out on the compact collectors. The results indicated that the seasonal performance of the vertical installation was higher than that of the sizing equivalent to a horizontal installation. Ahmed et al. [17] carried out small-scale experiments and a numerical analysis on novel borehole heat exchangers. The shape of the cross-section and the presence of spacers were considered. As a result, the thermal performance of an oval shape was better under the impact of groundwater flow than a custom U-tube shape.

This study proposed a modular GHX to reduce installation costs and improve the workability in GSHPs. In addition, a numerical study was carried out to analyze the performance of the modular GHX. In fact, even if a low-cost modular type GHX were to be developed, its introduction would be limited by the absence of readily available tools for capacity design in this field. Therefore, for the field application of the modular GHX, a performance prediction equation that enables simple capacity design is essential.

2. Methodology

2.1. Simulation Model

To develop a performance prediction equation for a modular GHX, a numerical analysis simulation model was constructed using the finite element subsurface FLOW system (FEFLOW), which enables the finite element analysis of groundwater flow, mass transfer, and heat transfer (Figure 3). The study by Kim et al. [18] was referenced for the construction of the numerical analysis model, and HDPE with a pipe diameter of 40 mm was grouted with concrete and installed 2 m below the ground surface. In addition, a one non-dimensional modular GHX unit was simulated under the assumption that adjacent heat exchangers were infinitely iterated. The numerical models of the GHXs and the ground in FEFLOW were validated in a previous study [19]. Since the number of cells per side was 8 or more, the mesh density was sufficient. In the numerical analysis, the flow rate was controlled at 14.98 L/min and the ground inlet temperature was limited to 5 °C to prevent the freezing of the heat exchanger under the heating operation conditions (Table 1). Table 2 shows the input properties of the components of the simulation model. Granite ground and weather data from Seoul, South Korea were used.

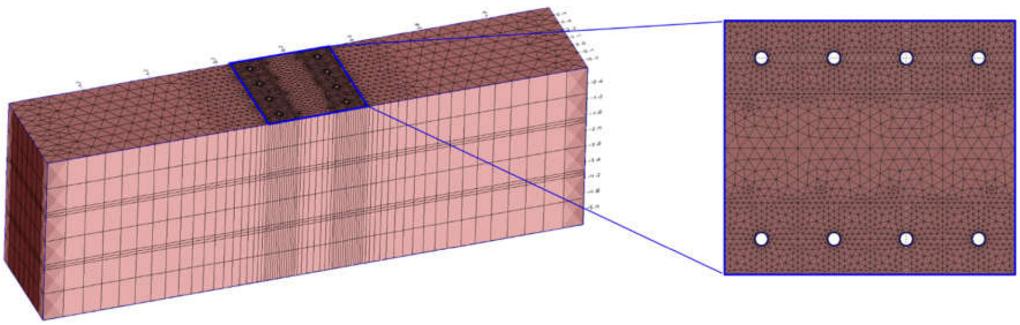

Figure 3. Mesh design of the numerical model.

2.2. Numerical Analysis Results

The numerical results for the average ambient and ground temperature were 0.42 °C and 8.00 °C during the period, respectively. This indicates that the ground source was a better heat source than the air source at the depth of 2–4 m. The results of the numerical analysis of the modular GHX revealed that the ambient temperature does not have significant influence on the ground temperature (Figure 4). The operation of the modular GHX was found to a have a relatively greater effect on ground temperature. LWT and EWT were found to decrease when subjected to operation conditions and increase with the increase of ground temperature during the non-operation period. From the daily data (12/5), it was found that LWT and EWT decreased during the operation period and increased during the non-operation period (Figure 5). Overall, EWT, LWT, and ground temperature continuously decreased as the operation continued and converged to certain levels after a week. The average EWT and LWT were calculated to be 8.11 °C and 7.86 °C during the operation period. The circulating water temperature was found to be strongly correlated with the ground temperature. Results of the numerical analysis showed that the EWT was correlated with the ground temperature and LWT. In a GSHP system, EWT is an important element that affects the performance of the heat pump and GHX, and the performance prediction equation can be used to calculate EWT using the ground temperature and LWT. In addition, the average heat exchange rate (HER) was found to be 20.07 W/m per unit length during the operation period.

Table 1. Simulation conditions.

Calculation Tool	FEFLOW + User subroutine	
GHX	HDPE (diameter: 40 mm)	
Grouting	Concrete	
Operation Condition	Initial Temp 16 °C/Initial ΔT 5 °C/Limitation Temp 5 °C	
	Operation period	12/1–12/20
	Operation time	09:00–18:00
Flow rate	14.98 L/min	

Table 2. Thermal properties.

Components	Thermal Conductivity (W/m·K)	Porosity	Heat Capacity (MJ/m^3K)
Concrete	1.50 W/m·K	0.001	2.80 MJ/m^3K
GHX (HDPE)	0.41 W/m·K	0.001	2.38 MJ/m^3K
Ground (granite)	3.50 W/m·K	0.01	2.92 MJ/m^3K

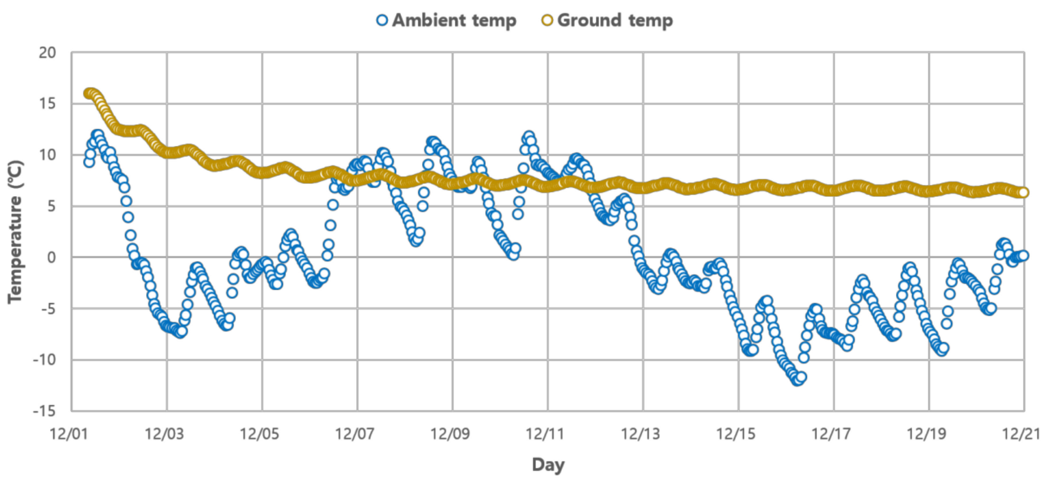

Figure 4. Ground and ambient temperature.

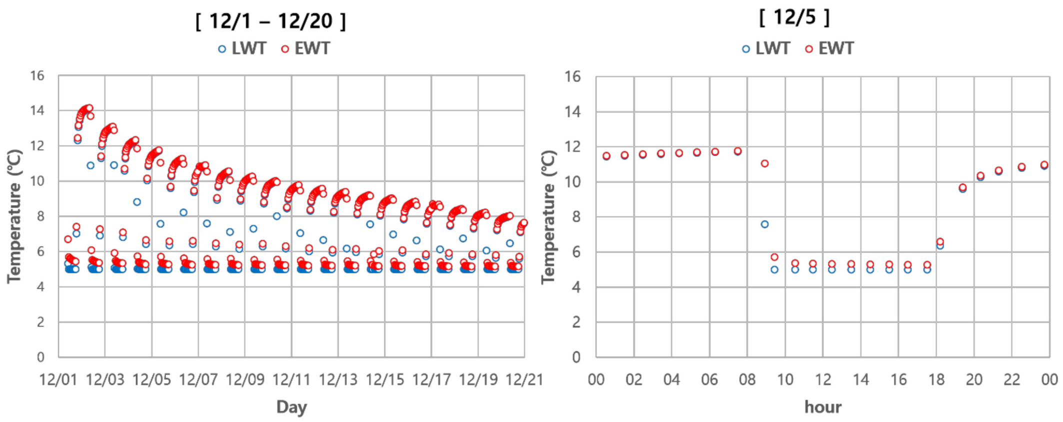

Figure 5. Leaving and entering water temperature.

3. Results and Discussion

3.1. Performance Prediction Model

The low installation cost and improved performance above a certain level of the modular GHX can be highly beneficial compared to other GHXs [18]. The field application of the modular GHX, however, is difficult if the correlations between performance factors and performance are not clearly defined. This study attempted to develop an EWT calculation equation that utilizes LWT and ground temperature using numerical analysis model data of the modular GHX. In general, the heat quantity obtained from, or released to, the ground can be calculated using Equation (1), which uses the circulating water ΔT on the ground source side and the flow rate. Meanwhile, with respect to the design of the closed-loop type GHX, the line source method can be used to calculate the effective thermal resistance of the borehole (R_b) and analyze the thermal characteristics of GHX. The line source method that uses Equation (2), however, was devised for the closed-loop type, and its application has been extended to the standing column well (SCW) type. Therefore, in this study, the borehole thermal resistance was considered by assuming the modular type to be the closed-loop type with a shallow installation depth.

$$Q_1 = m \cdot c \cdot \Delta T \tag{1}$$

$$Q_2 = \frac{L_{bore}\left(T_g - T_w\right)}{R_b} \tag{2}$$

Theoretically, Equation (1), which uses the temperature difference of the circulating water on the heat source side, and Equation (2), that uses the borehole thermal resistance, must produce the same heat quantity (Figure 6). Based on this ($Q_1 = Q_2$), Equation (3) for EWT was derived.

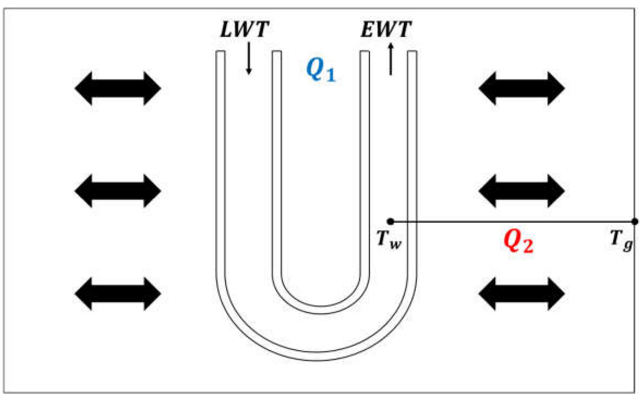

Figure 6. Concept of the heat transfer process under the ground surface.

Equation (3) was obtained by assuming that $T_w = \frac{EWT+LWT}{2}$. In this instance, F_Q can be expressed as a constant value that is determined using properties such as the borehole thermal resistance (R_b), the mass of circulating water (m), and specific heat (c), as shown in Equation (4) [20]. In other words, F_Q is defined as a constant that is determined by the ground condition and the operation setting value of the circulating water. The value of F_Q was calculated by assuming that L_{bore}, which is the vertical length of the GHX, was 2 m.

$$EWT = \frac{1-0.5F_Q}{1+0.5F_Q}LWT + \frac{F_Q}{1+0.5F_Q}T_g \tag{3}$$

$$F_Q = \frac{L_{bore}}{m \cdot c \cdot R_b} \tag{4}$$

The ground temperature is affected by air, solar radiation, and the heat transfer caused by the operation and non-operation (recovery) of the modular GHX. To predict a more accurate EWT, a ground temperature model considers the fluctuations caused by both the operation period (Equation (5) and non-operation period (Equation (6) based on the differential equation of unsteady heat balance [21]. Here, delta T is the temperature difference between the initial temperature and the temperature after time t. Moreover, k is the thermal conductivity (W/m·K), Q is the heat transfer rate of GHX (W), S is the surface area of GHX (m^2), C is the heat capacity of the ground (J/K), and t is the time(s).

$$\text{delta T} = \frac{Q}{kS}\left(1-e^{-\frac{kS}{C}t}\right)\ (\text{recovery period in heating, operation period in cooling}) \tag{5}$$

$$\text{delta T} = \frac{Q}{kS}(e^{-\frac{kS}{C}t})\ (\text{operation period in heating, recovery period in cooling}) \tag{6}$$

R_b in Equation (4) was calculated as the sum of the fluid flow and pipe conduction thermal resistance (R_p) and the thermal resistance of the grouting material (R_{gt}).

$$R_b = R_p + R_{gt} \tag{7}$$

R_p was calculated using Equations (8) and (9) for a single U-tube and double U-tubes, respectively [19]. d_i, d_o, h_{conv}, and k_p denote the inner diameter, outer diameter, convective heat transfer coefficient, and thermal conductivity of the pipe, respectively.

$$R_p = [(\frac{1}{\pi d_i h_{conv}} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k_p})]/2 \tag{8}$$

$$R_p = [(\frac{1}{\pi d_i h_{conv}} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k_p})]/4 \tag{9}$$

R_p of the modular GHX was calculated using Equation (10) by assuming the modular GHX to be the closed-loop type with two double U-tubes.

$$R_p = [(\frac{1}{\pi d_i h_{conv}} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k_p})]/8 \tag{10}$$

R_{gt} was calculated using Equation (11) by assuming the borehole shape factor as C-shape, because the shape factor of the modular GHX was not defined (Figure 7 and Table 3).

$$R_{gt} = \left[\beta_0\left(\frac{d_b}{d_o}\right)^{\beta_1} \times k_{gt}\right]^{-1} \tag{11}$$

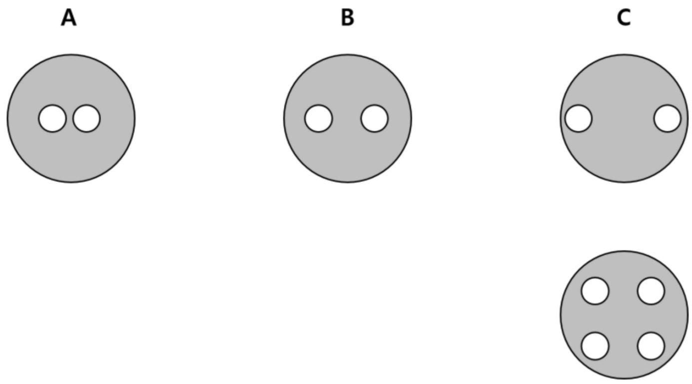

Figure 7. Borehole resistance shape factors for U-tube.

Table 3. Coefficients for the borehole resistance shape factor.

	β_0	β_1
A	20.10	−0.9447
B	17.44	−0.6052
C	21.91	−0.3796

3.2. Results of Performance Prediction Model

The ground temperature and EWT prediction models were used to calculate temperature levels during the heating period (1–10 December). Figure 8 shows the ground temperature and EWT results derived from the numerical model and prediction model. From the beginning of the operation of the modular GHX, both the ground temperature and EWT showed a tendency to decrease, and the decrease in temperature slowly decreased over time. The prediction models exhibited patterns that were similar to those of the numerical data. The equation data and simulation data, however, exhibited differences of 0.35 and 0.19 °C for the ground temperature and EWT during the analysis period (Table 4).

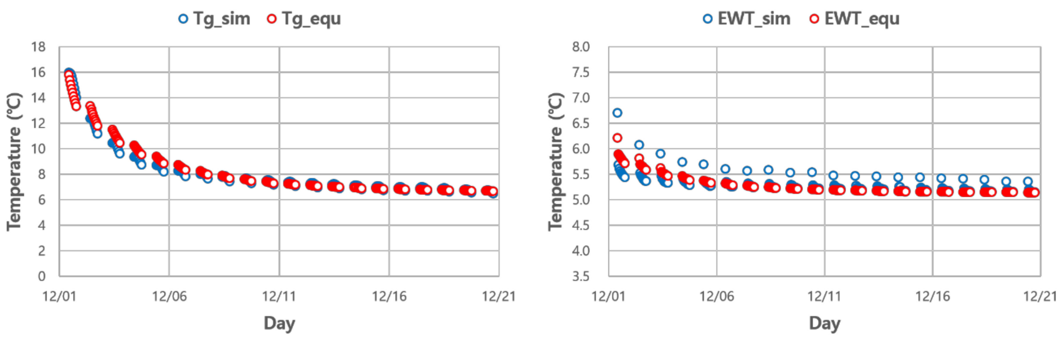

Figure 8. Result of the performance prediction equation.

Table 4. Comparison of simulation and equation data.

	Simulation	**Equation**
Calculation method	FEFLOW	Performance prediction equation
Ground condition	Granite (3.50 W/m·K)	
Calculation period	12/1–12/20	
Calculation time	09:00–18:00	
Average T_g (°C)	8.00 °C	8.35 °C
Average EWT (°C)	8.11 °C	7.92 °C

An error analysis was conducted to examine the errors in the equation and numerical data. The indices used in the error analysis were the root mean square error (RMSE) and the coefficient of variation of the RMSE (CV(RMSE)), which were calculated using Equations (12) and (13). According to the ASHRAE guidelines [22], when the CV(RMSE) is between 10 and 20%, the prediction model can be generally considered to be the best empirical model. In addition, when the index is within 30%, the prediction model can be said to be sufficiently calibrated. The error analysis results showed that the CV(RMSE) values of the ground temperature and EWT prediction models were 5.20% and 1.33%, respectively, indicating that the derived models were valid (Table 5).

$$\mathrm{RMSE} = \sqrt{\frac{\sum\left(\mathrm{EWT_{eq}} - \mathrm{EWT_{si}}\right)^2}{\mathrm{N}}} \tag{12}$$

$$\mathrm{CV[RMSE]} = \frac{\mathrm{RMSE}}{\overline{\mathrm{EWT_{si}}}} \times 100\ (\%) \tag{13}$$

Table 5. Results of the error analysis.

	RMSE	CV (RMSE)
Ground temperature prediction model	0.37	5.20%
EWT prediction model	0.13	1.33%

The main cause of the errors appears to have been the borehole resistance of the modular GHX that could not be accurately calculated. In other words, the most significant limitation of the derived equation was that the borehole resistance of the modular GHX was calculated using the calculation method that is applied to the vertical closed GHX. To facilitate the field application of the modular GHX, it is necessary to reduce errors and to make the prediction of performance relatively easier.

4. Validation of the Simulation and Prediction Equation

4.1. Experiment Set-Up

To validate the results of the simulation and prediction equation, a GSHP system for a modular GHX prototype was constructed and operated for a short time (Figure 9 and Table 6). The configuration of the GHX was slightly different from that in the numerical model. However, the composition pipe and grouting were the same. Three GHXs were installed at 1 m intervals, and hooks were installed along the length of each GHX for transportation.

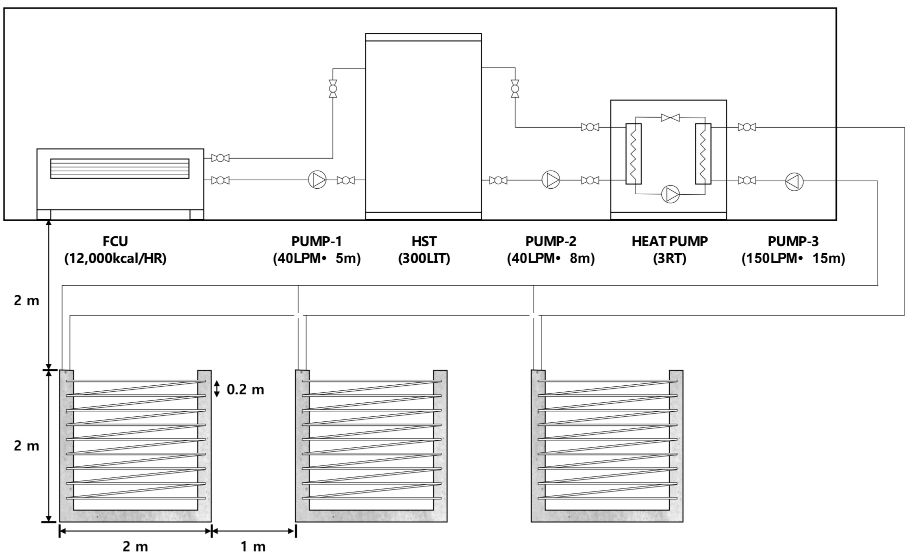

Figure 9. Schematic of GSHP system for the prototype of modular GHXs.

Table 6. Experiment conditions.

Location	Yangsan-si, Gyeongsangnam-do, Republic of Korea	
Operation Conditions	Heat source temperature,	4 °C
	Load temperature	40 °C
	Operation period	1/14
	Operation time	11:00–17:00
Flow rate	83 L/min	

The modular GHX prototype was installed 2 m below the ground surface after the concrete curing process. The system consisted of three GHXs, a fan coil unit (FCU), a heat pump, a heat storage tank (HST), and three circulating pumps (Figure 10 and Table 7). The experiment was carried out for 8 h with a heat source and load temperature of 4 °C and 40 °C, respectively.

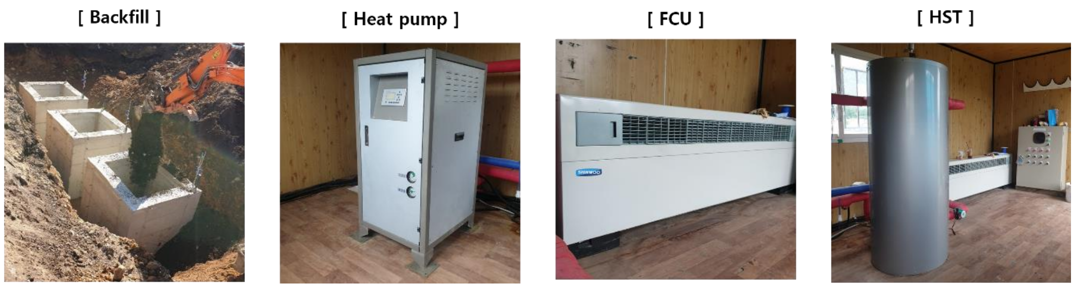

Figure 10. Backfill and experiment equipment.

Table 7. Specifications of the components in the system.

Heat pump	Capacity	Heating	10.69 kW
		Cooling	11.16 kW
	Power consumption	Heating	3.35 kW
		Cooling	2.6 kw
GHX	Pipe (HDPE)	Diameter	40 mm
		Length	67.27 m (per unit)
	Grouting	Concrete	
Calculating pump	Pump-1	40 L/min, 5 m	
	Pump-2	40 L/min, 8 m	
	Pump-3	150 L/min, 15 m	
HST	Capacity	300 L	
	Dimension	Diameter	610 mm
		Height	1530 mm
FCU	Capacity	Heating	12,300 kcal/h
		Cooling	8800 kcal/h
	Power consumption	55 W	

4.2. Experiment Results and Validation

During the operation, the average ambient temperature was 5.88 °C, and the EWT and LWT were 12.64 °C and 11.86 °C, respectively (Figure 11). Because the heat source temperature was always higher than the set-point (4 °C), the results showed that the system on/off depended on the load temperature.

In addition, the heat exchange rate of the modular GHXs was 22.46 W/m during the experiment. This indicates that the modular GHXs received enough heat from the ground, although they were installed 2 m below the ground surface.

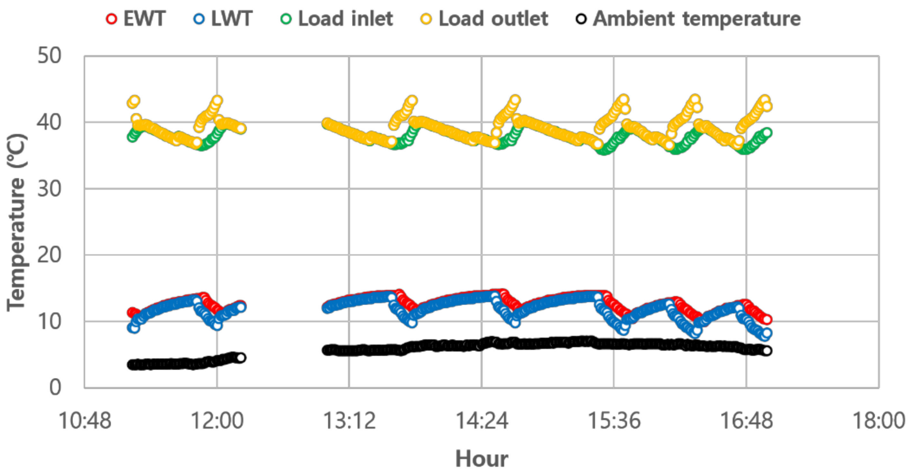

Figure 11. Heat source and load temperature.

The simulation, equation, and experimental results were compared for the validation of the developed equation. The experimental conditions differed from those of the simulation and equation (Table 8). In other words, the differences in weather and operation conditions resulted in a different heat source temperature range in the simulation and experiment. Experimental results showed a difference of 10.64% from the simulation and 18.08% from the equation. However, the heat exchange rates in the simulation, from the equation, and in the experiment were in good agreement with each other.

Table 8. Comparison of simulation, equation, and experiment results.

	Simulation	Equation	Experiment
Operation period	12.1–12.20 (09:00–17:00)		1.14 (11:00–17:00)
Flow rate	14.98 L/min		83 L/min
EWT	8.11 °C	7.92 °C	12.64 °C
ΔT	2.15 °C	2.36 °C	0.79 °C
Heat exchange rate	20.07 W/m	18.40 W/m	22.46 W/m

5. Conclusions

This study proposed a modular ground heat exchanger (GHX) that can reduce the initial investment cost of ground source heat pump (GSHP) systems and is relatively easier to introduce into small buildings. To facilitate the field application of the modular GHX, the examination of factors affecting performance and an equation for easily calculating capacity are required. Therefore, the performance of the modular GHX was analyzed, and a performance prediction equation model was developed through a numerical study. The results of this study can be summarized as follows:

(1) A numerical model of the modular GHX was constructed using the finite element subsurface FLOW system (FEFLOW), and a numerical study was conducted during the heating period (20 days). The average heat exchange rate (HER) was found to be 21.61 W/m during the operation period, and the average ground temperature and EWT were calculated to be 8.20 and 5.31 °C, respectively.

(2) The factors that may affect the performance of a modular GHX, which is installed at a shallow depth of 2–4 m, are the ground and ambient temperatures. When their data were compared with EWT, the ground temperature was found to have a larger influence.
(3) A performance prediction model with ground temperature and LWT as variables was developed using the line source method. It was compared with numerical data, and an error analysis was conducted. EWT and HER exhibited errors of 0.002 °C and 1.041 W/m^2, respectively, based on the period average values. In addition, an error analysis was conducted for the data calculated using the prediction equations and numerical analysis data. The coefficient of variation of the root mean square error (CV(RMSE)) values of the ground temperature and EWT prediction models were found to be 5.20% and 1.33%, respectively, indicating that the models were valid.
(4) Further examination of the proposed performance prediction model is required to determine whether it can predict performance within a valid error range under various conditions. In addition, the verification of the validity of the prediction model by comparing it with empirical data is necessary.
(5) A modular GHX prototype experiment was carried out for a short period to validate the results of the simulation and from the equation. The experimental results showed a 22.46-W/m heat exchange rate. These results were similar to those of the simulation and from the equation.

In this study, the performance of modular GHXs was analyzed through numerical studies to develop performance prediction models. In the future, further simulations and experiments under similar conditions will be carried out to ensure a more accurate numerical analysis and its validation. Moreover, the feasibility of modular GHXs will be reviewed for the introduction to buildings.

Author Contributions: J.K. and Y.N. carried out the numerical simulations and wrote the entire manuscript. J.K. constructed the simulation model and developed the performance prediction model. Y.N. reviewed the results and the entire manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Korean Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20188550000430).

Conflicts of Interest: The authors declare no conflict of interest.

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