Proceedings of Building Simulation 2011:
12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

MODELING OF HEAT TRANSFER IN GEOTHERMAL HEAT EXCHANGER USING GHX ZONAL MODEL METHOD

MoonJung Choi [1], SeungHyo Baek[1], MyoungSouk Yeo[2] and KwangWoo Kim[2]
[1]Department of Architecture and Architectural Engineering,
Graduate School of Seoul National University, Seoul, Korea
[2]Department of Architecture and Architectural Engineering,
Seoul National University, Seoul, Korea

ABSTRACT

Two types of Ground Heat Exchanger (GHX) zonal models are suggested for a new analysis method that can reduce analysis time and reflecting heat transfer mechanisms occurring on the GHX section; using a circular pattern (Circular) and replacing the circle with a square shape (Square). The GHX zonal model is suggested to analyze a 2-dimensional unsteady-state thermal performance involving heat interference between pipes in a borehole. Comparing results from the simulations and PHYSIBEL program (BISTRA), the temperature distribution of GHX zonal models is similar to that of BISTRA, therefore the analysis grid of the GHX zonal model is regarded as appropriate.

INTRODUCTION

The Ground Heat Exchanger (GHX) is the main part of the geothermal system. As the thermal performance of GHX determines the thermal performance of the whole geothermal system, a proper thermal performance analysis is needed to improve the thermal efficiency of the whole system and to avoid economic losses caused by inefficient operation or improper capacity of GHX.

For accurate dynamic thermal performance analysis, various heat transfer mechanisms occurring on the GHX section should be applied to the thermal analysis. Because the temperature on the GHX section is constantly changing over time through heat exchange with the ground, heat flux generated in GHX and the thermal efficiency of the GHX can be calculated over time. Therefore, an exact temperature distribution of the GHX section is important for accuracy.

Existing theories for the analysis of GHX use either a method of simplifying the GHX section or a numerical analysis method. The simplified GHX model is inadequate for dynamic analysis, as it does not consider heat interference between the two pipes located in the borehole or the thermal effect of the grout in a GHX section. On the other hand, a detailed analysis method using numerical analysis such as a finite element method (FEM) or a finite volume method (FVM) can provide a more accurate dynamic thermal analysis of GHX, but is very time-consuming. Therefore, new dynamic thermal analysis model for the GHX section is required that not only consider the heat transfer mechanism occurring on the section but can also reduce analysis time.

In this study, two types of GHX zonal model are suggested for a 2-dimensional calculation model that analyzes inside the borehole boundary while considering the heat transfer mechanisms occurring on the GHX section. The results from simulation using the GHX zonal model are validated with the PHYSIBEL program to verify the temperature of the nodes. The BISTRA program is one of the PHYSIBEL programs used for a 2-dimensional transient thermal analysis. Dynamic thermal analysis under the same conditions is conducted and we find that the temperature distribution on the GHX section from the GHX zonal model is similar to that of PHYSIBEL.

GHX ZONAL MODEL

Analysis of heat transfer mechanism and thermal influence factors on GHX cross section

GHX consists of many boreholes and a ground known as boreholes field. A borehole includes heat carrier fluid, a U-tube pipe and a grout material. The heat carrier fluid that flows along the U-tube pipe transfers the heat vertically, and the heat exchange between the fluid and the ground is generated horizontally at a particular depth. GHX with a single U-tube pipe is used in most system, so the GHX section has two pipes. As the heat carrier fluid enters into the pipe, the inlet pipe absorbs/ releases heat from/ to the ground; therefore, the temperature of the fluid would change and there would be a temperature difference between the two pipes at the same level of the ground.

Heat transfer occurring on the section of GHX consists of three parts; heat interference between the two pipes in the borehole (shown in Figure 1 ⓐ), heat transfer between the fluid in the pipe and the ground (shown in Figure 1 ⓑ, ⓒ), and heat interference between the two boreholes in the borehole field (shown in Figure 1 ⓔ). Heat transfer mechanisms and thermal influence factors can be expressed in figure 1 as follows.

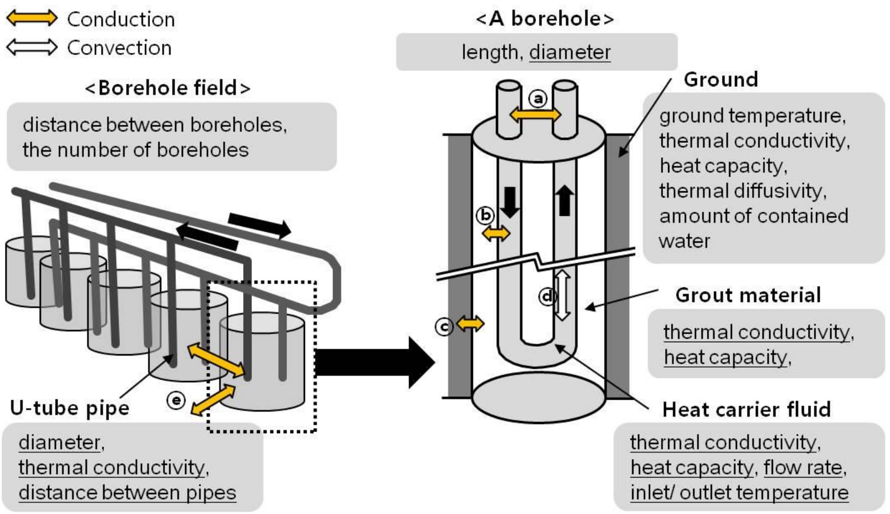


Figure 1 Heat transfer mechanisms and thermal influence factors of GHX (Underlined factors are considered in this study)

As the heat carrier fluid runs inside the pipe as shown in Figure 1 ⓓ and absorbs/ releases heat for the building from/ to the ground at the same time in the borehole, the inlet fluid temperature and outlet fluid temperature can differ at a particular level of the ground.

As the temperature of the inlet fluid differs from that of the outlet fluid, heat interference between the two pipes may occur on the section of GHX (shown in Figure 1 ⓐ). In the heating mode, as the heat carrier fluid running through the U-tube pipe absorbs the heat from the ground, its temperature rises. The outlet fluid temperature may be higher than the inlet fluid temperature at the same level of the ground at the same time in heating mode; the temperature difference between the two fluid temperatures causes the heat to flow from the outlet pipe to the inlet pipe causing a heat transfer offset between the fluid and the ground.

Heat transfer between the fluid in the pipe and the ground (shown in Figure 1 ⓑ, ⓒ) is the main heat transfer mechanism of GHX, and the heat is transferred through the pipe and the grout material. According to the demands for heating/ cooling, the heat carrier fluid in the pipe absorbs/ releases the heat from/ to the ground and contains heat conduction and convection.

It is worth considering the heat interference between boreholes (shown in Figure 1 ⓔ) for an accurate thermal analysis. The short distance between the adjacent boreholes allows a small section of the ground to exchange heat for each borehole, and the adjacent boreholes thus affect each other thermally so that heat exchange between the fluid and the ground is insufficient. These heat interferences between boreholes are influenced not only by the distance between the boreholes but also by the ground's thermal characteristics, especially the dynamic stability of ground, which refers to the time required for the ground to return to its initial temperature.

Although the dynamic stability of the ground, as a function of thermal conductivity, diffusivity and the amount of contained water of the ground is not an important influencing factor in the existing theories and analysis programs, it can affect the change of ground temperature and GHX operation in the long term.

Analysis grid

In this study, the thermal performance analysis model for GHX deals with a cylinder-shaped borehole cross section that contains a single U-tube pipe. An Analysis model for a cylinder-shaped borehole containing two vertical pipes that are located symmetrically analyses the 2-dimensional unsteady-state heat transfer and each node represents the same temperature area on the section of GHX.

Numerical analysis such as a finite element method (FEM) or a finite volume method (FVM), as shown as Figure 2 (a), divide the object into numerous small nodes for analysis. Because solving the problem in spite of calculation accuracy is time-consuming, we can consider an alternative that reduces the number of nodes defining an area representing similar temperature to that of a node. One of the ways to reduce the number of nodes is to use a circular pattern inside the borehole section while maintaining the original shape. Another way is to use an alternative shape for the borehole section to simplify calculation by using rectangular coordinates.

Figure 2 (b) shows the circular patterns adopted by the GHX zonal model on GHX section. Because heat is diffused outwards from the center of the circle-shaped borehole section, the central circles of the borehole are considered as a grid. Heat transfer between the pipes can be analyzed similarly to the real heat transfer mechanism but it is difficult to define the thermal resistance and distance between the nodes for shape.

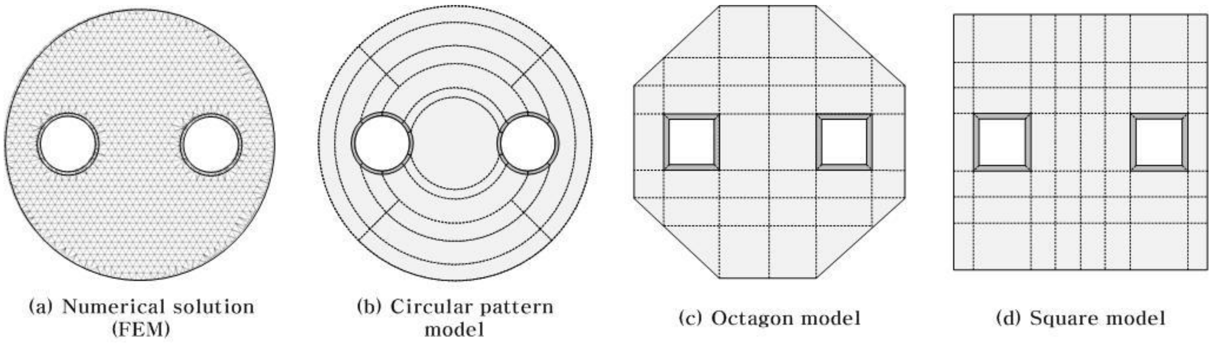

(a) Numerical solution (FEM) (b) Circular pattern model (c) Octagon model (d) Square model

Figure 2 Analysis modelling for GHX

To simplify thermal analysis, the shape of borehole can be changed to another shape such as an octagon, rectangle or square. Using an octagon shape for the GHX section means it is easier to define thermal resistance and the distance between the nodes as shown as Figure 2 (c). However, the octagon shape creates triangulated areas at the borehole boundary where it meets the ground, making it difficult to standardize the heat exchange pattern between the nodes and the ground.

Figure 2 (d) is an analysis model in which the circle is replaced with a square of which the area is equivalent to that of the borehole. In this model, the distance between nodes can be clearly defined and it is easy to calculate the heat transfer with the ground. For accurate thermal analysis, the contact length at the borehole boundary is multiplied by the ratio of the perimeter of the square to that of the circle in order to ensure an equal heat transfer rate between the nodes.

The Circular pattern model has the shape most similar to that of real borehole among suggested analysis modelling and is expected to represent a similar temperature distribution on the GHX section. However, the Square model is the simplest method for analyzing the GHX section with ease of calculation. In this study, the Circluar GHX zonal model and the Square GHX zonal model are used to analyze the heat transfer on the GHX section.

Table 1 Considered heat transfer mechanisms in existing theory for thermal analysis of GHX

HEAT EXCHANGE BETWEEN	LINE SOURCE THEORY	CYLINDRICAL SOURCE THEORY	DETAILED ANALYSIS METHOD
Fluid - ground	considered	considered	considered
Pipe - pipe	not considered	not include thermal characteristics of grout material	considered
Borehole - borehole	not considered	not considered	not include effect of dynamic stability of ground

ANALYSIS OF GHX SECTION

Existing theory on GHX analysis

Many theories have been proposed for the design or thermal analysis of GHX including the line source theory and the cylindrical source theory. The line source theory and the cylindrical source theory are mainly used to determine the size of the boreholes or to evaluate the performance of GHX using simple modeling of the GHX section. Existing theories on GHX thermal analysis use a simplified GHX model with a line (or a cylinder) heat source at the centre of the GHX section. With the simplified GHX model, it is difficult to consider the heat interference between the two pipes located in the borehole or the thermal effect of the grout in a GHX section.

On the other hand, a detailed analysis method using numerical analysis such as a finite element method (FEM) and a finite volume method (FVM) can provide a more accurate dynamic thermal analysis of GHX, but it is very time-consuming. It is usually used in energy analysis of the building not in design of the system of the building.

The line source theory, which assumes a U-tube pipe as an infinite line at the center of the infinite ground, analyzes the thermal performance of GHX on a steady state, ignoring the heat interference between the pipes and the thermal characteristics of the grout material.

In the cylindrical source theory, several pipes on GHX section are simplified into a pipe using an equivalent diameter. The equivalent diameter D ($=\sqrt{n}D_o$) for n pipes with outer diameter D_o is used to analyze the heat exchange between the fluid and the ground. The heat interference between pipes is not included in this method.

A detailed analysis method using numerical analysis can evaluate the thermal performance of GHX accurately. In this method numerical analysis such as FEM (finite element method) or FVM (finite volume method) is used to calculate the temperature of GHX and it simulates the real heat transfer phenomenon. However, its analysis is time-consuming and is too complex to use in designing GHX.

Table 1 shows the heat transfer mechanisms considered in the existing theory.

Calculation method

The heat transfer between nodes is assumed as a 2-dimensional unsteady-state heat transfer to consider the thermal capacity of the material. Heat flux absorbed/ released in a node during a time step is equal to the sum of the heat flux from an adjacent node due to the temperature difference between nodes, and it can be expressed by equation (1) :

$$\rho c_p V \frac{dT_i}{dt} = \sum_j \left(\frac{1}{R_{tot}}\right)_j \left(T_i - T_{adj,j}\right) \qquad (1)$$

- Circular GHX zonal model

A control volume in the Circular GHX zonal model is defined according to each component material of the GHX section and the heat transfer mechanism as previously stated. The circular pattern inside the borehole considers the heat transfer from the pipes to the ground without change of simulation shape.

The GHX section is basically divided using the central circles of the borehole, and each radius of the central circles can be determined where the central circle meets the pipe. The grout area contacts the two pipes together is determined according to the distance between the pipes and the size of the pipe where heat interference occurs between the pipes. The pipes are located vertically to the ground and the heat carrier fluid flowing inside the pipe creates heat exchange with the grout material. However, a temperature difference might occur between the two pipes at the same depth and it may cause a temperature difference between the left-side and the right-side in the borehole. To consider the asymmetry of temperature distribution, the circular patterns are split into 4 segments using diagonal lines.

To set up the same logic to generate a grid for various borehole geometries, we can use the central angle, with the center of the pipe as its center. The part of a pipe that is closer to another pipe has the smaller central angle to generate narrow grids that provide simulation accurate.

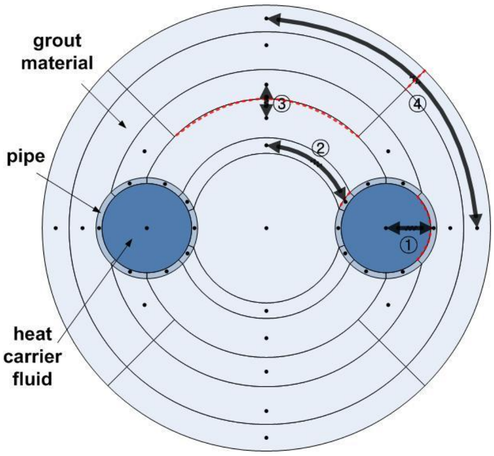


Figure 3 Circular GHX zonal model grid and thermal resistance between nodes

The area inside the pipe is regarded as a node and each pipe has 8 nodes determined by the central angle according to the location. The values of π/8, π/4, and π/2 are used as a unit of angle in this modeling. The number of nodes in the Circular GHX zonal model is 37 and an example of the GHX zonal model grid is shown in Figure 3.

The thermal resistances between the adjacent nodes (R_{tot}, [℃/W]) considered in the Circle GHX zonal model are classified into 4 types:

- thermal resistance between fluid and pipe
- thermal resistance between pipe and grout
- radial thermal resistance in grout
- arc-directional thermal resistance in grout

The thermal transfer between the fluid and the pipe (Figure 3 ①) consists of heat convection on the inner surface of the pipe and heat conduction through half of the pipe. Also, heat conduction is generated between the pipe and the grout material (Figure 3 ②) through half the thickness of the pipe and the radial distance between the two adjacent nodes. As heat is diffused to the radial direction by heat conduction (Figure 3 ③), we can apply cylindrical heat transfer in this case. Finally, heat is exchanged along the arc line (Figure 3 ④). In figure 3, the contact area between the nodes is expressed as a dotted line.

- Square GHX zonal model

Using the fact that the area of the square GHX zonal model is equivalent to that of the GHX section, a side of the square can be calculated by the following equation:

$$D_b' = \sqrt{\frac{\pi}{4} D_b^2} \qquad (2)$$

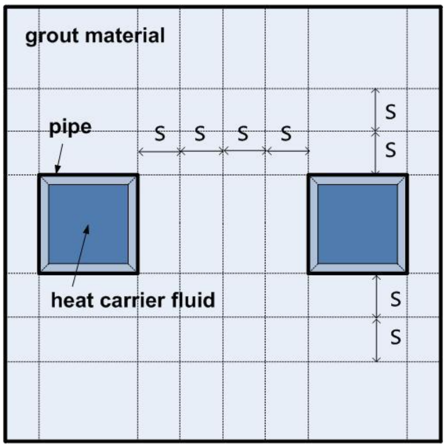


Figure 4 Square GHX zonal model grid

To generate an analysis grid of the Square GHX zonal model, all sides of the pipe squares are extended to the side of the borehole square. The space between the two pipes is divided into 4 equal nodes horizontally, and each of the two nodes is added to the up and down side of the pipe squares having the same distance.

In the Square GHX zonal model, there are two types of thermal heat transfer, similar to those in the Circular GHX zonal model. Heat transfer is influenced by the distance and contact area between two adjacent nodes. As the distance and contact area between nodes differ from those of the original GHX section, the ratio of the perimeter of the square to that of the circle is applied to the nodes that are located at the borehole boundary or around the pipes.

Thermal resistances between the adjacent nodes (R_{tot}, [℃/W]) considered in the Square GHX zonal model are classified into 3 types:

- thermal resistance between the fluid and grout
- thermal resistance of heat conduction between nodes
- thermal resistance of heat conduction between nodes using the distance multiplied by the ratio

Similarly to the Circular GHX zonal model, two types of heat transfer are generated between the fluid and the total heat convection resistance on a surface and the heat conduction resistance through the pipe are used to calculate total thermal resistance of the pipe. The bold lines in Figure 4 indicate where the ratio is multiplied to define the distance and contact area between nodes to reflect the actual heat transfer mechanism in the calculation.

However, the heat transfer for the inner nodes is calculated using the length of the rectangle without multiplying it by the ratio.

The ratio is calculated by the following equation (3):

$$\text{ratio} = \frac{D_b}{D_b'} = \frac{\sqrt{\pi}}{2} \qquad (3)$$

SIMULATION OF GHX ZONAL MODEL AND VALIDATION

Simulation conditions

Conditions and inputs for simulation using the GHX zonal models and the PHYSIBEL simulation for validation of the GHX zonal model are shown in Table 2. The properties for pipes, grout and fluid material are assumed as under a condition close to that of the actual use. The initial temperature of the inlet fluid (left), outlet fluid (right), and grout was 7℃, 10℃, and 15℃, respectively and the temperature of the boundary area (ground) is constant at 15℃.

Results

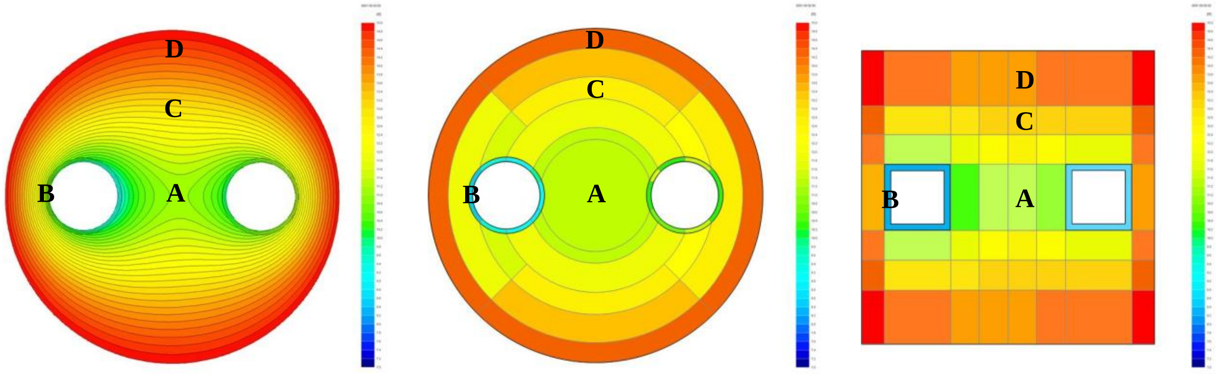
Results from the Circular GHX zonal model and the Square GHX zonal model appear to be similar in temperature distribution ranging from 7℃ to 15℃ as shown Figure 3. The temperature of the left side is lower than that of the right side due to the difference between the initial temperatures of the two pipes, and the outer nodes of the model are similar to those of temperature. The overall temperature distribution of both models appeared to be reasonable.

To compare the exact temperature in the simulation, 4 points as expressed in Figure 5 are selected. Point A, the centre of the GHX section, is selected to validate the temperature affecting the heat interference between the two pipes. In the results from the two simulation models, the temperature of the centre is similar as 11.22℃ and 11.43℃, but the node that represents the centre of the Circular GHX zonal model is too large to reflect the sensitive temperature transition. The Square GHX zonal model has the advantage of being able to analyze in detail by dividing nodes finely but the temperature of the centre is slightly higher than that of Circular model.

Pipes are an important component that carries heat from the fluid to the grout, so the temperature of the pipes is considered for accurate analysis. At point B, the temperature of the Circular model is 8.62℃, and the heat capacity of the pipe is considered to be small and is significantly influenced by the temperature of the fluid. The temperature of the Square model is 11.04℃, which is higher than that of the Circular model.

Table 2 Input data for simulation

PARAMETER		VALUE
Calculation duration [day]		1
Bore-hole	External diameter [m]	0.15
	Depth [m]	0.1
Pipes	External diameter [m]	0.034
	Thickness [m]	0.003
	Thermal conductivity [W/m℃]	0.42
	Density [kg/㎥]	965
	Specific heat [J/kg℃]	2,310
	Distance between pipes [m]	0.08
Fluid	Flow rate [kg/s]	0.3
	Convective heat transfer coefficient [W/m℃]	200
	Initial inlet fluid temperature [℃]	7
	Initial outlet fluid temperature [℃]	10
	Thermal conductivity [W/m℃]	0.45
	Density [kg/㎥]	960
	Specific heat [J/kg℃]	4,000
Grout	Thermal conductivity [W/m℃]	0.74
	Density [kg/㎥]	1,310
	Specific heat [J/kg℃]	2,846
Ground	Boundary ground temperature [℃]	15



(a) result from BISTRA

(b) result from Circle GHX zonal model

(c) result from Square GHX zonal model

Figure 5 Results from simulation

Table 3 Comparison between results from BISTRA, Circle, and Square GHX zonal model (A, B, C and D are expressed in Figure 5 (a))

NODE	**A**			**B**			**C**			**D**		
Simulation	BISTRA	Circle	Square	BISTRA	Circle	Square	BISTRA	Circle	Square	BISTRA	Circle	Square
Temperature [℃]	10.47	11.22	11.43	10.74	8.62	11.04	13.18	12.52	13.08	14.51	14.41	14.48
Error rate [%]	0.0	7.1	9.1	0.0	-19.7	2.8	0.0	-5.0	-0.8	0.0	-0.7	-0.2

Point C is a halfway point between the centre-line of the borehole and the ground where the heat diffusion to the ground can be seen, and we can find that the temperature is 12.52℃ in Circle model and 13.08℃ in Square model which is around the average temperature of the fluid and the ground.

Finally, point D where is adjacent to the ground is selected to validate the heat transfer with the ground. Both results at point D show that temperatures of two model are around 14.5℃ which is similar to the ground temperature keeping 15℃.

Validation

The result using BISTRA with the same conditions as those of the GHX zonal models is shown in Figure 5 and Table 3. Comparing the results from the GHX zonal models, the temperature distribution of the result from BISTRA demonstrates the temperatures of the two GHX zonal models. The Circular and Square GHX zonal models appear to be reasonable by roughly comparing the temperature distribution .

A comparison of the exact temperature at each point on the GHX section is shown in Table 3. The results at point A from the GHX zonal models are slightly higher than those from BISTRA. This is because when a large area is defined as a node, it is strongly influenced by the ground temperature.

The most significant temperature difference occurred at point B between the BISTRA and the Circular model. The pipe temperature from BISTRA increase over time by up to 10.7℃ during simulation time. However, the pipe temperature from the Circular model decrease to 8.62℃, strongly affecting the fluid temperature owing to the largest contact area for the fluid. In the case of the Square model, the temperature is 11.04℃, which is similar to 10.74℃ from BISTRA and the Square model is considered to be relatively accurate.

The results from the three simulation models are almost the same at points C and D.

Discussion

By comparing the results from the GHX zonal models with the results from BISTRA, the GHX zonal model suggested for accurate analysis and reduction of simulation time is considered reasonable. However, the centre zone where temperature differences occur need to be compensated. The temperature of the borehole centre from the Square GHX zonal models is higher than that from BISTRA, whereas others are similar to the results from BISTRA.

Comparing the Square GHX zonal model to the Circular GHX zonal model, the method used to generate the analysis grid and calculation principle is simple and the result from the Square model appears to be more accurate. In the Circular model, the overall temperature distribution is simple to comprehend, but some temperatures considerably differ. Table 4 shows a comparison between the Circular GHX zonal model and the Square GHX zonal model for accuracy, applicability and compensation.

CONCLUSION

The Circular GHX zonal model and the Square GHX zonal model are suggested to analyze the thermal performance of GHX considering heat transfer mechanisms that occur on the GHX section especially the heat interference between the two pipes in a borehole. The study deals with a cylinder-shaped borehole cross section containing two vertical pipes. The GHX zonal model is a 2-dimensional unsteady-state thermal heat transfer analysis and calculates the temperature distribution of the GHX section.

The results from the computer simulation using the GHX zonal models represent the temperature distribution of the GHX section, and the temperature difference between the results from the GHX zonal models and the results from PHYSIBEL at the same point is less than 10% for most nodes. By verifying the temperature of the node at the same area, an analysis grid of the GHX zonal model is validated as reasonable. Both results are slightly higher at the central area than those in PHYSIBEL, and it is considered that defining a large area as a node in the centre is strongly influenced by the ground temperature. However, the temperature difference between the results from the Square GHX zonal model and the results from PHYSIBEL is less than 3% at the another nodes.

Comparing the results from the Square GHX zonal model and the Circular GHX zonal model, the Square GHX zonal model is more accurate for calculating temperature and has a simple methodology for defining an analysis grid. Also, with this model it is easy to connect with the ground for the analysis including the heat transfer between the fluid and the ground and between the boreholes.

In this study, the GHX zonal model does not include the influence on the ground and the heat interference between the boreholes. By verifying a 2-dimensional unsteady-state analysis method inside a borehole, the GHX zonal model will be developed into a 3-dimensional unsteady-state analysis considering the influence on the ground and heat interference between the boreholes. Moreover, additional validation with the experiment is needed for comparison between the ground temperature and the results.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0004093)

Table 4 Comparison between the Circular GHX zonal model and the Square GHX zonal model

MODEL	**CIRCLE ZONAL MODEL**	**SQUARE ZONAL MODEL**
Strength	- Equiform to origin borehole shape - Possibility to brief analysis using the small number of nodes	- Simple calculation method to analyze - Simple methodology to generate analysis grid - Ease to connect with the ground
Weakness	- Difficulty defining thermal resistance or distance between nodes - Difficulty connecting with the ground	- Difficulty matching the temperature on origin GHX section

NOMENCLATURE

c_p : Specific heat [J/kg^{o}C]
D_b : Borehole diameter [m]
D'_b : Equivalent diameter of borehole [m]
R : Thermal resistance [^{o}C/W]
T : Temperature [^{o}C]
V : Volume [m^3]
ρ : Density of material [kg/m^3]

REFERENCES

Carslaw, H.S., Jaeger, J.C. 1959. Conduction of Heat in Solid, Oxford University Press, Oxford.

Deerman, J.D., Kavanaugh, S.P. 1990. Simulation of vertical U-tube ground-coupled heat pump systems using the cylindrical heat source solution, ASHRAE Transactions 97, 287-295.

Frank P. Incropera, David P. Dewitt, Theodore L. Bergman, Adrienne S. Lavine. 2007. Introduction to Heat Transfer, 5th edition. John Wiley and Sons (Asia).

Kavanaugh, S.P. 1984. Simulation experimental verification of vertical ground-coupled heat pump systems, Ph.D. Dissertation, Oklahoma State University.

Katsunori Nagano, Takao Katsura, Sayaka Takeda. 2006. Development of a design and performance prediction tool for the ground source heat pump system, Applied Thermal Engineering. Volume 26. Issues 14-15. October 2006. Pages 1578-1592

PHYSIBEL. 2010. BISTRA v3.0w Manual 01.

Xiaowei Xu, Jeffrey D. Spitler. 2006. Modeling of Vertical Ground Loop Heat Exchangers with Variable Convective Resistance and Thermal Mass of the Fluid. ECSTOCK 2006