C O M M O N S D E E D

저작자표시-비영리-변경금지 **2.0** 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:

저작자표시. 귀하는 원저작자를 표시하여야 합니다.

비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.

변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 이용허락규약(Legal Code)을 이해하기 쉽게 요약한 것입니다.

Disclaimer

Master's Thesis of Engineering

Thermal Performance Evaluation and Applicability of Mat-type Horizontal Ground Heat Exchanger

매트형 수평형 지중 열교환기의 열적 성능과 적용성 평가

February 2023

Graduate School of Engineering
Seoul National University
Architecture & Architectural Engineering Major

SANGHA LEIGH

Thermal Performance Evaluation and Applicability of Mat-type Horizontal Ground Heat Exchanger

Advised by Prof. Myoung Souk Yeo

Submitting a master's thesis of
Engineering

February 2023

Graduate School of Engineering
Seoul National University
Architecture & Architectural Engineering Major

SANGHA LEIGH

Confirming the master's thesis written by
SANGHA LEIGH
February 2023

Chair	____________________	(Seal)
Vice Chair	____________________	(Seal)
Examiner	____________________	(Seal)

Abstract

To achieve carbon neutrality, buildings are also required to reduce their use of fossil fuels, and for this reason, the conversion to renewable energy is in progress. The geothermal source can supply energy that is relatively stable. However, it is mainly used in public facilities and large buildings because the installation cost for ground source heat pump using vertical GHEs is not small. GHEs that increase the surface area of the GHE rather than the straight-line type are being studied to compensate for the installation cost problem.

In this study, the thermal performance of the horizontal GHE was evaluated through Energyplus simulation and experimentation to evaluate the applicability of the horizontal mat-type GHE, and the energy consumption of each combination was compared and analyzed.

Mat-type GHE modeling was conducted for the simulation application. Through this model, the heat absorption of one module (20 capillary tubes) of a mat-type GHE was derived when simulating the heating of a simple system consisting of radiant heating floor and heat pumps in Incheon.

To verify the mat-type GHE model, the amount of heat rejection was compared with the Energyplus simulation and the experiment. First, the ground temperature model derived the soil parameters required for simulation using the trial-and-error method. Through the Energyplus simulation, the maximum heat rejection per module (20 capillary tubes) of the mat-type GHE in winter was about 124W, and at this time, the temperature difference between the inlet and outlet of the GHE was about 1.6℃. When the experiment was conducted in the test cell that was constructed, the heat rejection amount was 124W, and the temperature difference was the same.

This was almost consistent if the heat loss caused by exposure of the trench pipe to outside air was not considered.

Simulations were conducted to find the appropriate use and heating method for the building when using a mat-type GHE in a validated model. The case of coupling office buildings and FCU, residential buildings, and floor heating was set and proceeded. Basically, it is difficult to directly compare the two cases because the heating time is different, but when hot water is made using late-night electricity, the heat pump energy consumption in residential buildings is low. Furthermore, by utilizing the outdoor air compensation control, it was possible to reduce additional energy consumption and ground temperature. This leads to a decrease in the design length of the GHE and a decrease in the required area of the horizontal GHEs. Therefore, it is appropriate to use ground source heat pumps using mat-type horizontal GHEs in combination with systems that use outdoor air compensation control for radiant heating floor for residential use.

Keyword : Ground Source Heat Pump, Horizontal Ground heat Exchanger, Capillary tube, Mat-type Ground Heat Exchanger
Student Number : 2021-28956

Table of Contents

Figure Contents

Table Contents

Chapter 1. Introduction

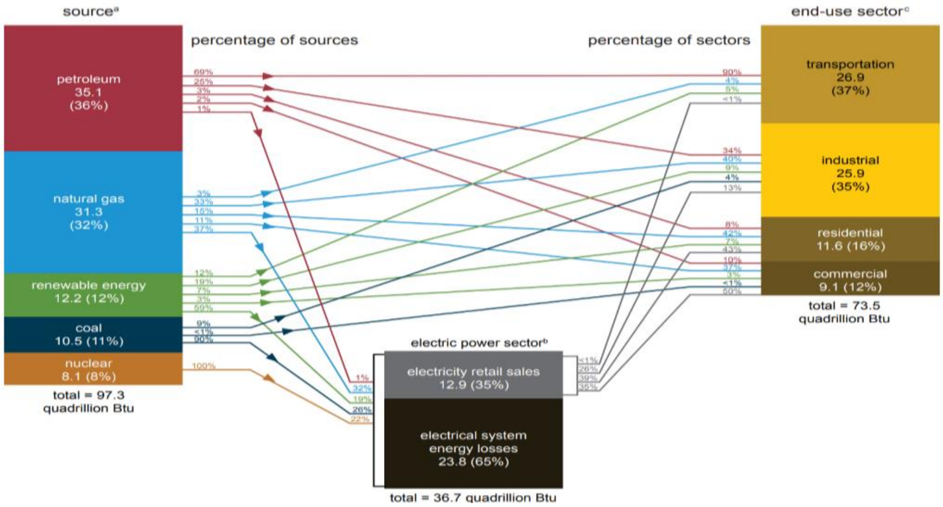
1.1. Study Background

As a reaction to global warming, the Kyoto Protocol and the Paris Agreement established and implemented the objective of attaining net carbon dioxide emissions of all nations without raising the average temperature of the Earth by more than 2°C relative to pre−industrial age. Residential and commercial buildings constitute 28% of all energy consumed in the US, according to the US Energy Information Administration. Among these, fossil fuels are used to power 75.4% of commercial buildings and 76.5% of residential buildings. Due to the high proportion of fossil fuels used in the sector, the conversion of the facility's system to new and renewable energy is required to achieve the reduction requirement. New and renewable energy sources are gaining attention as alternatives to fossil fuels. Most renewable energy sources have the limitation of being difficult to provide reliable energy. This is a vulnerable for building system that demands constant energy consumption. However, geothermal sources may supply consistent energy regardless of the time of day.

Closed loop ground heat exchangers (hereinafter referred to as GHE) are categorized into two types by direction, vertical and horizontal. The cost of installing vertical types is rather high.[1] The horizontal type is less expensive, but because it is installed at the shallow underground obtaining a sufficiently stable heat is difficult.[2,3]

---

[1] Benli. H. (2013). A Performance Comparison between a Horizontal Source and a Vertical Source Heat Pump Systems for a Greenhouse Heating in the Mild Climate Elaziğ, Turkey. *Applied Thermal Engineering*, 50(1), 197–206.
[2] Jin, S., Lee, J., Kim, T., & Leigh, S. (2012). Evaluation of the Heating Performance of Vertical and Horizontal GSHP Systems by Simulation. *Proceeding of Annual Conference of the Architectural Institute of Korea*, 32(2), 265–266.
[3] Hwang, Y., Lee, K., Cho, S., & Choi, J. (2011). Evaluation Comparison of Initial Construction Cost and Geothermal Heat Pump Dimension on Vertical and Horizontal Types. Journal of Korean Institute of Architectural Sustainable Environment and Building Systems, 109–112.



[Figure 1.1] energy consumption by source and sector, 2021[4]

The size of the site where the GHE will be installed is also an important consideration when choosing between these two types. Suburban area, where estate is cheap and less crowd, has opportunity to choose a horizontal type GHE. On the other hand, in urban areas, where real estate is expansive and crowded, the options that can be chosen are often limited to vertical types. Since horizontal type has space constraints as described above, there have been many attempts to improve energy efficiency by changing its configuration. Slinky and coil types are representations of horizontal GHE alternatives. Although these types require less site area than the conventional horizontal GHE type, there are disadvantages in that they require more labor, such as twisting pipes, and extra material costs owing to the GHE's longer length.

A mat-type GHE is being tried to overcome this problem. The mat with a capillary tube has a large surface area, so a modular unit may be expected to increase performance, by reducing installation space, labor, and the construction period. However, for practical use, capacity design is essential. Furthermore, studies and verifications

[4] The United States Uses a Mix of Energy Source. (2022, January 10). U.S. Energy Information Administration. https://www.eia.gov/energyexplained/us-energy-facts/

on mat−type GHEs are also required to verify their performance Additionally, the method for estimating capacity of mat−type GHE, which consists of capillary tubes, should be calculated using its area, unlikely that normal GHE is calculated using its length. In this study, the thermal performance of mat−type GHE was investigated to increase the prevalence of horizontal type GHE. And base on this analyzed thermal performance, evaluation about capacity design method and adaptability was performed.

1.2. Purpose of Research

In this study, to increase the applicability of horizontal GHE, higher efficiency was promoted by using a capillary mat. Furthermore, applicability is evaluated by coupling the radiant system, which makes it reasonable to use high temperature chilled water and low temperature hot water made by mat−type GHE as a terminal system. For the reasons listed above, research about the characteristics of common horizontal GHE was reviewed. And the elements which effects to the temperature and performance of horizontal GHE. After that, an approximate capacity design was processed, and thermal performance was evaluated through modeling mat−type GHE by using Energyplus, which is a commercialized building energy simulation tool. To validate the simulation model, an experiment was performed in a test−cell. Based on validation, the terminal system which is reasonable for the outlet temperature of mat−type GHE, radiant system is coupled, and it is compared to conventional systems with vertical GHE through simulation. By comparing thermal performance and energy consumption, the applicability of the mat−type GHE was evaluated. The research scope and methodology along the process of the study are shown below.

(1) Characteristics of GHE and preliminary considerations about a horizontal GHE experiment.

To analyze the characteristics of GHE, composition, classification criteria, and mathematical analysis were reviewed, and the effects of elements on the performance of GHE were assessed. Also, inlet and outlet temperature differences and the evaluation method of horizontal GHE are reviewed through prior research on experimental tests.

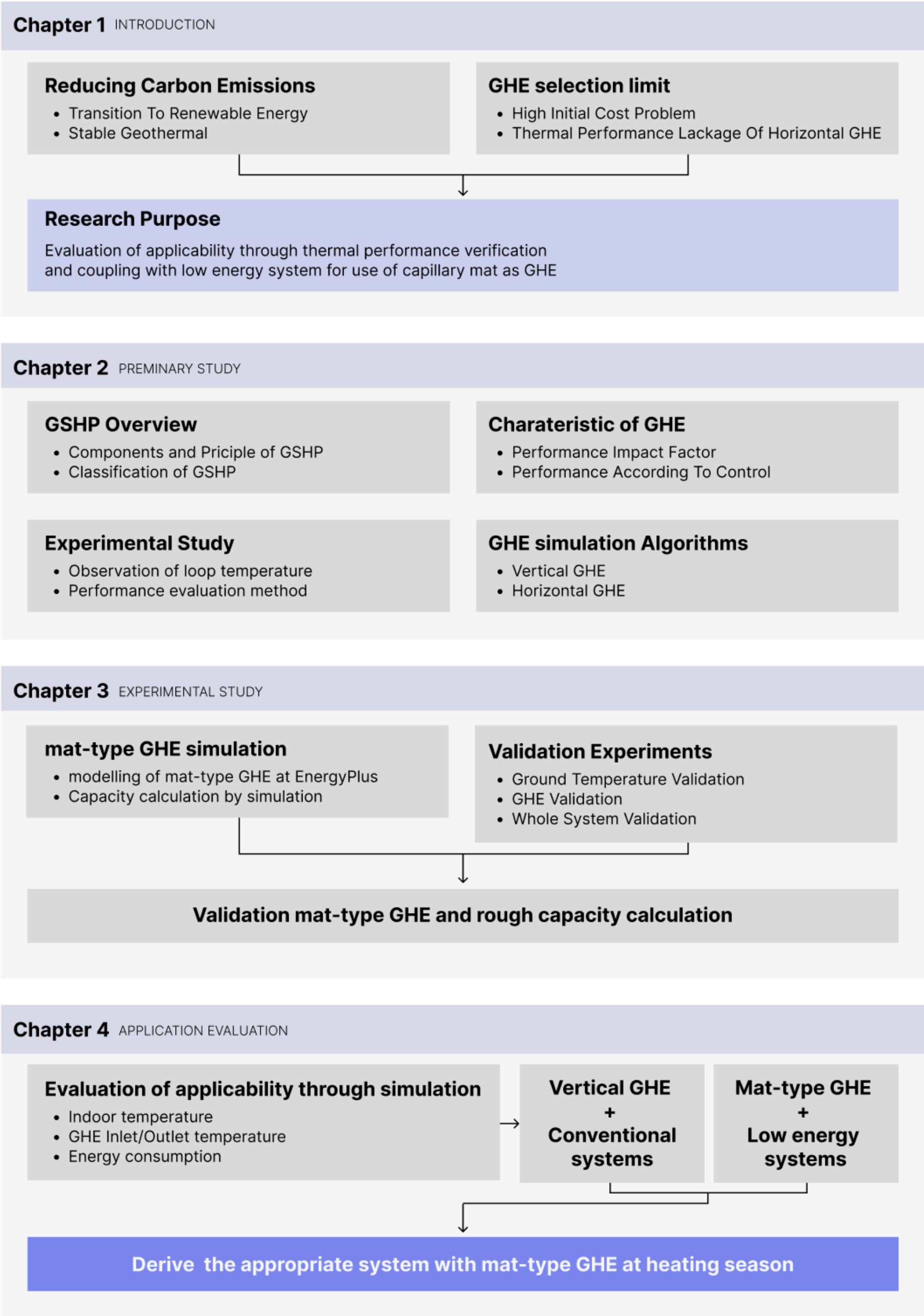
(2) Validating the model of mat-type GHE by using commercialized simulation programs.

Lump capacity design is performed by estimating the amount of heat collected through mat-type GHE using the simulation program Energyplus. And then validation is performed at the test-cell. The simulation model is validated by comparing the inlet and outlet water temperatures of mat-type GHE obtained by actual measurement. And, finally, redeem the previous capacity design method.

(3) Applicability evaluation of low-energy systems using mat-type GHE

Simulation is progressing to evaluate the applicability of mat-type GHE as an alternative system to conventional GHE for lowering energy use. Low-energy systems, consisting of mat-type GHE and radiant systems, and conventional systems, consisting of vertical GHE combined with conventional FCU, are compared by analyzing the energy consumption in small buildings.

The research scope and methodology are shown in [Figure 1.2].



[Figure 1.2] Research flow chart

Chapter 2. Preliminary Study

In this chapter, the features of the ground source heat pump (hereinafter referred to as GSHP) and the characteristics of the GHE according to each shape were first considered. Existing literature and prior studies were investigated and examined.

Consideration was given to the principles and categorization criteria of the GSHP. The thermal performance, algorithm, and modeling approach of the heat pump based on the performance and shape of the GHE were reviewed, and the thermal performance assessment and capacity design method of the capillary mat-type GHE were provided.

2.1. Ground Source Heat Pump Overview

2.1.1 Ground Source Heat Pump Mechanism

Geothermal is heat stored underground, and it accounts for around 47% of solar heat storage.[5] The temperature in the earth near the surface ranges from 10-20℃, depending on the ground. Geothermal is split into deep heat (40-150℃ or more) and shallow heat (10-20℃) based on temperature. Deep geothermal exists 300 meters below the surface and is primarily utilized for direct power generation. Geothermal energy from shallow depths can be collected and supplied anywhere. Most geothermal industries in Korea are shallow geothermal, and they are commonly used in ground source heat pumps.[6]

GHE and a heat pump are the main components of a GSHP. Depending on the area, brine is used to avoid freezing in the GHE,

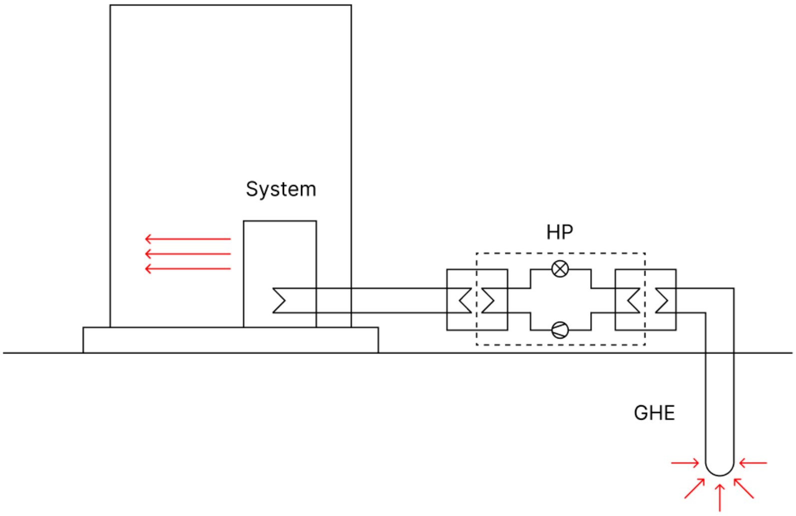
---

[5] Geothermal. (2022, November 8). KNREC. https://www.knrec.or.kr/biz/korea/intro/kor_geo.

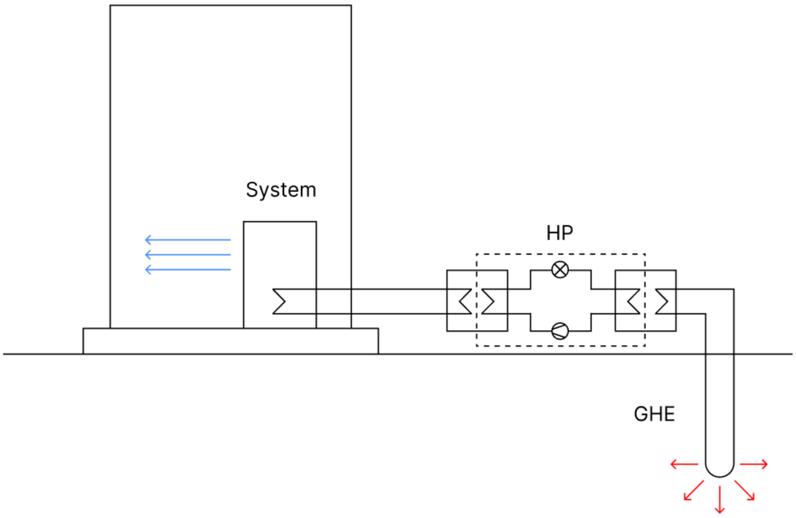
[6] [New Renewable Energy] Exploration of New Renewable Energy Source Part 3 - Geothermal Energy. (2020, January 5). KNRECblog. http://blog.energy.or.kr/?p=20648

which uses water as its heat transfer medium. By laying a pipe underground, it serves to absorb heat from the heat pump's heat source. At this point, the ground serves as a heat source, as seen in [Figure 1.2].

Heat from the GHE is transferred to the refrigerant in the heat pump's evaporator. When the refrigerant evaporates, it transforms into a low-pressure, low-temperature gas that is drawn into the compressor. The refrigerant is delivered to the condenser in a high-temperature, high-pressure state as it is compressed in the compressor, where heat is released. At this point, hot water and heat storage systems are heated using the heat that has been released. The expansion side decompresses the high-pressure liquefied refrigerant, which returns to the evaporator in a liquefied condition at low pressure and low temperature. The refrigerant circulates underground in the evaporator, rises due to the heat recovered from the heat, then enters the heat pump again, and so on. If the heat pump is switched on at the station using a four-way valve, cooling is also an option. The heat transfer medium's heat is absorbed by the earth, which works as a heat sink.



(a) Winter season

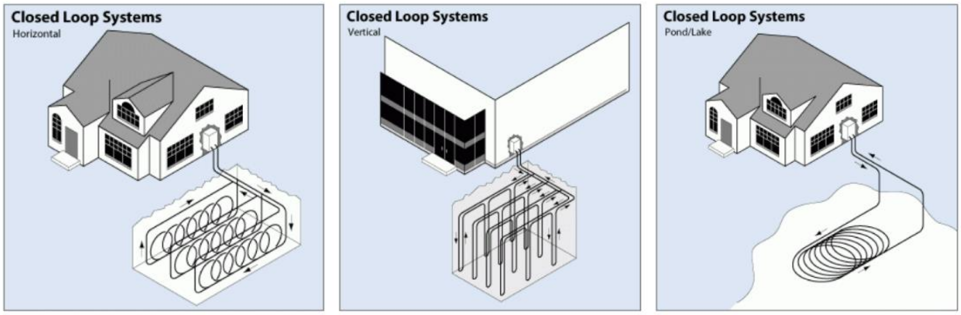


(b) Summer season

[Figure 2.1] Underground Heat Flow Diagram for Heating and Cooling Operations

2.1.2 Classification by the configuration

A wide terminology for soil, groundwater, or surface water, geothermal heat can be categorized as a particular kind of heat source. The other approach is now a closed-loop method, whereas the groundwater method is an open-loop method. A heat exchanger is installed in the ground as part of a GSHP system known as a ground coupled heat pump (GCHP). The installation and configuration of the GHE may be used to categorize the GCHP. The GHE installation type may be broadly classified into vertical and horizontal. In the vertical type, borehole between 100 and 200 meters deep is drilled, a U-shaped high-density polyethylene (HDPE) pipe working as an GHE is installed, and the extra space is filled with grout. The horizontal type involves placing the trench of the GHE horizontally at a depth of 1 to 5 meters underground. Currently, the approach is chosen based on cost and land area.

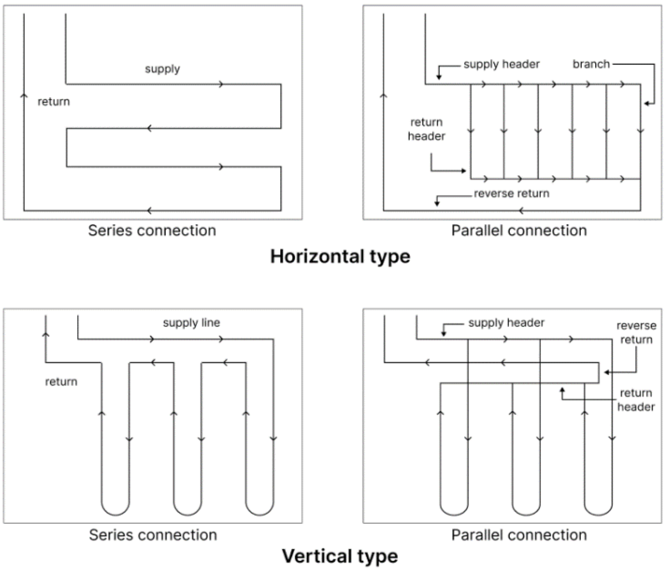


[Figure 2.2] Classification of GSHPs by heat source and configuration[7]

[7] Geothermal Heat Pumps. U.S. Department Of Energy. https://www.energy.gov/energysaver/geothermal-heat-pumps

2.1.3 Arrangement of GHE

The pipeline arrangement type is classified as single pipe/multiple pipes in common with vertical and horizontal, and multiple pipes are further classified as a series connection and a parallel connection. The series connection type, in general, adopts a pipe with a wide diameter, so the heat exchange performance per pipe length is high, and the pipe length is decreased, lowering costs, but the pipe length is limited due to pressure loss in the pipe. This approach is mostly used by the parallel method because it uses small diameter pipes to reduce purchase costs and installation costs. Each circulation circuit loop must be the same length and flow rate. Furthermore, the header is installed in a pipe bigger than the diameter of the loop to balance the pressure acting on the inflow and outflow of the loop.[8]



[Figure 2.3] Schematic Design of Series and Parallel Connections of Horizontal and Vertical Systems

[8] Lim, H. (2005). Comparison of Geothermal System Characteristics. Korea Journal of Geothermal Energy, 1(2), 57–65.

2.2. Literature Review

2.2.1 Performance of GHE

The closed GHE is buried underground and works as the GSHP's heat source. Site−specific soil conditions have a significant effect on the GHE. Due to the effect of outside air and solar radiation, the temperature of the soil varies substantially up to about 5 meters below the surface and increases as the depth decreases. At a certain depth, the temperature approaches the annual average. Thus, the more the buried depth, the greater the overall heat col−lection performance because of the enhanced performance of the heat source's supply capacity.[9,10] Since the horizontal heat exchanger is positioned at a depth of around 2 meters below the surface, it is more affected by the soil, and ground conditions become more significant. Other ground parameters include properties, thermal conductivity and moisture content of the soil, and thermal conductivity of the pipe and backfill. As the thermal conductivity and moisture content of these parameters improve, so does their heat absorption efficiency.

In addition to the installation conditions, there is a strategy for enhancing performance through control. As the GSHP system is initially constructed based on the building's load, it operates automatically when in use. Underground temperatures continue to decrease when heat is continuously absorbed. However, if a recovery interval is provided by intermittent operation to recover underground temperature, it can improve performance and reduce the design length of the GHE by increasing the thermal energy collected.[11] In

---

[9] Nam, Y., & Chae, H. (2013). Prediction of the Heat Exchange Rate for a Horizontal Ground Heat Pump System Using a Ground Heat Transfer Simulation. Korean Journal of Air-Conditioning and Refrigeration Engineering, 25(6), 297–302.

[10.] Nam, Y., & Oh, J. (2014). Study on the Characteristic of Heat Exchange for Vertical Geothermal System Using the Numerical Simulation. Journal of the Korean Solar Energy Society, 34(2), 66–72.

[11] Baek, S., Yeo, M., & Kim, K. (2017). Effects of the Geothermal Load on the Ground Temperature Recovery in a Ground Heat Exchanger. Energy and Buildings, 136(1), 63-72.

addition, as [Figure 2.4] the underground temperature decreases more slowly the shorter the interval between the operation and the recovery time of the underground temperature.

2.2.2 Experiments of Different Configuration GHE

There are some experiments we must see how to conduct and assess the different types of Horizontal GHEs. Through this, the actual entering fluid temperature (hereinafter referred to as EFT) and the performance of the GHE are to be identified.

Arif Widiatmojo[12] conducted experiments to compare the Slinky type and mat type GHEs. Although the Slinky type was high, the coefficient of performance (hereinafter referred as COP) stated that meaningful comparison was problematic, so the experiment was not conducted on the same day. Zhenpeng Bai[13] carried out research to assess the heat transfer rate of capillary tubes in the coastal area.

The heat transfer rate per area of the mat was 30W/m^2 when the seawater temperature was 3.7℃ in January and 150W/m^2 when the seawater temperature was 24.6℃ in summer when the 3m*1m capillary mat was vertically stacked to create a cube and buried 5m underground. It was verified that this was correct, with a 3% error in the value obtained by numerical analysis. BC, Ihm[14] conducted an experiment by analyzing the heating performance of a slinky type horizontal GHE. It was monitored for 35 days, with an average difference of 1.8℃ between EFT and leaving fluid temperature(hereinafter referred as to LFT). When the outside air

---

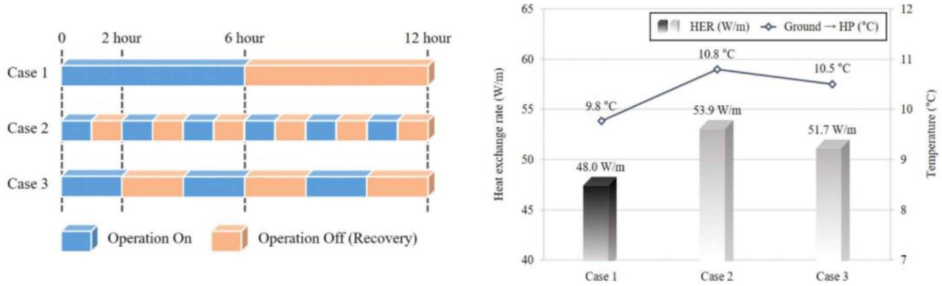
[12] Widiatmojo, A., Gaurav, S., Ishihara, T., Tomigashi, A., Yasukawa, K., Uchida, Y., Kaneko, S., & Yoshioka, M. (2019). Experiments Using Capillary Mat as GHE for Ground Source Heat Pump Heating Application. Energy and Power Engineering, 11(11)..

[13] Bai, Z., Li, Y., Zhang, J., Fewkes, A., & Zhong, H. (2021). Research on the Design and Application of Capillary Heat Exchangers for Heat Pumps in Coastal Areas. Building Services Engineering Research and Technology, 42(3), 333–348.

[14] Ihm, P., & Cho, S. (2016). Experimental Study for Horizontal Geothermal Heat Pump Heating Performance Analysis. Transactions of the Korea Society of Geothermal Energy Engineers, 12(2), 7–12.

temperature is low, the temperature difference reduces, as does the COP. During the experimental period, the COP was 2.1, which was assessed to be the reason for insufficient ground heat exchange due to the heat pump's brief operation due to the low load of testcell. BH, Son15 conducted an experiment by setting a Slinky-type GHE in heating period (March and April) and a cooling period (June and August).

The average temperature difference between EFT and LFT was 1.3℃ for the heating period and 2.4℃ for the cooling period. In various studies, the difference of LFT and EFT of horizontal GHE was 2~4℃, and the LFT was 5~10℃ in the heating period and 25~30℃ in the cooling period.



(a) Operation method

(b) Average HER(heat exchanger rate) and EWT(entering water temperature)

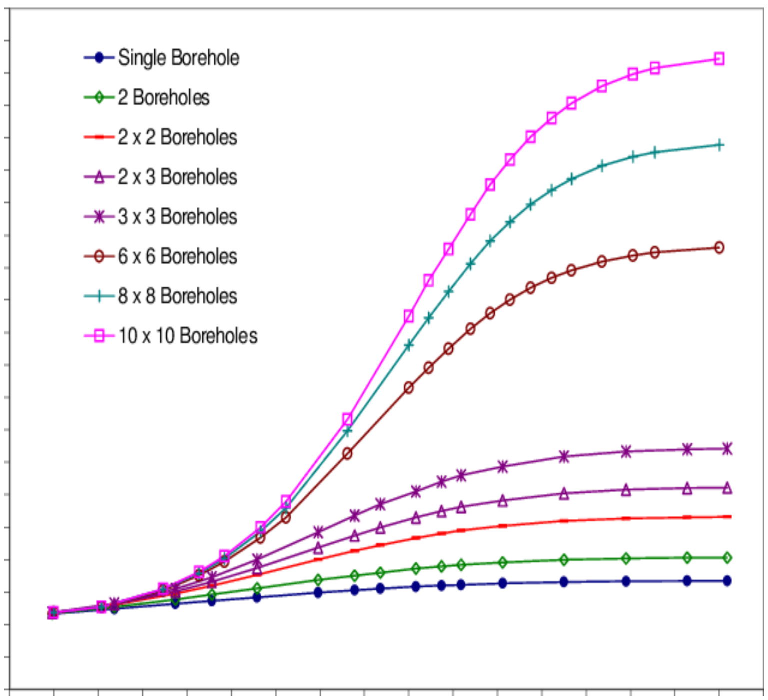
[Figure 2.4] Interval Control and Heat Exchange rate[16]

[15] Son, B. (2012). Performance Analysis of Ground-Coupled Heat Pump System with Slinky-Type Horizontal Ground Heat Exchanger. The Society of Air-Conditioning and Refrigerating Engineers of Korea, 24(3), 230–239.

[16] Bae, S., Jeon, J., Kwon, Y., & Nam, Y. (2020). Study on the Operation Method of Ground Source Heat Pump System Considering Recovery of Ground Temperature. Transactions of the Korea Society of Geothermal Energy Engineers, 16(4), 24–30.

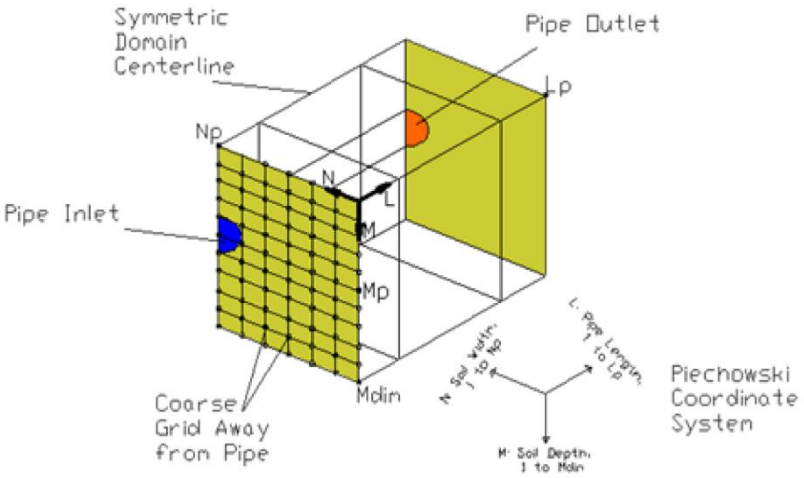
2.2.3 Simulation Algorithm of GHE in EnergyPlus

EnergyPlus analyzes a vertical GHE, or borehole, using a model with a geothermal response function(g−function). Esklison [17] estimates and uses the heat flux transported to the earth over time by various batches using the finite difference approach in the model of the g−unction. The time required for a ground simulation that takes a long time to analyze numerically can be reduced, as demonstrated in the [Figure2.5]. G−functions are supported by the commercial programs EED, GLDpro, and GLHEpro that assist capacity design.



[Figure 2.5] Temperature response factors (g-functions) for various multiple borehole configurations compared to the temperature response curve for a single borehole[18]

[17] Eskilson, P. (1987). Thermal analysis of heat extraction boreholes.
[18] Xu, X., & Spitler, J.D. (2006). Modeling of Vertical Ground Loop Heat Exchangers with Variable Convective Resistance and Thermal Mass of the Fluid.



[Figure 2.6] Piechowski Coordinate System

EnergyPlus simulation of a horizontal GHE uses a numerical model developed by Piechowski.[19] This model is numerical analysis using a backward finite difference approach to calculate the temperature of the heat transfer fluid that is being heated by an underground buried pipe. The pipe is in a cylindrical coordinate system, whereas the ground is in a cartesian coordinate system. For this, it is required to make the eight assumptions following.

1. The soil is homogeneous, and the soil type does not change along he pipe.
2. The soil temperature at a certain distance from the pipe is assumed to fluctuate, only with diurnal and seasonal variation, and does not depend on the GHE operation,
3. In case of multiple GHEs, it is assumed that the distance between loops is big enough to avoid thermal interference between them.
4. The heat transfer in the soil is assumed to be axis−symmetric.
5. The heat transfer in the soil in the direction parallel to the pipe

[19] 19. Piechowski, M. (1999), Heat and mass transfer model of a Ground Heat Exchanger: theoretical development. Int. J. Energy Res., 23: 571-588.

is negligible.[20]

6. The air−soil surface boundary is assumed to be of the convective type.

7. The temperature and velocity of the circulating fluid are assumed to be constant at any cross section of the pipe.

8. The influence of gravity on the soil moisture transfer in the unsaturated soil is assumed to be negligible.

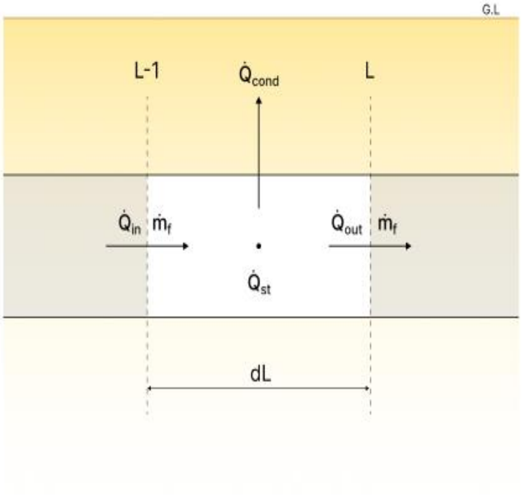
According to the preceding assumption 5, it is possible to construct the energy conservation equation for the differential section of the GHE. The heat pump's entering fluid temperature is now determined by the temperature of the last slice. (2.1)

$$-v\frac{\partial T_{\mathrm{f}}}{\partial l}+\frac{2U_{\mathrm{i}}}{r_{\mathrm{p,o}}\rho_{\mathrm{f}}c_{\mathrm{f}}}\frac{\partial T_{\mathrm{p}}}{\partial r}\bigg|_{\mathrm{r_{p,o}}}=\frac{\partial T_{\mathrm{f}}}{\partial t} \tag{2.1}$$

which

T_{f}	:	Absolute temperature of fluid (K)
T_{p}	:	Absolute temperature of pipe (K)
$\mathrm{r_{p,o}}$	:	Pipe outside radius (m)
ρ_{f}	:	Density of fluid (kg/m^3)
c_{f}	:	Specific heat of fluid (J/kgK)
v	:	Flow velocity (m/s)
U	:	overall heat transfer coefficient (W/m^{2}K)

[20] Piechowski, M. (1998), Heat and mass transfer model of a ground heat exchanger: validation and sensitivity analysis. Int. J. Energy Res., 22: 965-979.



[Figure 2.7] Schematic for deviation of the circulating fluid energy balance for the control length of pipe

The heat and mass transfer equation in the Soil region is as follows.

$$C\frac{\partial T}{\partial t} = \nabla(K\nabla T) + \nabla(D_\varepsilon \nabla\theta_l) + L\varepsilon\rho_l\frac{\partial K_h}{\partial y} \tag{2.2}$$

$$\frac{\partial\theta_l}{\partial t} = \nabla(D_\theta\nabla\theta_l) + \nabla(D_T\nabla T) + \frac{\partial K_h}{\partial y} \tag{2.3}$$

which

C	:	Volumetric heat capacity (J/m^{3}K)
K	:	Soil thermal conductivity (W/mK)
K_h	:	Unsaturated hydraulic conductivity of soil (m/s)
D_ε	:	Latent heat diffusion coefficient (W/mK)
D_T	:	Thermal moisture diffusivity (m^2/Ks)
L	:	Latent heat of vaporization of water (J/kg)
θ_l	:	Moisture volume fraction (m^3/m^3)
ε	:	Phase conversion factor (−)
ρ_l	:	Density of liquid water (kg/m^3)

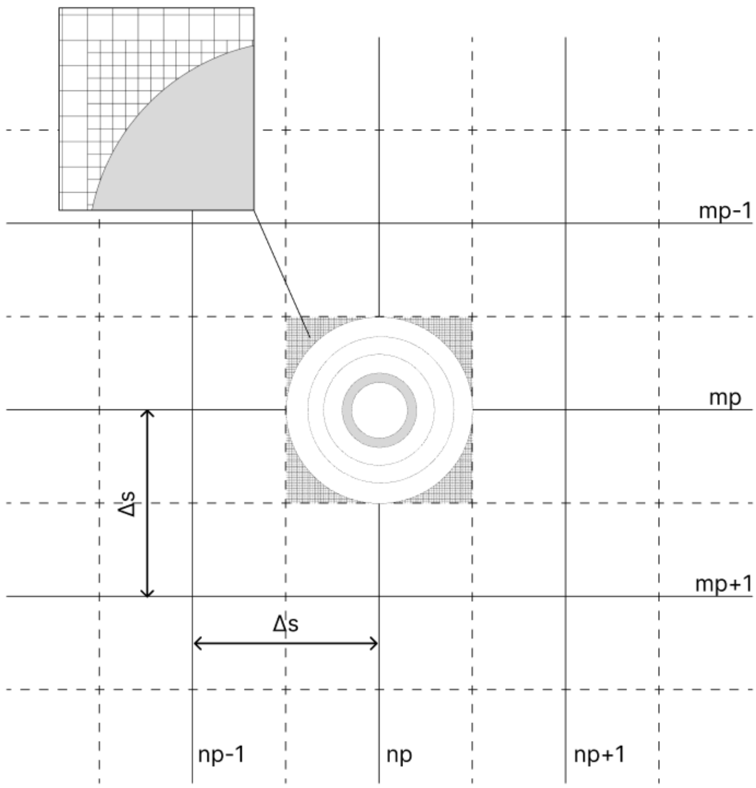
However, if these two equations are applied to the whole soil area, the computing load increases, and the simulation time disadvantage occurs. The largest temperature gradient occurs in a narrow band with a radius of 0.15 meters around the pipe, which has a significant influence on the heat transfer rate. The steepest temperature gradient exists in an area 0.15 meters from the pipe[21], thus the calculation should be made by dividing the thermal analysis near the pipe, where the gradient is large, and the soil, where the gradient is comparatively small, as shown in [Figure 2.8]. By applying Equation (2.2) and (2.3) near the pipe to analyze the nodes and Equation (2.4) to the soil in the distance, it is possible to reduce the computing load and simulation period without significantly sacrificing accuracy. It is essential for GSHP simulation, which requires a large soil area and a long simulation period.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha_s}\frac{\partial T}{\partial t} \tag{2.4}$$

which

α_s : Soil thermal diffusivity (m^2/s)

[21] Piechowski, M. (1996). A ground coupled heat pump system with energy storage. PhD thesis, Department of Mechanical and Manufacturing Engineering, The University of Melbourne.



[Figure 2.8] Schematic for the calculation of the outer boundary temperature for the radial region

2.2. Literature Review Summary

This chapter analyzed the basic principles, classification, and simulation algorithms of GSHP, identified the options of GHE, and described the numerical analysis method of horizontal GHE. By investigating experimental studies on horizontal GHE, the variation in heat transfer fluid temperature and the GHE evaluation method were reviewed.

(1) GHSP refers to a system that uses a ground thermal as a source of a heat pump. GHE used in general buildings uses low-temperature heat sources that exist in nature. Cooling and heating are available through a 4-way valve, and when heating, the soil is used as a heat source to reject ground heat through the heat transfer fluid, and when cooling, the soil is used as a heat sink to radiate heat through the heat transfer fluid.

(2) GHE is classified according to the use of soil, groundwater, or ponds as heat sources. GHE units that use soil as a heat source are divided into vertical and horizontal types according to the installation direction. The selection of vertical and horizontal types is mainly determined by the size of the site that can be installed. GHE is divided into serial and parallel connections. The serial connection mainly uses large pipes, which have better heat exchange performance per unit length, and the parallel connection has small pipes, which reduce purchase and installation costs.

(3) The heat absorption performance of GHE is mainly determined by the depth of burial and the thermal conductivity of the soil installed. Choosing a reinstallation method to improve the performance of the installed GHE is costly and time-consuming. Other methods for improving performance are possible through a control strategy. Heat absorption performance may be improved by intermittently operating the GSHP to recover the underground temperature when the GSHP is in a stopped state. The shorter the operation time and recovery time, and the more intervals, the better the performance. This operation has a greater effect on soil with low thermal conductivity.

(4) The horizontal GHE is interpreted by numerical analysis. However, if the entire simulation object is mainly calculated in the same way, it is inaccurate, or the simulation load increases. Therefore, it should be calculated by dividing it into the periphery of the pipe, where the temperature gradient is large, and the undistributed ground part, the temperature gradient is relatively small. Heat and moisture analysis is calculated in detail through a cylindrical coordinate system at the periphery of the pipe, and in the undistributed ground, the analysis is carried out in a cartesian coordinate system with a relatively large node.

(5) In the experiments of several horizontal GHEs, the temperature difference between EFT and LFT was 2 to 4°C on average. The temperature of the loop was operated in the range of 5 to 10°C in the heating period and 25 to 30°C in the cooling period. In addition, GHE performance evaluation was performed by calculating the heat absorption of GHE and the work of the heat pump compressor as COP.

Chapter 3. Mat-type GHE Research

This chapter deals with verification for the simulation application of mat-type GHE. First, a test cell and field experiment are simulated through EnergyPlus.9.6, and after simulation, verification is performed by comparing the simulation results with the experimental results.

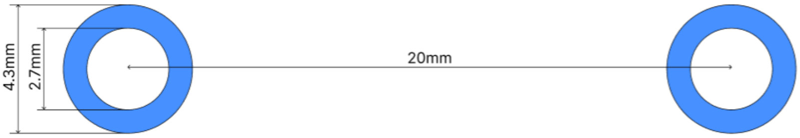
3.1. Capillary Mat Simulation

3.1.1 Mat-type GHE Modelling

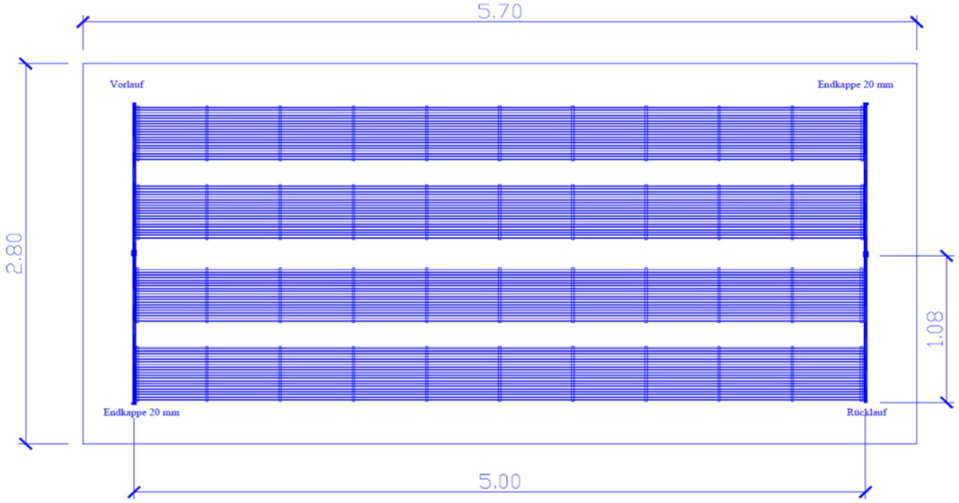
A module of a capillary mat has 20 rows of capillary tubes with a diameter of 0.0043 m, and each of them has a 5 m length. This configuration can be categorized as a "horizontal parallel" arrangement. The capillary tube is made of polypropylene, and its properties show that due to the narrow pipe diameter, the surface area of the whole capillary mat is increased compared to the same volume of the pipe, and thus the responsiveness is high.

<Table 3.1> Capillary mat properties

Parameter	Specification
Material	Polypropylene
Pipe Outer Diameter (m)	0.0043
Pipe Inner Diameter (m)	0.0027
Pipe Spacing (m)	0.02
Pipe Thermal Conductivity (W/mK)	0.38
Pipe Density (kg/m^3)	955
Pipe Specific heat (J/kgK)	2301



[Figure 3.1][Capillary mat pipe cross section



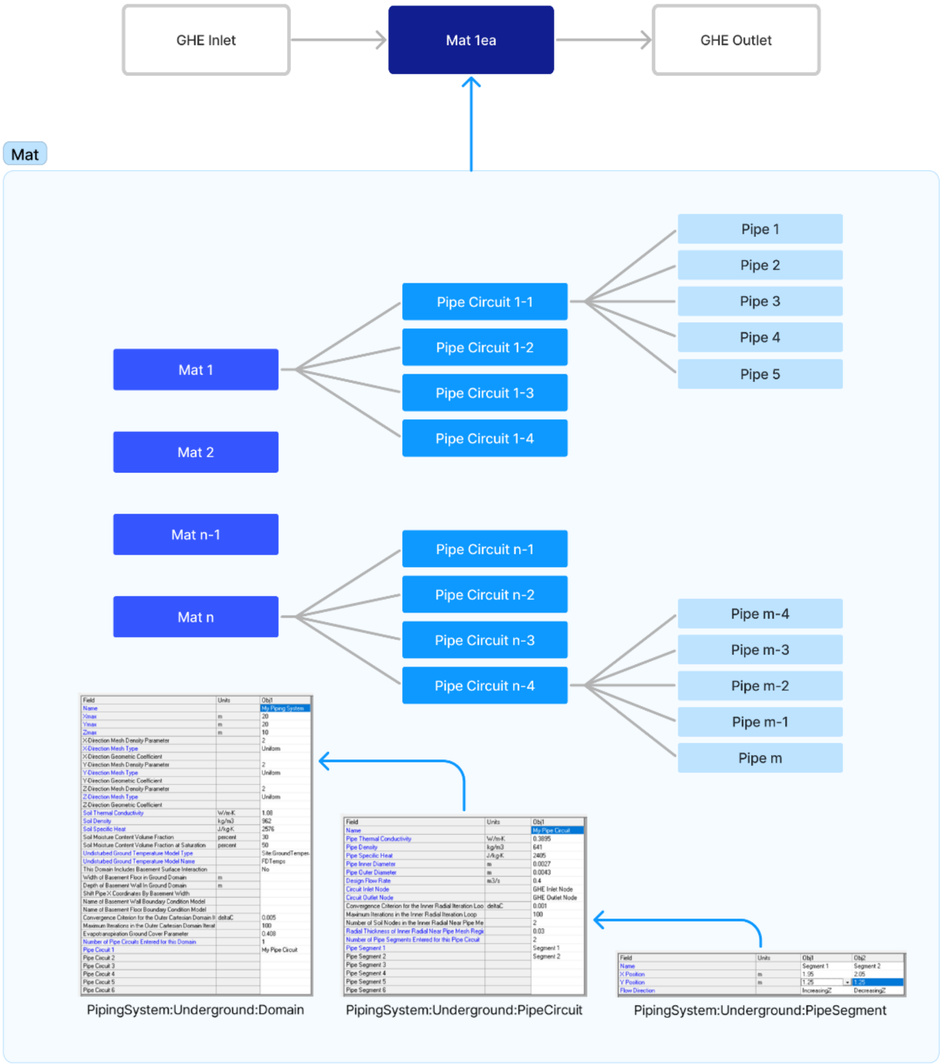
[Figure 3.2] Capillary mat (4 module) configuration[22]

EnergyPlus supports the simulation of horizontal GHE through the GroundHeatExchanger:HorizontalTrench' class. This class only supports a typical horizontal u-shape serial arrangement. If capillary mats are used in this class, simulation results will be incorrect.Therefore, modeling a capillary mat at the 'PipingSystem:underground' class, which uses the same algorithm for heat transfer as the horizontal GHE described in the previous chapter. The parameters, flow direction, and mesh size can all be chosen manually as opposed to the 'GroundHeatExchanger:Horizontal Trench' class, which automatically adjusts some of the elements. But the input process of the "PipingSystem:underground" class is complex for capillary mats with a large number of tubes.

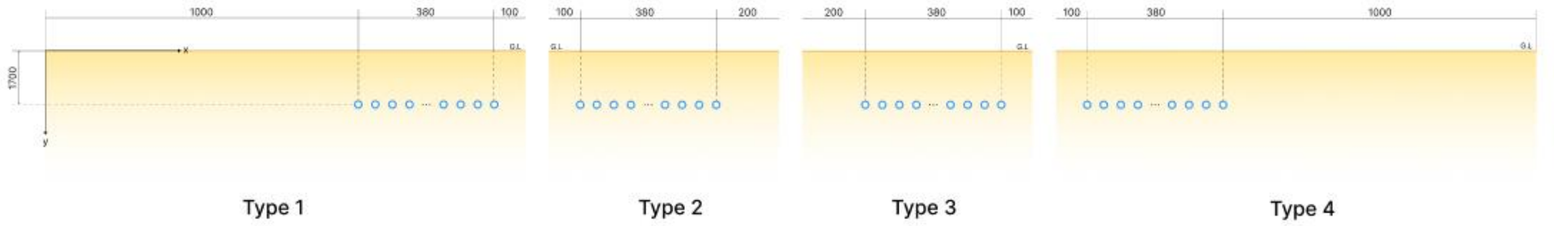
---

[22] Clina Heiz- und Kühlelemente GmbH. Available at: https://www.clina.de/en/products (Accessed: November 19, 2022).

Therefore, to modelling a mat-type ground heat exchanger, an input process must be made in the form shown in the figure below, [Figure 3.3]. After it was installed, it was entered as [Figure 3.4] in consideration of the side spacing of the ground heat exchanger.



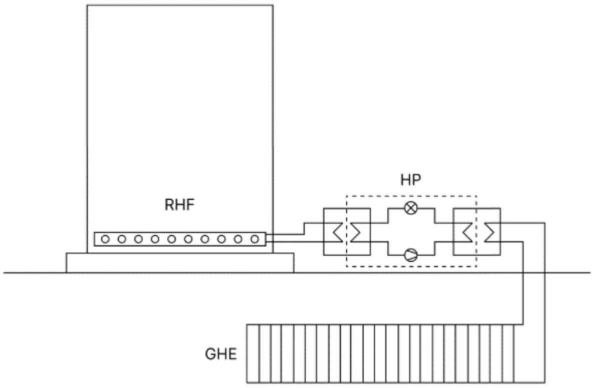
[Figure 3.3] Capillary mat input diagram



[Figure 3.4] Capillary mat modelling in EnergyPlus "Underground:PipingSystem' class

3.1.2 Pre-Simulation

To determine the approximate amount of heat collected by the mat-type GHE, EnergyPlus 9.6 was used to run a simulation.[23] The Zone model imitated an officetel 1 zone to which a typical house's U-value was applied. The GSHP was simply configured to provide radiant heating floor. In general, a horizontal GHE is buried at a depth of at least 1.2 meters, Similarly, the capillary mat, which contains 80 tubes (4 modules), is buried at a depth of 1.5 meters. Manufacturer-recommended flow rate value was entered. The region was set to Incheon. The simulation period was two months, from January 1st to February 27th, including the lowest outdoor temperature on January 4th. The heating setpoint was set to 20℃. The heating operation was scheduled from 5:00 to 18:00 considering the occupant's staying time and the delay effect of the radiant heating floor, because the target building type of the simulation is officetel as office.



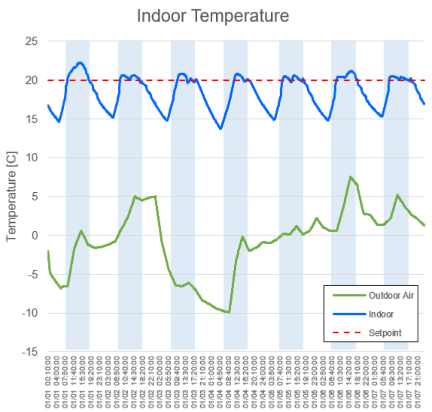
[Figure 3.5] Simulation System diagram

---

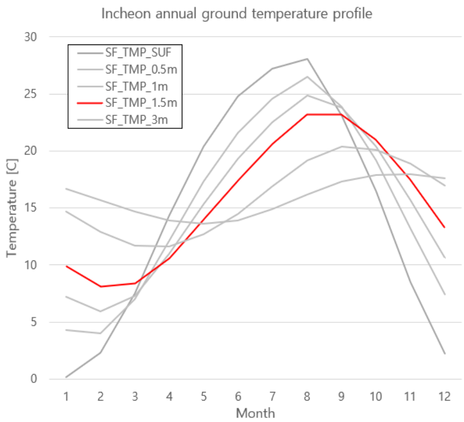
[23] Leigh, S., Jang, H., Liu, S., Leigh, T., & Yeo, M. (2022). A Comparison and Thermal Performance Analysis of Mat-Type Horizontal Ground Heat Exchanger with Vertical Ground Heat Exchanger at Winter Season. Proceeding of the SAREK Conference, 632–635.

<Table 3.2> Simulation for mat-type GHE Input Summary

Input object	Value
Simulation period	1/1 ~ 2/27
Zone area	$15m^2$
Heating peak load	1100W
Heatpump COP	3
GHE buried depth	1.5m
GHE flowrate	4.35 LPM
The number of capillary tubes	80 ea(4 modules)
Location	Incheon
Heating setpoint	20℃
Heating Time	Everyday 05:00~18:00



[Figure 3.6] Indoor and outdoor air temperature profile



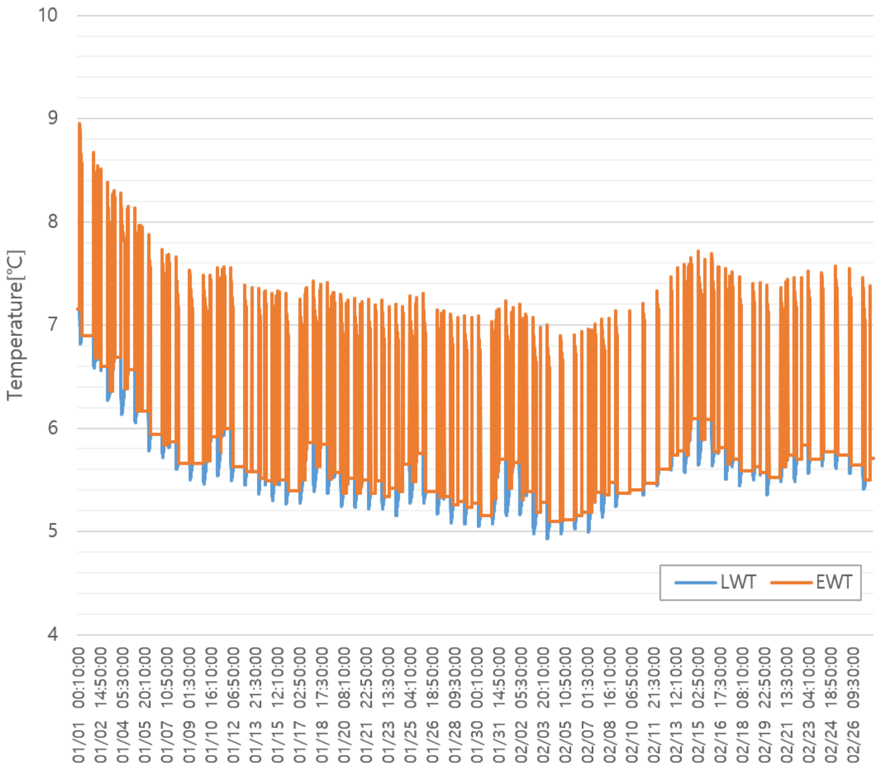
[Figure 3.7] Incheon region annual ground temperature by depth[24]

[24] Korea Meteorological Administration, Comprehensive climate change monitoring information, 2022.05.04. // (Korea Meteorological Administration, http://www.climate.go.kr/home/09_monitoring/surfacetemp/Sf_tmp, 2022.05.04.)

The indoor temperature starts heating at 5:00 and reaches 20℃ at about 9:00, except for January 4, the coldest day. Since the heat pump EFT has a large load at the beginning of the daily load standard, Fluid enters the heat pump about 9℃ at 5:00 and drops to 7℃. And it recovers to about 8.6℃ the next day. Comparing this with the ground temperature in the Incheon area, it is 9.9 ℃ at 1.5m depth in January, which is considered an acceptable temperature considering that it is the average value for a month. The average difference between EFT and LFT was 1.6℃, using Equation(3.1) to calculate the heat absorption of a capillary mat.

$$Q = mc_p\Delta T \tag{3.1}$$

During the simulation period, the average heat absorption of the capillary mat as GHE was 442W, or approximately 110W per module, about 30W/m^2.



[Figure 3.8] EFT and LFT profile during 1/1~2/27

3.2. Field Test

3.2.1 Field Test Overview

An experiment was conducted to verify the previous underground heat exchange simulation. The experiment is currently located close to the sea in Asan, [Figure 3.9]. The subject is composed of two test cells comparative experiments. The mat-type horizontal GHE is assigned 12 modules for each test cell, and a total of 24 modules are installed in the experimental field [Figure 3.10]. The internal circulating fluid of all GHEs was put into the pipe at a concentration of 40% ethylene glycol for antifreezing of the pipes from the ground [Figure 3.11].

[Figure 3.9] GHE installation location (Asan-si)[25]

[25] "Satellite Image." Google Map, Google, 11 Jan. 2023, https://www.google.co.kr/maps/place.

[Figure 3.10] Mat-type GHE installation

[Figure 3.11] Pipes from underground GHE

3.2.2 Experiment

An experiment was conducted to find out the actual heat rejection amount to ground of the mat−type GHE. The experiment period was from 17:00 on December 12 to 1:00 on December 13, and the water in the underground tank was circulated through a pulse operation every 5 minutes, and the flow rate was set to 8 LPM on the mat−type GHE 6 module. The results are summarized in a <Table 3.3> as follows. The heat rejection amount of 6 modules was calculated through the following equation according to the temperature difference obtained as a result.

$$Q = mc_p\Delta T \tag{3.2}$$

The specific heat of GHE circulation fluid with an ethylene glycol concentration of 40% was calculated as 3486J/kgK. The recovery temperature was maintained continuously at a temperature of 1.7m deep where mat−type GHE was buried. When the inlet temperature was 14.4°C, 124W was radiated with the largest temperature difference.

<Table 3.3> Experiment results

	Temperature difference			Rejection rate (W)	Rejection rate per module (W)
Max.	1.6	Supply	14.4	744.5	124.1
		Return	12.7		
Aver.	0.8	Supply	13.4	368.6	61.4
		Return	12.6		
Min.	−0.1	Supply	12.8	−52.1	−8.7
		Return	12.9		

3.2.3 Validation Simulation

The ground temperature can't be check by output of Energy Plus. But by using correlation equation, shown in EnergyPlus Engineering Reference, can check the ground temperature indirectly. There are three ground temperature models that can be used in EnergyPlus, but the model that is often used is KusudaAkhenbach model. The ground temperature model utilized Kusuda and Akhenbach's hypothesized correlation Equation (3.2)[26.]

$$T(z,t) = \bar{T}_s - \Delta\bar{T}_s \cdot e^{-z \cdot \sqrt{\frac{\pi}{\alpha\tau}}} \cdot \cos\left(\frac{2\pi t}{\tau} - \theta\right) \quad (3.3)$$

Which

$\bar{T}_s$	:	Average annual soil surface temperature (℃)
$\Delta\bar{T}_s$	:	The amplitude of the soil temperature change throughout the year (℃)
z	:	depth (m)
α		The thermal diffusivity of the ground (m^2/day)
τ		Time constant,365
t	:	Time, Day of the Year
θ	:	The phase shift, or day of minimum surface temperature (−)

The relational equation applied to EnergyPlus is simpler than the original and cannot express the ground temperature inversion. If a temperature inversion occurs, the Xing model should be used. The Xing model has been widely used since Kusuda−Akhenbach model, which was proposed in the 1960s, and can be applied to EnergyPlus as the original way to express temperature inversion. If a temperature inversion occurs on the measured data, the 'Xing model' should be used. However, temperature inversion did not occur within the measured depth within the measured data, the calculation was

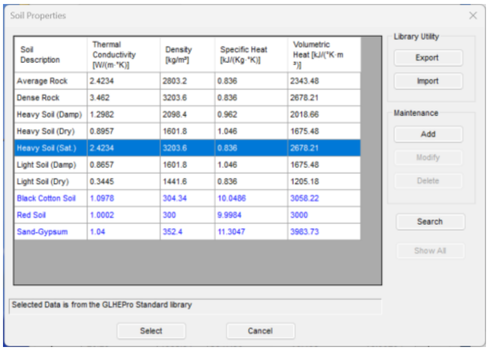
[26] Kusuda, T., & Achenbach, P.R. (1965). EARTH TEMPERATURE AND THERMAL DIFFUSIVITY AT SELECTED STATIONS IN THE UNITED STATES.

performed through the Kusuda–Akhenbach model.

For the properties of the soil, when the mat–GHE was buried, the soil condition was examined, and the value existing in the database of the GHE length calculation program 'GLHEpro'[27] was referred. Considering the test site photograph [Figure 3.13] and the reclaimed land, the soil is estimated to be in a saturated state, and the corresponding soil density, specific heat, and thermal conductivity values are selected. When these values are selected and the underground temperature is calculated, the values are as shown in [Figure 3.12]. As a result, the parameters used in the ground temperature simulation are shown in <Table 3.4>. The results of simulating the underground temperature for time and depth are shown in [Figure 3.14] and [Figure 3.15].

(a) Long–sighted Excavating

(b) Close–up shot soil



Soil Description	Thermal Conductivity [W/(m·°K)]	Density [kg/m³]	Specific Heat [kJ/(Kg·°K)]	Volumetric Heat [kJ/(°K·m³)]
Average Rock	2.4234	2803.2	0.836	2343.48
Dense Rock	3.462	3203.6	0.836	2678.21
Heavy Soil (Damp)	1.2982	2098.4	0.962	2018.66
Heavy Soil (Dry)	0.8957	1601.8	1.046	1675.48
Heavy Soil (Sat.)	2.4234	3203.6	0.836	2678.21
Light Soil (Damp)	0.8657	1601.8	1.046	1675.48
Light Soil (Dry)	0.3445	1441.6	0.836	1205.18
Black Cotton Soil	1.0978	304.34	10.0486	3058.22
Red Soil	1.0002	300	9.9984	3000
Sand-Gypsum	1.04	352.4	11.3047	3983.73

(c) Soil properties in GLHEpro

[Figure 3.12] Site soil photo

[27] IGSHPA, 2016, "GLHEPro 5.0 Users' Guide", School of Mechanical and Aerospace Engineering, Oklahoma State University

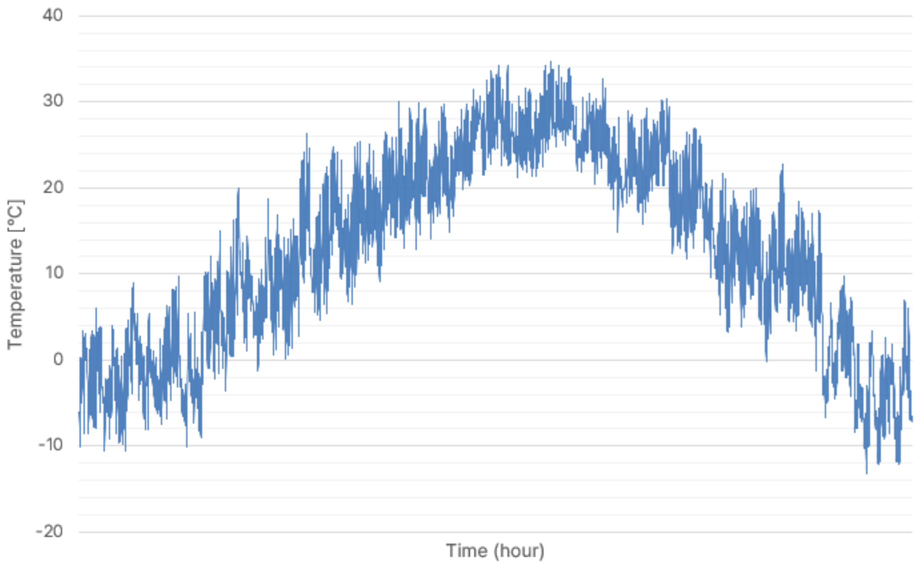
Such as the annual average temperature and annual amplitude, these are values that can be determined after one year of measurement. However, it cannot be measured in the current situation, so it was calculated using the weather data from the Korea Meteorological Administration[28]. There are data sets from 2019 to 2022, and 2022 was chosen. The weather data have a 5-minute timestep, and it is estimated that they are raw data with several long- and short-term missing values and error values. Error values were replaced with interpolated values using prior and subsequent data. For short-term missing values were interpolated using Python, and for long-term, a couple of days or more, missing values were replaced from past data (2019~2021) with a similar pattern to the 2022 value.

The Phase Constant of Soil Surface Temperature value was found with trial and error by comparing it with the underground temperature value by depth measured in the field through python. At this time, the thermal diffusion rate of the soil was calculated to be 0.087 m2/day, and the thermal conductivity of the soil was modified to 2.697 W/mK and used. The values are shown in <Table 3.4> below.

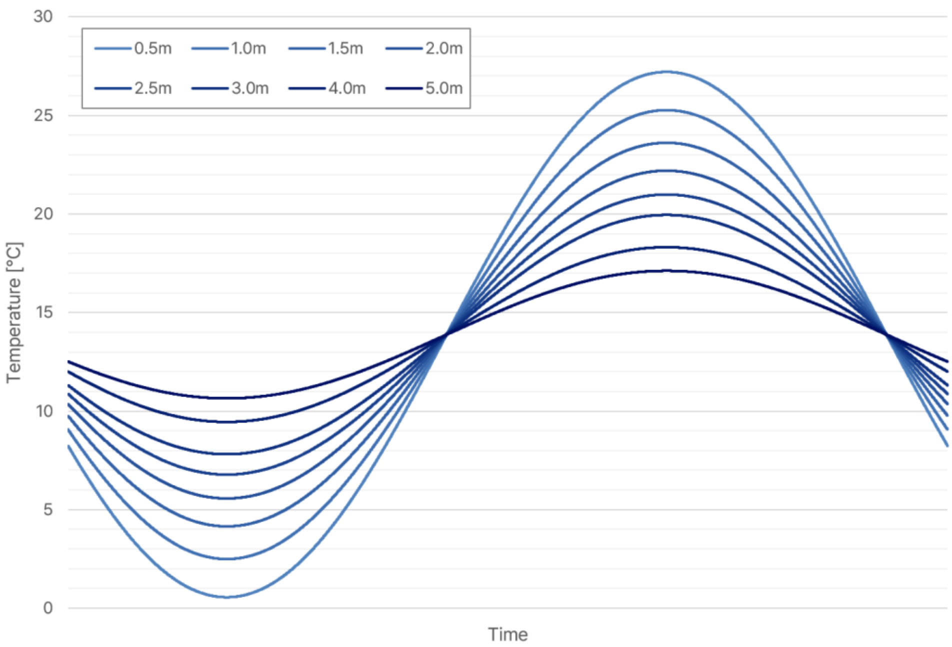
<Table 3.4> Soil properties

Parameter	Specification
Annual Average Soil Surface Temperature(C)	13.88
Amplitude of Soil Surface Temperature(C)	15.78
Phase Constant of Soil Surface Temperature (-)	-49
Soil Thermal conductivity (W/mK)	2.697
Soil density (kg/m^3)	3203.6
Soil specific heat (J/kgK)	836
Soil volumetric heat (kJ/Km^3)	2678.21

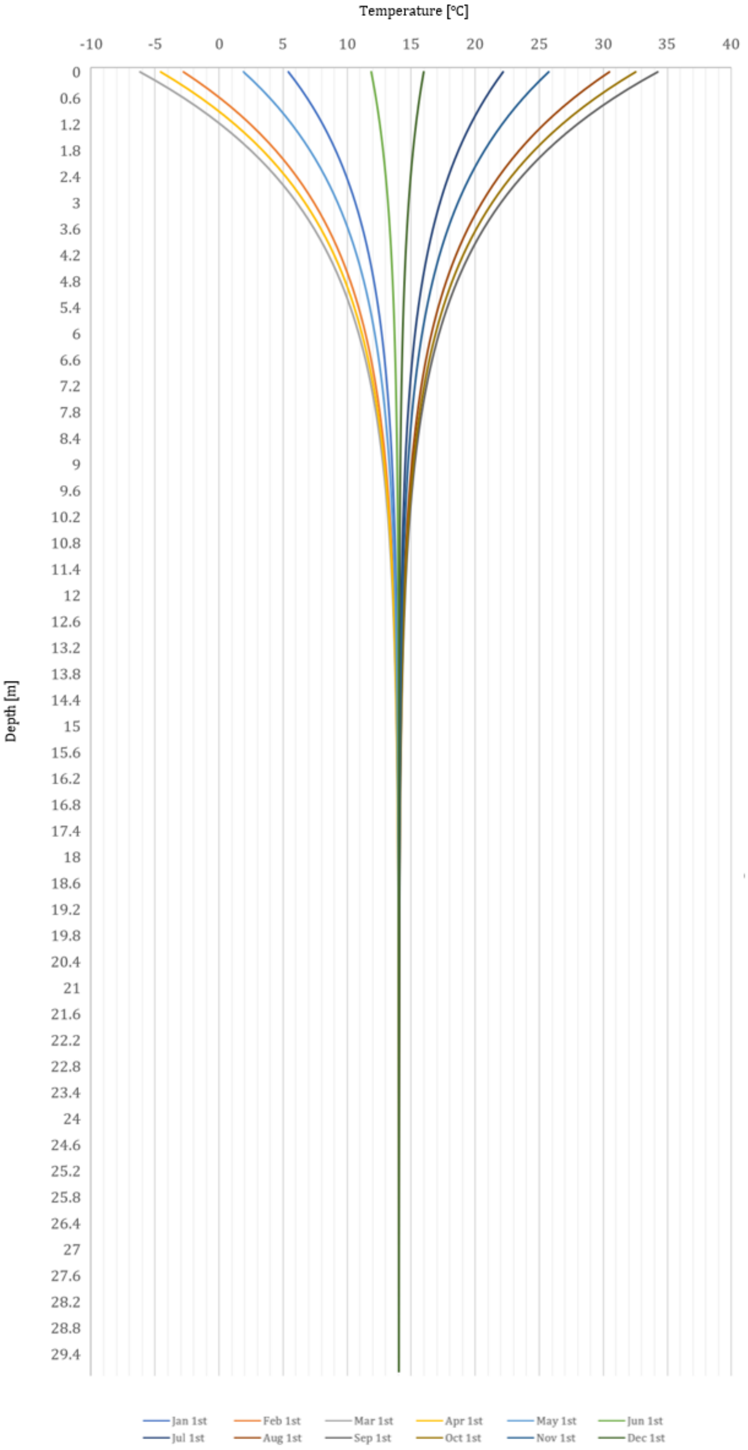
[28] Korea Meteorological Administration, Open MET Data Portal, 2023.01.10. // (Korea Meteorological Administration, https://data.kma.go.kr/data/grnd/selectAwosRltmList.do?pgmNo=638, 2023.01.10.)



[Figure 3.13] Inju-myeon Annual Outdoor Temperature



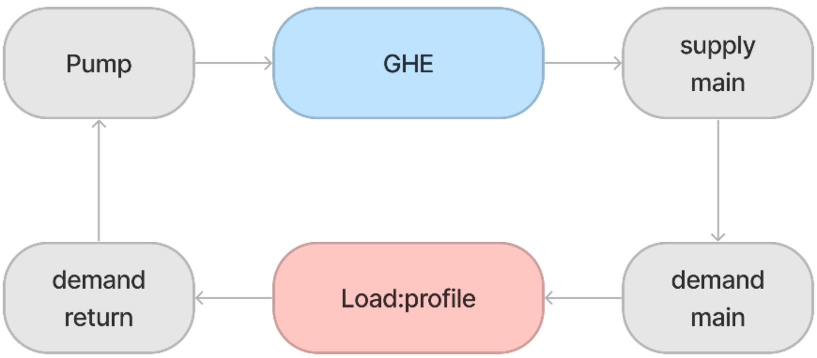
[Figure 3.14] Annual ground temperature simulation result



[Figure 3.15] Simulation result of ground temperature vs depth

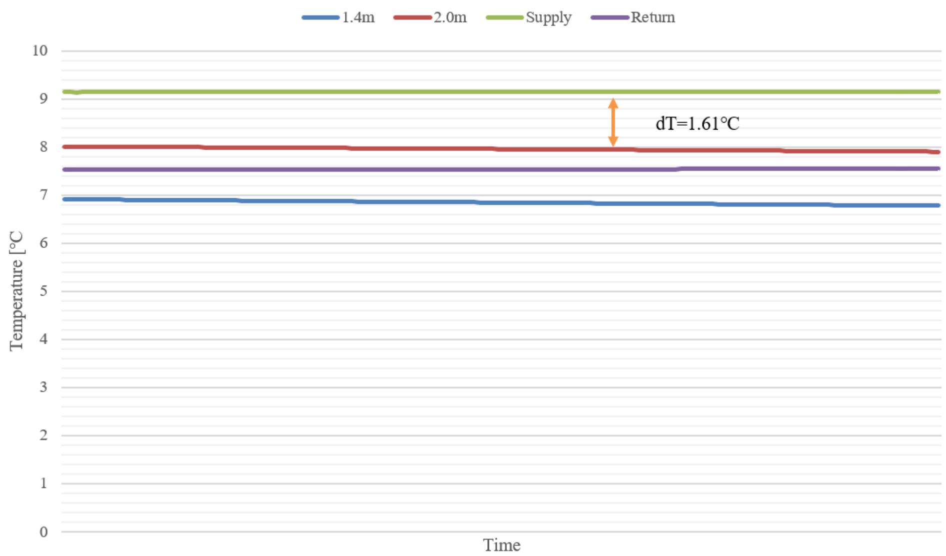
As shown in [Figure 3.14], the underground temperature converges to an annual average temperature at about 15m. The depth above that is maintained constantly as shown in <Figure 3.13>. The depth of 2 to 5m, where horizontal GHE is mainly buried, varies greatly due to the reception of outside temperature. In this respect, a fundamental performance difference between the vertical GHE and the horizontal GHE occurs.

To verify the value of the conducted experiment of 3.2.2, heat rejection amount. Simulation within Energyplus and observed whether the results were similar. The load to the ground was simulated through the 'Load profile' class. The configuration of the system is shown in [Figure 3.15] below. The simulation period was set from December 12 to 13 and a 124W load corresponding to the maximum load was continuously loaded to the ground. The results are shown in [Figure 3.16].



[Figure 3.16] Rejection test simulation system diagram

The simulation used the previously determined soil temperature model, and the simulation period was from December 12 to December 13. As a result, heat was dissipated with a temperature difference of about 1.6°C. This is similar to the experiment that was conducted, and the recovery temperature was similar to about 7.5°C when the temperature at the depth of 1.7m was calculated with the previous ground temperature model. Although the underground temperature is not the same as at the actual site, the model is reasonably simulated in Energyplus as the temperature is returned to the depth temperature under each soil condition, and there are no big differences in the heat rejection amount or the supply and return fluid temperature difference.



[Figure 3.17] Simulation Results

3.3. Summary

This chapter provides an overview of mat−type GHEs, modeling within Energyplus simulations, and the thermal performance of mat−type GHEs through simulation. In addition, the results of the heat rejection test conducted in the field test and the results simulated by the simulation were compared and verified. The summary of the research results in this chapter is as follows.

(1) The mat−type GHE consists of a capillary bundle with a diameter of 0.0043 m made of propylene, and one module is divided into a bundle of 20 pipes. In the commercial program Energyplus, there is no separate input class for mat−type GHE, and when input through a normal straight horizontal GHE, the direction of the fluid is simulated differently. Furthermore, the straight horizontal GHE makes it difficult to enter numbers because some parameters are automatically determined. Instead use the 'Piping System:underground' class. This class allows you to freely enter parameters involved in the simulation while sharing the analysis algorithm with the straight horizontal GHE, allowing you to model the mat−type GHE within Energyplus. However, there is a disadvantage in that modeling becomes difficult because input must be made for individual pipes.

(2) A heating experiment was conducted to approximately find out the thermal performance of the mat−type GHE modeled through Energyplus. A small cell was simulated and coupled with floor radiant heating. At the time, the area was set to Incheon, and the underground conditions were based on general underground data. The result was that about 110W per mat−type GHE module was collected from the underground, which was calculated to be about 30W/m2 per area. In addition, it has been confirmed that the temperature of the loop is maintained and recovered to the underground temperature of the Incheon area, so it is used for sizing information.

(3) In order to see if the mat−type GHE model calculated by simulation is appropriate, an experiment was conducted to measure the heat rejection amount by circulating the fluid in the mat−type GHE at the site where the experiment was built. The recovery temperature was returned to a temperature of 12.7°C of 1.7m where the GHE was installed, and the heat rejection amount was measured and calculated at 124W when the maximum temperature difference per module was 1.6°C. This was simulated as Energyplus, and 124W of load was continuously applied to the mat−type GHE. At this time, it seems to be recovered to the underground temperature of 1.7m underground in the Energyplus, and the temperature difference is also maintained at 1.6°C, so the model implemented in the Energyplus was reasonable.

Chapter 4. Mat−type GHE Application Plan

In this study, to determine the applicability of mat−type GHE, the target building to which the GHE can be applied is classified by usage. Furthermore, the applicability as a heat source is investigated through a comparative analysis of mat−type GHE and vertical GHE by building use.

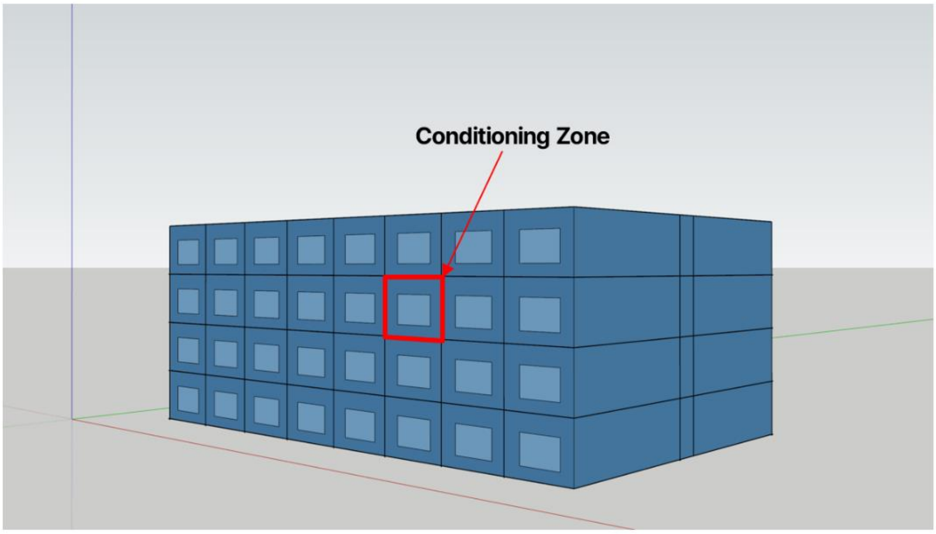
Normally, during the heating season, office buildings use fan coil units as terminal systems, and residential buildings use radiant heating floors (RHF) as terminal systems. By comparing the characteristics and thermal behavior of mat−type GHE when applied in two different types of buildings, compared to vertical GHE, it can be determined which building types and which systems are suitable for applying mat−type GHE.

4.1. Simulation overview

4.1.1 Building model

As previously mentioned, this study examined two commercial and residential buildings. As a means of comparison, officetels serving both functions served as the target structure [Figure 4.1]. Thermal transmittance and the floor plan are shown <Table 4.1>. The terminal method, heating time, and room time of the heating system were applied differently to distinguish the cases used for each purpose.

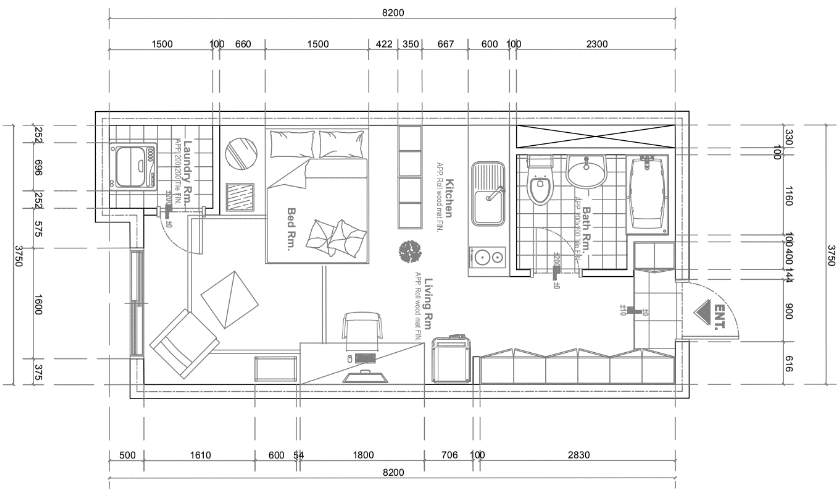
This study identifies the characteristics and applicability of mat−type GHE by comparing vertical GHE and mat−type GHE; therefore, simulations were conducted on a total of four cases in addition to the heating system's terminal method as shown <Table 4.2>. The system diagrams of each case are shown in [Figure 4.2].



[Figure 4.1] Building overview and conditioning Zone

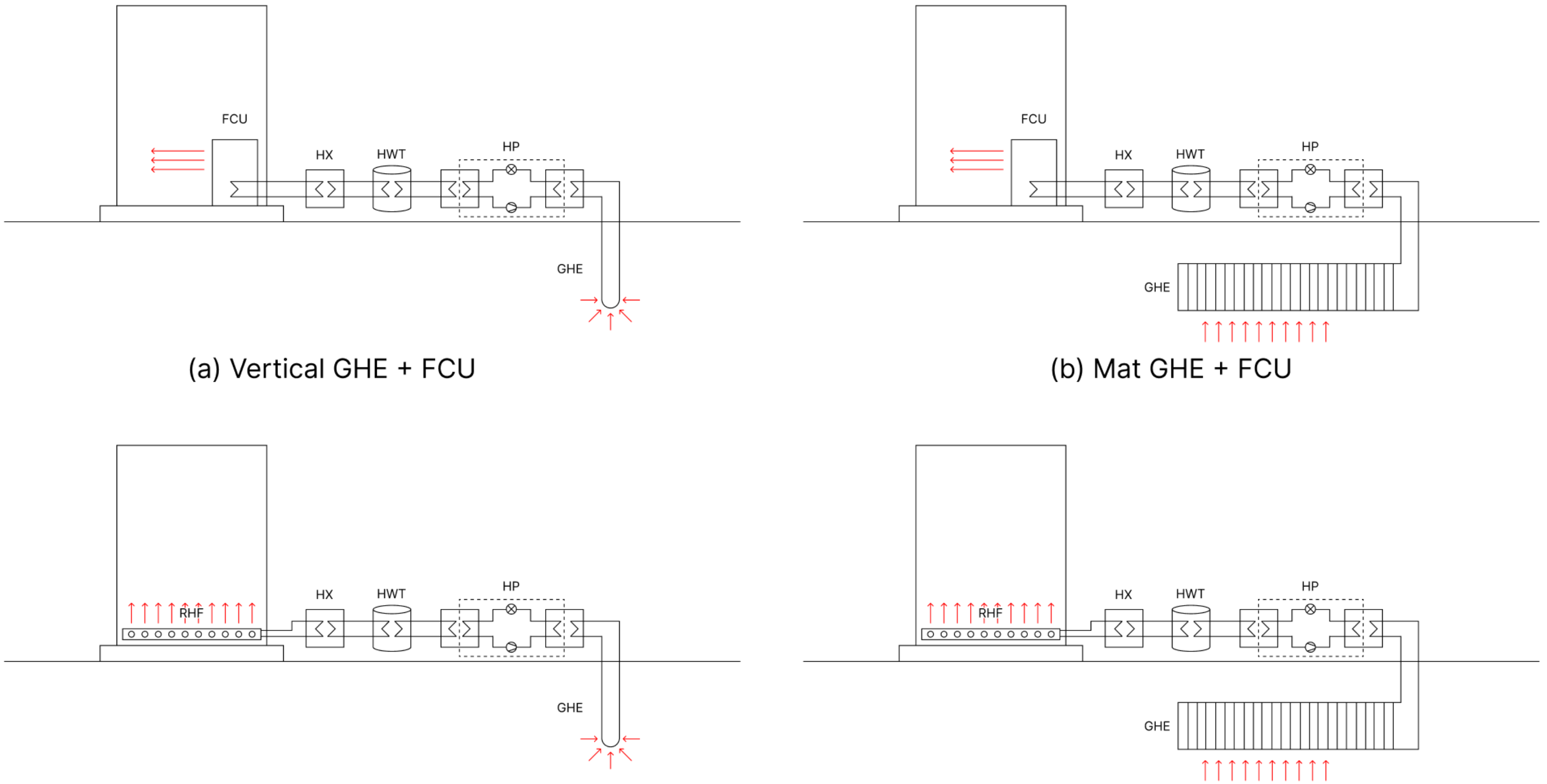
<Table 4.1> Thermal transmittance and floor plan of simulation model

Structure	Thermal transmittance (U-value)
Exterior Wall	0.211 W/m^{2}K
Floor	0.637 W/m^{2}K
Ceiling	0.637 W/m^{2}K
Window	0.834 W/m^{2}K
Floor Plan	



<Table 4.2> Simulation cases

Case	Usage	Terminal	Heat source	Terminal Control
Case1	Office	FCU	Vertical GHE	On/off control
Case2	Office	FCU	Mat-type GHE	On/off control
Case3	Residential	RHF	Vertical GHE	On/off control
Case3*	Residential	RHF	Vertical GHE	Heating curve control
Case4	Residential	RHF	Mat-type GHE	On/off control
Case4*	Residential	RHF	Mat-type GHE	Heating curve control



(a) Vertical GHE + FCU (b) Mat GHE + FCU

(c) Vertical GHE + RHF (d) Mat GHE + RHF

[Figure 4.2] System diagram

4.2. simulation at office buildings

4.2.1 Simulation Overview

In cases 1 and 2, the applicability of mat-type GHE is studied by comparing the energy consumption and COP of the heat pump used in the heating process of the FCU at the office building.

In this section, heating was operated through on/off control to satisfy the room's set temperature of 20°C from 8:00 to 18:00 according to the office schedule. FCU used hot water made from the ground source heat pump, and vertical GHE and mat-type GHE were used as heat sources for the heat pump. The FCU was designed in consideration of the actual load, and the heat pump was designed by reflecting the system load of the FCU. The data entered in the simulation can be found in <Table 4.3> presented below. The heat pump in the target office was assumed to be a COP 3.5 product with a heating capacity of about 1300W, and the amount of heat to be obtained from the ground at the peak load of the zone is 730W. In Chapter 3, the heat exchange amount of the mat-type GHE 1 module was derived as 110W, so a total of 7 mat-type GHEs were designed to handle the underground load.

<Table 4.3> Case 1, Case 2 Simulation input values

Input object	Value	
Simulation period	1/1 ~ 1/31	
Location	Seosan	
Zone area	3.0m*8.0m*3m	
Heat pump COP	3.5	
Heat pump Capacity	1300W	
GHE type	Vertical	Mat
GHE size	82m	7 modules
Heating setpoint	20℃	
Heating Time	Office schedule 8:00~18:00	
Heating System	Fan Coil Unit	

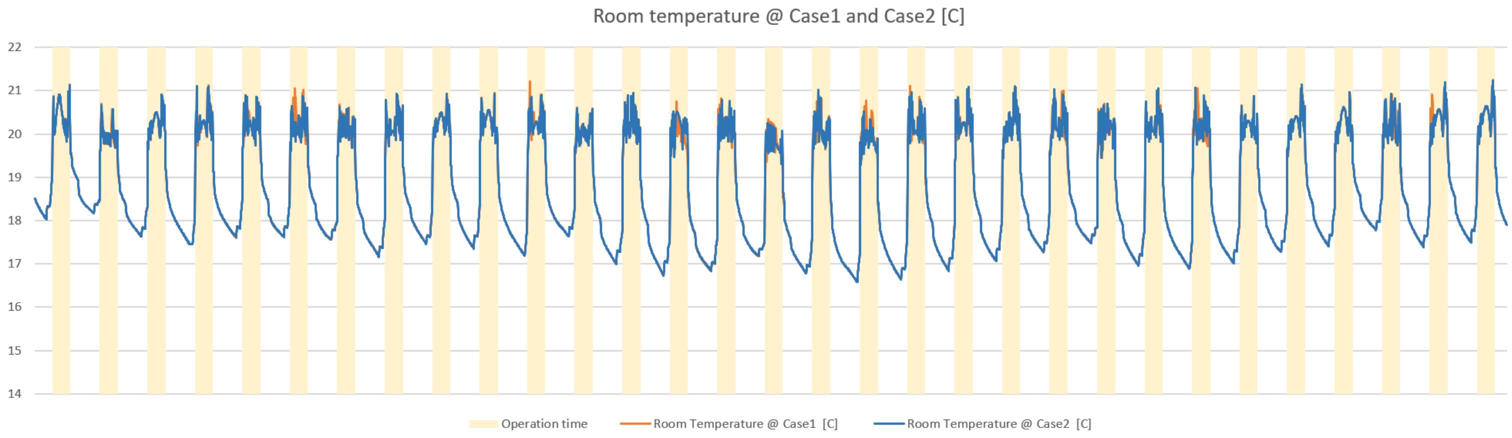
4.2.2 Simulation Results

Both Cases 1 and 2 satisfied the actual set temperature during heating. By comparing the energy usage of Cases 1 2, the energy consumption of each GHE was identified, the COP of the heat pump was compared to the efficiency of obtaining heat from the GHE, and the stable heat supply capacity as a heat source was checked.

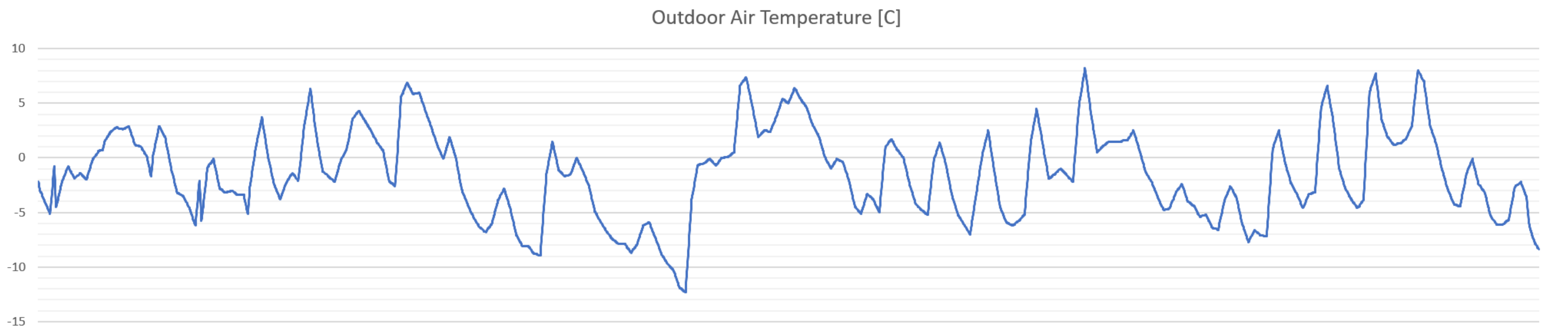
Comparing the energy usage of the entire system in each case, it seemed that case 1 using vertical GHE used less energy by 7%. This is presumed to be due to the change in HP's COP due to the difference in water outlet temperature according to the installation depth of the vertical GHE and the horizontal GHE. As shown in<Figure 4.6> and <Figure 4.7> below, HP EFT/LFT in the ground during the simulation period decreases as the heating period progresses. In the case of mat-type GHE, the installation center is closer to the surface than vertical GHE, so the ground temperature is close to the outside temperature and the ground temperature is low. For this reason, the temperature of the heat transfer fluid obtained from the ground through the GHE and supplied to the HP gradually decreases, which causes the COP of the HP to be lowered.

<Table 4.4> Energy consumption and COP of heat pump

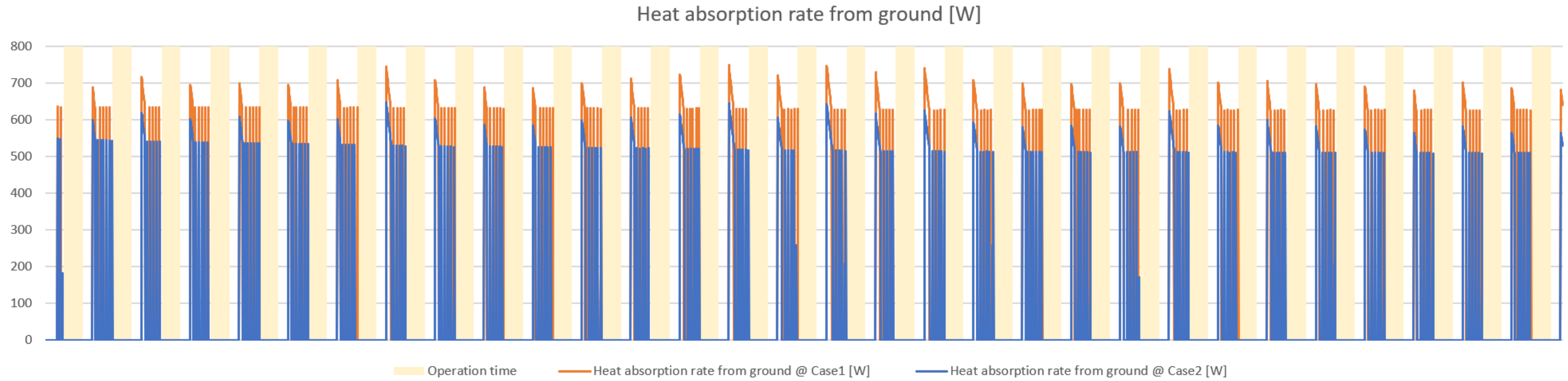
Object	Case1	Case2
Heat pump energy consumption [kWh]	25.5	28.2
Pump energy consumption [kWh]	45.3	48.0
Total energy consumption [kWh]	70.8	76.2
Heat pump COP [min]	2.76	2.46
Heat pump COP [max]	3.70	3.47
Heat pump COP [avg]	2.99	2.69



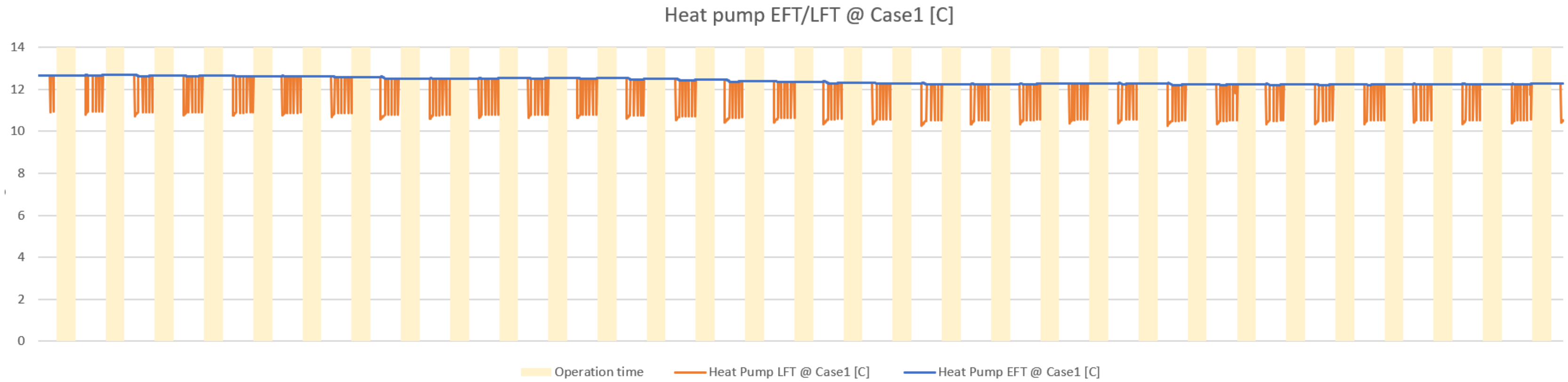
[Figure 4.3] Room temperature during Case1 and Case2



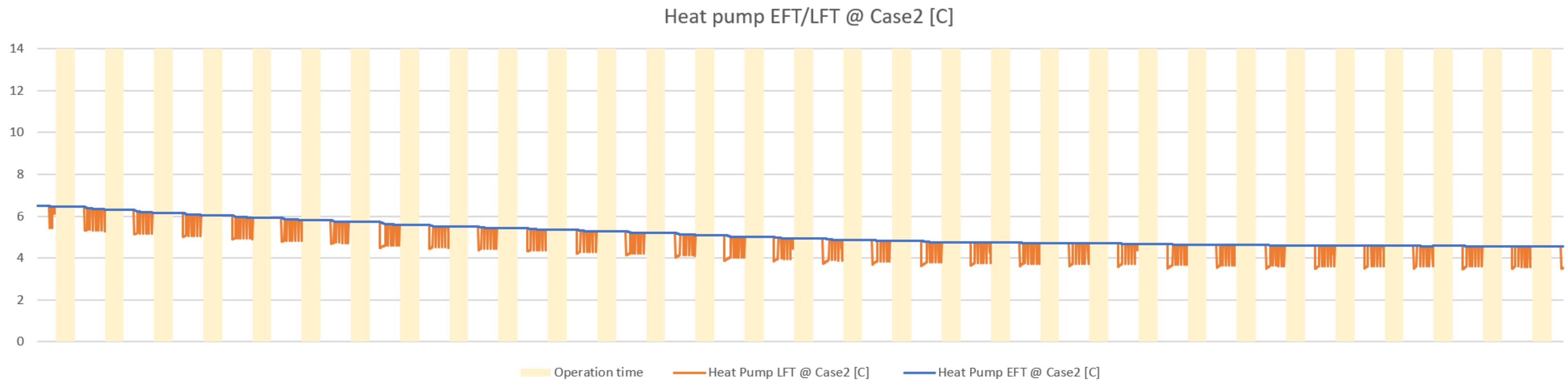
[Figure 4.4] Outdoor air temperature



[Figure 4.5] Heat absorption rate from ground at Case1 and Case2



[Figure 4.6] Heat pump EFT/LFT at Case1



[Figure 4.7] Heat pump EFT/LFT at Case2

First, the heat transfer fluid temperature in the two cases was compared in [Figure 4.6] and [Figure 4.7]. During the simulation period, the ground temperature is represented by a temperature section corresponding to 1.4m and 2.0m on the graph. The temperature of the heat transfer fluid that enters the heat pump through the GHE is decreasing, but it flows within the temperature range of 1.4 to 2.0m where the mat−type GHE is installed. Because it is installed deeper underground, vertical GHE maintains EFT temperature almost constant at a higher temperature. It means that it can absorb heat more stably on the ground than the mat type GHE, and in [Figure 4.5], the heat absorption of the GHE is stably maintained, whereas case 2 has a lower heat absorption than Case 1.

4.3. simulation at residential buildings

4.3.1 Simulation Overview

In Case 3 and 4, the applicability of mat−type GHE is analyzed by comparing the energy consumption and COP of the heat pump used in the RHF heating process at residential buildings.

In this section, heating was performed on resident time to satisfy the set temperature of 20℃ through on/off control, from 18:00 to 7:00. RHF for residential buildings, mentioned at 4.1 was designed according to the heating load of the target zone, as shown below. The heat pump was designed by reflecting the system load of RHF. The input values used in the simulation can be confirmed in <Table 4.5> presented below. The heat pump in the target residential space was assumed to be a COP 3.5 product with a heating capacity of about 600 W, and an input value embedded in the energy plus was used. At the peak load of the thread, the amount of heat that must be obtained from the ground is 320 W. In Chapter 3, the heat exchange amount of mat−type GHE 1 unit was derived as 110W, so a total of three mat−type GHEs were designed to handle the ground load.

<Table 4.5> Case 3, Case 4 Simulation input values

Input object	Value	
Simulation period	1/1 ~ 1/31	
Location	Seosan	
Zone area	3.0m*8.0m*3m	
Heat pump COP	3.5	
Heat pump Capacity	600W	
GHE type	Vertical	Mat
GHE size	20m	3 modules
Heating setpoint	20℃	
Heating Time	Residential schedule 19:00~7:00	
Heating System	Radiant Heating Floor	

4.3.2 Simulation Results

Both systems used in Cases 3 and 4 satisfied the room set temperature during the simulation day. Because the terminal systems used in both cases are wet-type RHF, over-shootings occur during the scheduled heating time.

Both Cases 3 and 4 satisfied the actual set temperature during heating during the control time. Similar to the comparative analysis of Cases 1 and 2, the energy consumption of Cases 3 and 4 was checked by comparing the COP of the heat pump to obtain heat from the GHE, and finally, the stable heat supply capacity as a heat source was checked by comparing the temperature change of the heat transfer fluid temperature between the GEH and the heat pump.

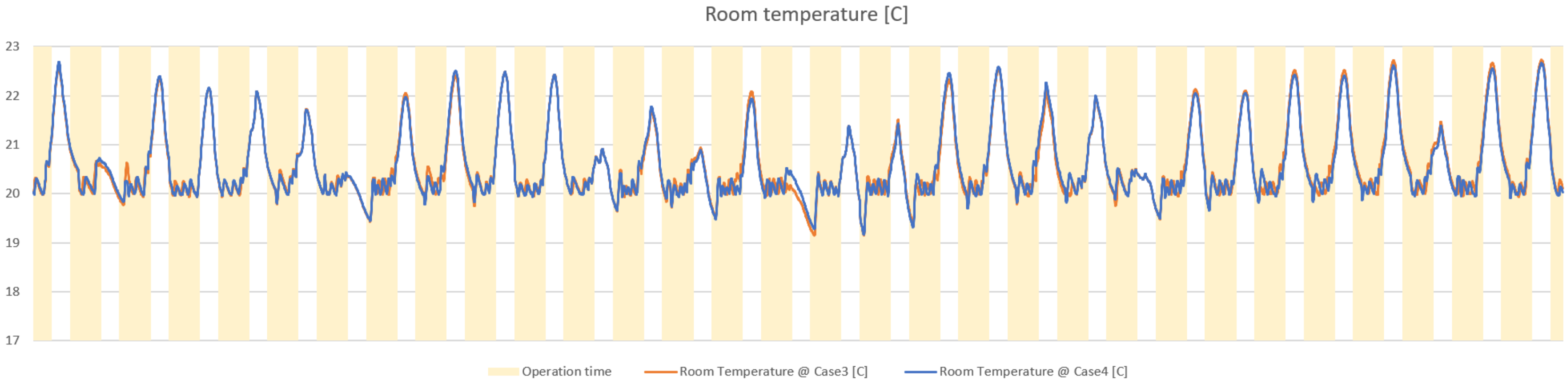
Comparing the energy usage of the entire system in each case, it seemed that case 4 using mat-type GHE used more energy by 22%.

<Table 4.6> Energy consumption and COP of heat pump

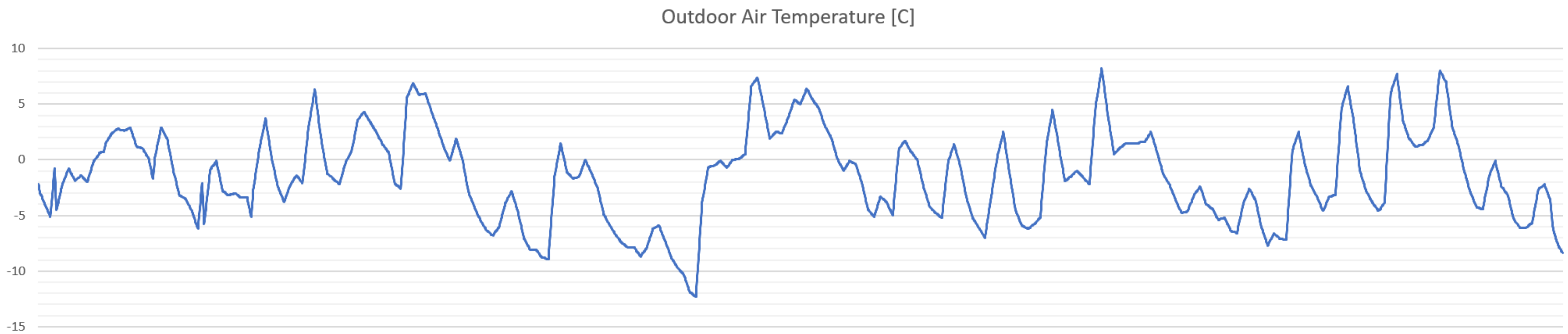
Object	Case3	Case4
Heat pump energy consumption [kWh]	35.4	36.8
Pump energy consumption [kWh]	7.8	15.8
Total energy consumption [kWh]	43.3	52.6
Heat pump COP [min]	2.8	2.5
Heat pump COP [max]	3.0	2.7
Heat pump COP [avg]	2.9	2.6

This is presumed to be due to the change in HP's COP due to the difference in water outlet temperature according to the installation depth of the vertical GHE and the horizontal GHE, similar to the comparative analysis between Case1 and Case2. As shown in [Figure 4.10] and [Figure 4.11] below, HP EFT/LFT in the ground decrease. In the case of mat−type GHE, the installation depth is closer to the surface than vertical GHE, so the ground temperature is low. For this reason, the temperature of the heat transfer fluid obtained from the ground through the GHE and supplied to the HP gradually decreases, which causes the COP of the HP to be lowered.

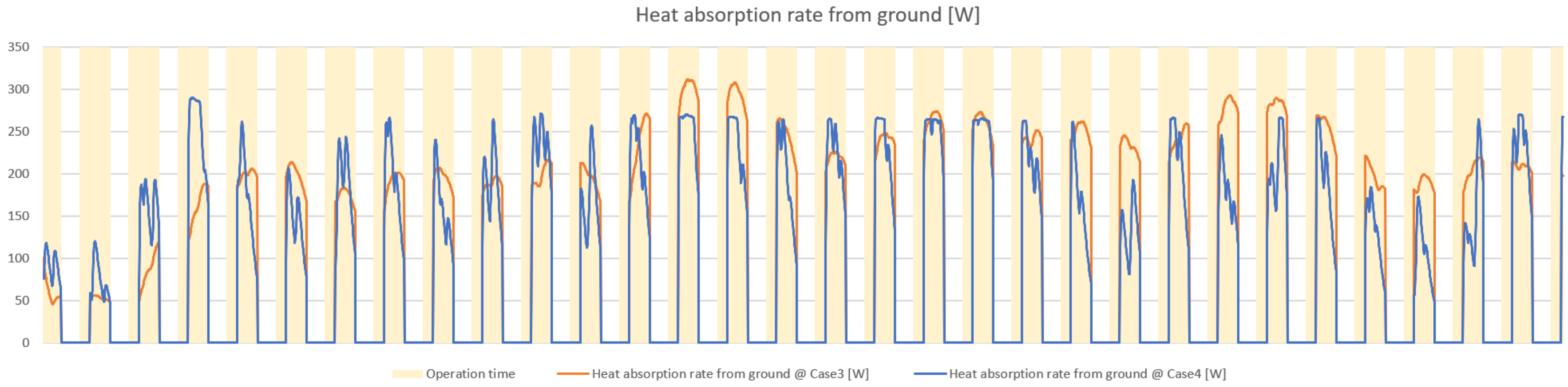
The heat transfer fluid temperature in the two cases was compared in [Figure 4.11] and [Figure 4.12]. During the simulation period, the ground temperature is represented by a temperature section corresponding to 1.4m and 2.0m on the graph. The temperature of the heat transfer fluid that enters the heat pump through the GHE is decreasing, but it flows within the temperature range of 1.4 to 2.0m where the mat−type GHE is installed. Vertical GHE, on the other hand, maintains EFT temperature almost constant at a higher temperature because it is installed deeper underground.It means that it can absorb heat more stably on the ground than the mat type GHE, and in [Figure 4.10], the heat absorption of the GHE is stably maintained, whereas case 4 has a lower heat absorption than Case 3.



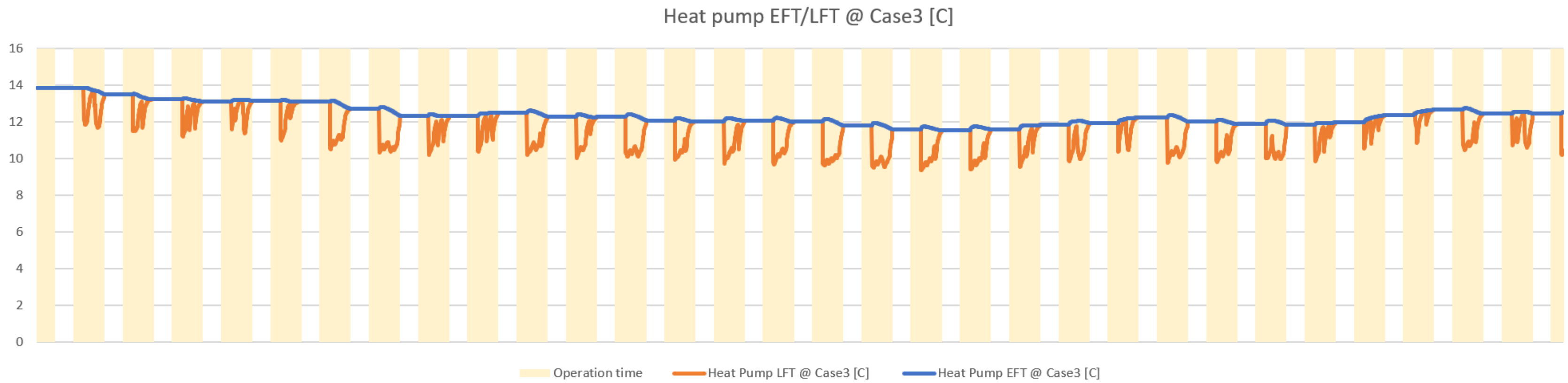
[Figure 4.8] Room temperature during Case3 and Case4



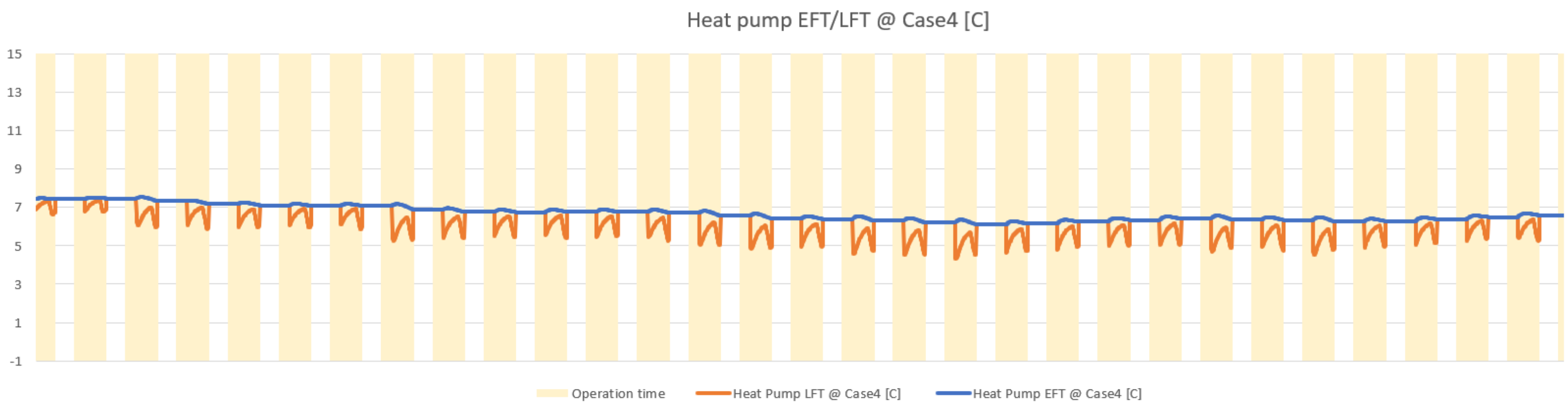
[Figure 4.9] Outdoor air temperature



[Figure 4.10] Heat absorption rate from ground at Case3 and Case4



[Figure 4.11] Heat pump EFT/LFT at Case3



[Figure 4.12] Heat pump EFT/LFT at Case4

4.4. Adaptability analysis for modified system

4.4.1. Modified system overview

The energy consumption of the heat pump system using the GHE is reduced by 39% for vertical GHE and 31% for mat-type GHE when floor heating is utilized compared to FCU. In addition, it can be confirmed that not only energy usage, but also heat absorption from the underground from [Figure 4.5] and [Figure 4.10] is reduced by about half. If the amount of heat absorption from the underground, that is, the underground load, can be reduced significantly, then the area of mat-type GHE that needs to be buried underground, that is, the number of modules, can be reduced. Therefore, it is concluded that mat-type GHE is more likely to be applied to residential buildings in the form of floor heating.

However, as mentioned above, if the underground load can be reduced, the area (number of modules) required for mat-type GHE installation can be reduced, thereby securing more applicability.

For all the heating presented in this study, a simple on/off control method was adopted without performing separate control. To reduce the underground load, it is necessary to reduce the system load at the end, and it is possible to reduce the system load and energy usage when performing control by applying a heating curve during floor heating.[29] Using Heating Curve, the radiant heating floor system may effectively reduce load by changing water temperature, typically used 55°C, to the outdoor air temperature. Cases 3 and 4, which were simulated in section 4.3, use radiant heating floor; hence, the simulation with heating curve is additionally performed. The heating curve now in use is as following, Equation (4.1).

[29] Jang, H., Liu, S., Xue, Y., & Yeo, M. (2022). Evaluation of Applicability of Outdoor Rest Contorl with Radiant Floor Heating Systems through Comparative Experiments. Magazine of the SAREK, 51(9), 40–49.

$$T_{hwt} = 45 - T_{OT} \tag{4.1}$$

Which

T_{hwt} : The supply hot water temperature (℃)

T_{OT} : The outdoor air temperature (℃)

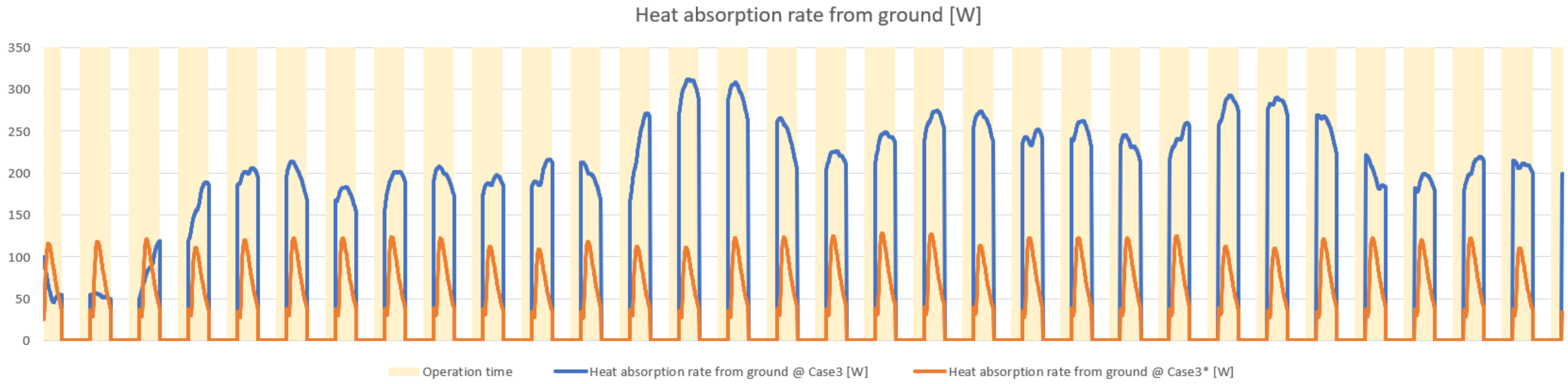
4.4.2 Simulation results

In the cases of Case 3* and Case 4*, to which the heating curve control is applied, the set temperature of the room to be controlled is satisfied, and the energy usage is reduced by about 53.8% and 36.9% compared to previous cases that performed simple on/off control. Although the use of pump power is similar because the end system is the same, it is analyzed that the energy usage of the heat pump is greatly reduced due to the decrease in system load. The heat pump EFT/LFT also does not deviate significantly from the underground temperature at the installed depth, and the underground load absorbed from the ground is significantly reduced as the system load is reduced.

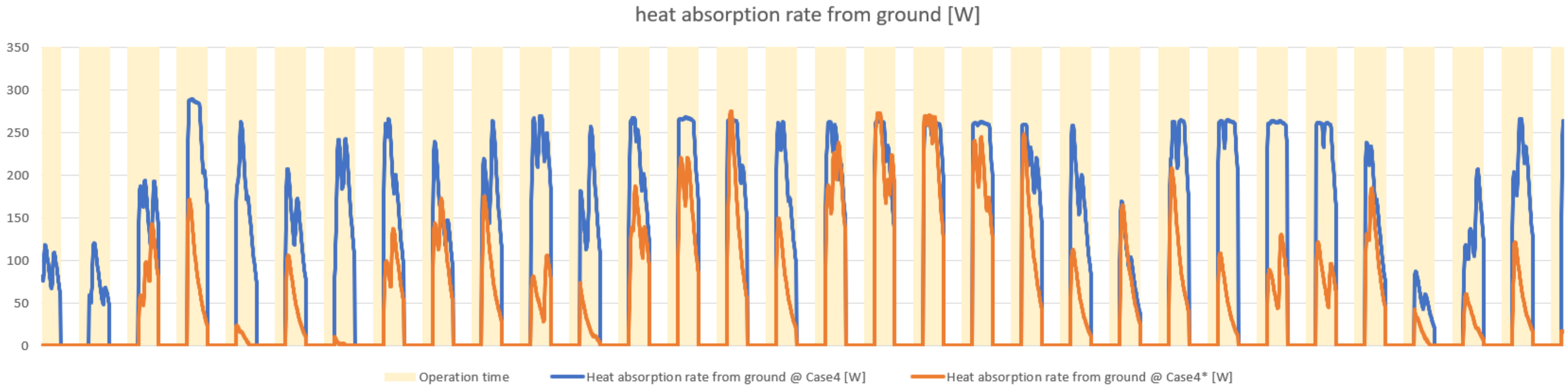
If mat-type GHE is used as a heat source for a system that performs radiant heating floor with heating curve control, it is expected that the applicability of mat-type GHE will be further improved as it can solve the installation area.

<Table 4.7> Energy consumption and COP of heat pump

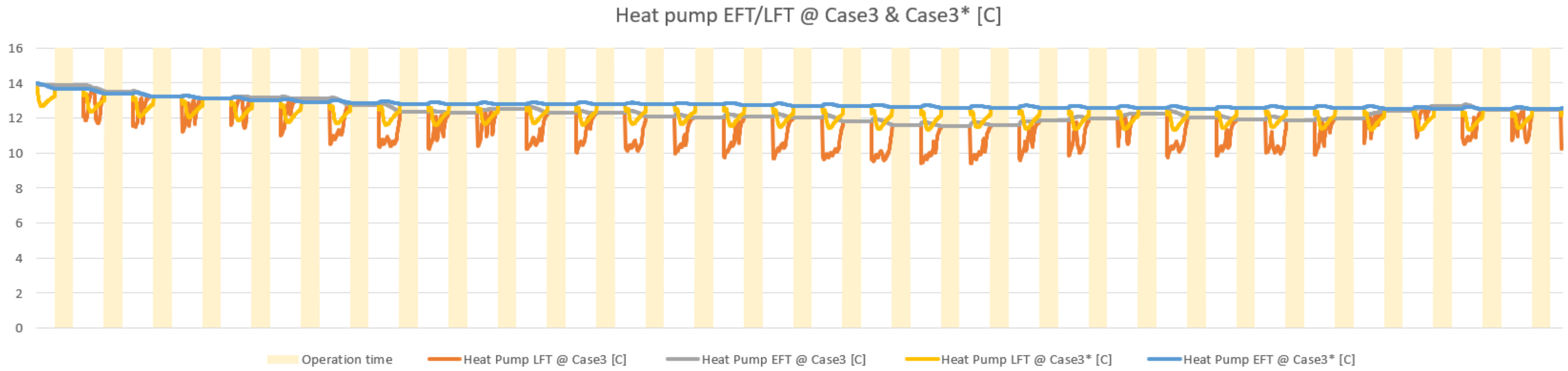
Object	Case3*	Case4*
Heat pump energy consumption [kWh]	12.2	18.4
Pump energy consumption [kWh]	7.9	14.8
Total energy consumption [kWh]	20.0	33.2
Heat pump COP [min]	2.8	2.6
Heat pump COP [max]	3.0	2.7
Heat pump COP [avg]	2.9	2.5



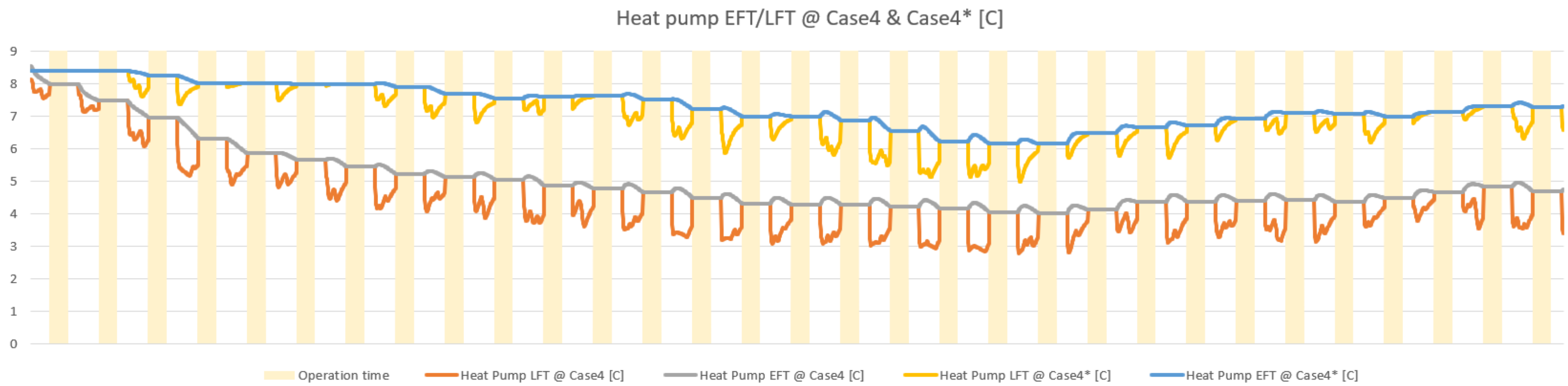
[Figure 4.13] Heat absorption rate from ground at Cas3 and Case3*



[Figure 4.14] Heat absorption rate from ground at Case4 and Case4*



[Figure 4.15] Heat pump EFT/LFT at Case3 and Case3*



[Figure 4.16] Heat pump EFT/LFT at Case4 and Case4*

4.5. Summary

In this chapter, compared EFT/LFT, COP, and energy consumption using Energyplus simulation to determine which types of buildings are suitable for use with mat-type GHE during the heating season and whether they are suitable for use with end systems. The summary of the research results in this chapter is as follows.

(1) Cases were compared to determine under what settings a mat-type GHE should be applied during the heating season. The building was chosen for its dual function as an office and a residence. The area of the officetel was set to $40m^2$ (8m*5m) based on a typical officetel. FCU was set to be heated to 20°C from 8:00 to 18:00 for office purpose, while RHF was heated from 19:00 to 7:00. for residential purpose. In addition, the GSHP was only operational from 23:00 to 9:00, which corresponded to the late-night electricity time.

(2) Through Case 1 and Case 2, applications in office buildings were compared. At this time, FCU was commonly used as the terminal system, and the heating time was set from 8:00 to 18:00. For COP, Case1 was higher than Case2 in both the maximum, minimum, and average. The total energy consumption during the period was 70.8 kWh in Case 1 and 76.2 kWh in Case 2, which was about 9% higher. The energy consumption of the heat pump was about 10%, and the energy consumption of the pump was about 6% higher than Case 1. At this time, the EFT/LFT of Case1 initially decreased by about 0.4℃ from 12.6℃ to 12.2℃, and Case2 decreased by 2.0℃ from 6.4℃ to 4.4℃.

(3) Through Case 3 and Case 4, the applications in residential buildings were compared. At this time, radiant heating floor was commonly used as the terminal system, and the heating time was set from 19:00 to 7:00. For COP, Case3 was higher than Case4 in both the maximum, minimum, and average. The total energy consumption during the period was 43.3 kWh in Case 3 and 52.6 kWh in Case 4, which was about 21.5% higher. The energy consumption of the heat pump was about 3.9%, and the energy consumption of the pump was

about double that of Case 3. At this time, the EFT/LFT of Case3 initially decreased by about 0.4℃ from 12.6℃ to 12.2℃, and Case4 decreased by 2.0℃ from 6.4℃ to 4.4℃.

(4) A system using radiant heating floor may additionally reduce heat pump energy consumption by controlling the supply hot water temperature. Radiant heating floor was compared in Cases 3* and 4* using heating curves. Energy consumption in both cases has been greatly reduced. Heat pump energy consumption decreased by 65.5% and 50%, respectively, while overall energy consumption decreased by 53.8% and 36.8%, respectively. Through this, controlling the heating curve for radiant heating floor reduces the heating load and reduces the ground load. Eventually, the design length of the GHE will be reduced. Therefore, if a mat-type GHE is used, it is considered appropriate to control with the heating curve by coupling with RHF for residential use.

Chapter 5. Conclusion

Due to the declaration of carbon neutrality, the application of renewable energy to facility systems, which account for a large amount of energy consumed by buildings, is expanding due to the reduction in the use of fossil fuels. As a result, various renewable energy systems, such as solar and wind power, are being introduced, but the energy source that produces stable performance is a geothermal source. However, due to the high initial installation cost of geothermal sources, they are mainly used by large public institutions. The high initial cost is primarily due to the high installation cost of the vertical GHE itself and the buried site required for horizontal GHE installation. Although there are various types of GHEs and each method has advantages and disadvantages, a great advantage of vertical GHEs over horizontal GHEs is that they can achieve stable performance and high performance even on narrow sites. To overcome the problem of horizontal GHE, which requires relatively many sites and has insufficient thermal performance, methods such as Slinky and Coil types have been devised to reduce necessary sites in addition to the existing straight type. Among them, there are no cases of research or actual adoption of mat-type GHE made by weaving capillary tubes. Therefore, in this study, basic design information was established by deriving the heat absorption amount of mat-type GHE through simulation to determine the applicability of mat-type GHE. In addition, verification was performed by comparing the actual data in the test chamber with the simulation model. In addition, according to the verified information, the applicable conditions were analyzed through energy consumption and HP EFT/LFT analysis by coupling with the terminal system currently used in work and residential buildings. The results of this study are summarized as follows.

(1) In the commercial program Energyplus, there is no separate input class for mat-type GHE, and when input through a normal straight horizontal GHE. But by using the ‘Piping System:underground' class, modeled the mat-type GHE within Energyplus. A heating experiment simulation was conducted to approximately find out the thermal performance of the mat-type GHE modeled through Energyplus. A small cell was simulated and coupled with floor radiant heating. At this time, the area was set so that the result was that about 110W per mat-type GHE module was absorbed from the underground, which was calculated to be about 30W/m2 per area. For validation of the mat-type GHE model calculated by simulation, an experiment was conducted to measure the heat absorption amount by circulating the fluid to the mat-type GHE at the site where the experiment was built. As a result, the heat rejection amount was measured 124W when the maximum temperature difference of the heat transfer fluid was 1.6°C. This was simulated in Energyplus, and 124W of load was continuously loaded to the mat-type GHE. The heat transfer fluid temperature recovered to the underground temperature of 1.7m underground in the Energy Plus, and the temperature difference was also maintained at 1.6°C, so the model in the Energy Plus was reasonable.

(2) For reviewing the applicability of the heating period of the mat-type GHE, all the heating and heat source supply methods performed in this study satisfied the heating demand during the heating period. In order to efficiently use the geothermal source, the simulation was conducted using the geothermal source only from 23:00 to 9:00 in order to use late-night electricity. When FCU was used as a terminal, a geothermal source was used at once to refill the hot water used in the afternoon, and the load was larger than when RHF, which performs heating at night, was used, thereby increasing GHE sizing. This is a common disadvantage of horizontal GHE, whose required area increases as the design capacity increases, and it should be avoided when applying mat-type GHE corresponding to horizontal GHE in coupling with FCU. When mat-type GHE was used as a heat source, energy usage was higher than when vertical GHE

was applied. This is related to the installation depth of each geothermal source system. Vertical GHE is installed at a higher level than mat-type GHE, so the amount of heat that the GHE can absorb varies even with the same underground load. In addition, the high altitude in winter has a higher underground temperature than the low depth, and in the case of vertical type, there is no restriction in the selection of FCU and RHF. However, in the case of horizontal GHE, since it is buried at a low depth, it is considered appropriate to use it in coupling with RHF, which uses less energy. In order to increase applicability, it is reasonable to reduce the required GHE area by lowering the load by heating with lower hot water, and as a method of implementing this, it is recommended to apply a heating curve to RHF rather than a general control of supplying hot water at 55℃.

(3) Currently, there is a disadvantage that the runtime is excessively long when the mat-type GHE is simulated through Energy Plus. And we can't see the underground temperature at a certain depth or coordinate. So, I think there is a need for an independent model in the future. Furthermore, in this study, burying in a general installation depth and plane was used, and it is thought necessary to find an appropriate burying method through various depths and burying forms.

Bibliography

1. Benli. H. (2013). A Performance Comparison between a Horizontal Source and a Vertical Source Heat Pump Systems for a Greenhouse Heating in the Mild Climate Elaziğ, Turkey. *Applied Thermal Engineering*, 50(1), 197–206.
2. Jin, S., Lee, J., Kim, T., & Leigh, S. (2012). Evaluation of the Heating Performance of Vertical and Horizontal GSHP Systems by Simulation. *Proceeding of Annual Conference of the Architectural Institute of Korea*, 32(2), 265–266.
3. Hwang, Y., Lee, K., Cho, S., & Choi, J. (2011). Evaluation Comparison of Initial Construction Cost and Geothermal Heat Pump Dimension on Vertical and Horizontal Types. *Journal of Korean Institute of Architectural Sustainable Environment and Building Systems*, 109–112.
4. The United States Uses a Mix of Energy Source. (2022, January 10). *U.S. Energy Information Administration*. https://www.eia.gov/energyexplained/us-energy-facts/
5. *Geothermal*. (2022, November 8). KNREC. https://www.knrec.or.kr/biz/korea/intro/kor_geo.
6. *[New Renewable Energy] Exploration of New Renewable Energy Source Part 3 - Geothermal Energy*. (2020, January 5). KNRECblog. http://blog.energy.or.kr/?p=20648
7. *Geothermal Heat Pumps*. U.S. Department Of Energy. https://www.energy.gov/energysaver/geothermal-heat-pumps
8. Lim, H. (2005). Comparison of Geothermal System Characteristics. *Korea Journal of Geothermal Energy*, *1*(2), 57–65.
9. Nam, Y., & Chae, H. (2013). Prediction of the Heat Exchange Rate for a Horizontal Ground Heat Pump System Using a Ground Heat Transfer Simulation. *Korean Journal of Air-Conditioning and Refrigeration Engineering*, *25*(6), 297–302.
10. Nam, Y., & Oh, J. (2014). Study on the Characteristic of Heat Exchange for Vertical Geothermal System Using the Numerical Simulation. *Journal of the Korean Solar Energy Society*, *34*(2), 66–72.
11. Baek, S., Yeo, M., & Kim, K. (2017). Effects of the Geothermal Load on the Ground Temperature Recovery in a Ground Heat Exchanger. *Energy and Buildings*, *136*(1), 63–72.

12. Bae, S., Jeon, J., Kwon, Y., & Nam, Y. (2020). Study on the Operation Method of Ground Source Heat Pump System Considering Recovery of Ground Temperature. *Transactions of the Korea Society of Geothermal Energy Engineers*, *16*(4), 24–30.
13. Widiatmojo, A., Gaurav, S., Ishihara, T., Tomigashi, A., Yasukawa, K., Uchida, Y., Kaneko, S., & Yoshioka, M. (2019). Experiments Using Capillary Mat as GHE for Ground Source Heat Pump Heating Application. *Energy and Power Engineering*, *11*(11).
14. Bai, Z., Li, Y., Zhang, J., Fewkes, A., & Zhong, H. (2021). Research on the Design and Application of Capillary Heat Exchangers for Heat Pumps in Coastal Areas. *Building Services Engineering Research and Technology*, *42*(3), 333–348.
15. Ihm, P., & Cho, S. (2016). Experimental Study for Horizontal Geothermal Heat Pump Heating Performance Analysis. *Transactions of the Korea Society of Geothermal Energy Engineers*, *12*(2), 7–12.
16. Son, B. (2012). Performance Analysis of Ground−Coupled Heat Pump System with Slinky−Type Horizontal Ground Heat Exchanger. *The Society of Air−Conditioning and Refrigerating Engineers of Korea*, *24*(3), 230–239.
17. Eskilson, P. (1987). Thermal analysis of heat extraction boreholes.
18. Xu, X., & Spitler, J.D. (2006). Modeling of Vertical Ground Loop Heat Exchangers with Variable Convective Resistance and Thermal Mass of the Fluid.
19. Piechowski, M. (1999), Heat and mass transfer model of a Ground Heat Exchanger: theoretical development. Int. J. Energy Res., 23: 571−588.
20. Piechowski, M. (1998), Heat and mass transfer model of a ground heat exchanger: validation and sensitivity analysis. Int. J. Energy Res., 22: 965−979.
21. Piechowski, M. (1996). A ground coupled heat pump system with energy storage. PhD thesis, Department of Mechanical and Manufacturing Engineering, The University of Melbourne.
22. Clina Heiz− und Kühlelemente GmbH. Available at: https://www.clina.de/en/products (Accessed: November 19, 2022).

23. Leigh, S., Jang, H., Liu, S., Leigh, T., & Yeo, M. (2022). A Comparison and Thermal Performance Analysis of Mat-Type Horizontal Ground Heat Exchanger with Vertical Ground Heat Exchanger at Winter Season. *Proceeding of the SAREK Conference*, 632-635.
24. Korea Meteorological Administration, Comprehensive climate change monitoring information, 2022.05.04. // (Korea Meteorological Administration, http://www.climate.go.kr/home/09_monitoring/surfacetemp/Sf_tmp, 2022.05.04.)
25. "Satellite Image." Google Map, Google, 11 Jan. 2023, https://www.google.co.kr/maps/place.
26. Kusuda, T., & Achenbach, P.R. (1965). Earth Temperature and Thermal Diffusivity at Selected Stations in the United States.
27. IGSHPA, 2016, "GLHEPro 5.0 Users' Guide", School of Mechanical and Aerospace Engineering, Oklahoma State University
28. Korea Meteorological Administration, Open MET Data Portal, 2023.01.10. // (Korea Meteorological Administration, https://data.kma.go.kr/data/grnd/selectAwosRltmList.do?pgmNo=638, 2023.01.10.)
29. Jang, H., Liu, S., Xue, Y., & Yeo, M. (2022). Evaluation of Applicability of Outdoor Rest Contorl with Radiant heating floor Systems through Comparative Experiments. *Magazine of the SAREK*, *51*(9), 40-49.

국문 초록

탄소중립 달성을 위해 건물에서도 화석연료의 감축이 요구되고, 이로 인해 재생 에너지로의 전환이 진행되고 있다. 지열원은 비교적 안정적으로 에너지를 공급할 수 있다. 하지만 일반적으로 사용하는 수직형 지중열교환기를 사용한 지열히트펌프를 이용하기위한 설치비용이 적지 않아 주로 공공시설 및 대형 빌딩에서 사용되고 있다. 이런 설치비용의 문제점을 보완하기위해 직선형이 아닌 지중열교환기의 표면적을 증가시키는 형태의 지중열교환기들이 연구되고 있다.

본 연구에서는 매트형 수평형 지중 열교환기를 적용가능성을 평가하기 위해 Energyplus 시뮬레이션 및 실험을 통해 수평형 지중열교환기의 열적 성능을 평가하였으며, 시뮬레이션을 통해 난방기에 건물에 적용할 시 매트형 수평형 지중열교환기와 사용하기에 적절한 건물의 용도 및 말단 시스템의 조합과 각 조합의 에너지소모량을 비교 및 분석하였다.

시뮬레이션 적용을 위해 매트형 지중열교환기 모델링을 진행하였다. 이 모델을 통해 인천지역에서의 바닥복사난방과 히트펌프로 이루어진 간단한 시스템의 겨울철 난방에 대한 시뮬레이션을 진행했을 때 매트형 지중열교환기 하나의 모듈(20 개의 모세유관)의 흡열량을 도출하였다.

매트형 지중열교환기 모델을 검증하기 위해 방열량을 Energyplus 시뮬레이션과 실험을 비교하였다. 우선 지중 온도 모델은 trial-and-error 방식으로 시뮬레이션에 필요한 토양의 파라미터를 도출하였다. Energyplus 시뮬레이션으로 겨울철 매트형 지중열교환기의 모듈(20개의 모세유관)당 최대 방열량은 약 124W이고 이때 지중열교환기를 순환하는 유체의 입·출구 온도차는 약 1.6℃였다. 이를 실제로 구축한 테스트셀에서 실험을 진행했을 때 방열량은 124W, 온도차는 동일하였다. 이는 트렌치 배관이 외기에 노출되어 손실되는 열량을 고려하지 않는다면 거의 일치하는 수치를 보였다.

‘

검증된 모델을 통해 매트형 지중열교환기를 사용했을 때 적절한 건물의 용도 및 난방방식을 찾기 위해 시뮬레이션을 진행했다. 사무용 건물과 FCU, 주거용 건물과 바닥난방을 커플링 했을 때의 경우를 설정하여 진행했다. 기본적으로 두 경우의 난방 시간이 달라 직접적인 비교가 어렵지만, 심야전기를 이용해 온수를 만든다고 하였을 때, 주거용 건물에서의 히트펌프 에너지 소모가 적었다. 그리고 외기보상제어를 적용하여 에너지소모의 추가적인 감소와 지중온도하락을 줄일 수 있었다. 이는 지중열교환기의 설계 길이의 감소로 이어지며, 수평형 지중 열교환기들의 소요면적의 감소로 이어진다. 그러므로 매트형 수평형 지중열교환기를 이용하는 지열히트펌프는 주거용으로 바닥복사난방 방식에 외기보상제어를 사용하는 시스템과 커플링하여 사용하는 것이 적절하다.

주요어 : 지열히트펌프, 수평형 지중열교환기, 모세유관,
매트형 지중열교환기
학번 : 2021-28956