

# **Commercial Program Development for a Ground Loop Geothermal System: G-Functions, Commercial Codes and 3D Grid, Boundary and Property Extension**

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By

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Kyle L. Hughes ENTITLED Commercial Program Development for Ground Loop Geothermal System: G-function, Commercial Codes and 3D Grid, Boundary and Property Extension BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Masters of Science in Engineering

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# Abstract

Hughes, Kyle L. M.S.Egr, Department of Mechanical and Materials Engineering, Wright State University, 2011. Commercial Program Development for Ground Loop Geothermal System: G-function, Commercial Codes and 3D Grid, Boundary and Property Extension

The rise in fossil fuel consumption and green house gas emissions has driven the need for alternative energy and energy efficiency. At the same time, ground loop heat exchangers (GLHE) have proven capable of producing large reductions in energy use while meeting peak demands. However, the initial cost of GLHEs sometimes makes this alternative energy source unattractive to the costumer. GLHE installers use commercial programs to determine the length of pipe needed for the system, which is a large fraction of the initial cost. These commercial programs use approximate methods to determine the length of pipe mainly due to their heat transfer analysis technique, and as a result, sometimes oversize the systems. A more accurate GLHE sizing program can simulate the system correctly, thus, reducing the length of pipe needed and initial cost of the system. We feel a more accurate GLHE sizing program is needed.

As part of a DOE funded project Wright State University has been developing a ground loop geothermal computer modeling tool, GEO2D, that uses a detailed heat transfer model based on the governing differential energy equation. This tool is meant to be more physically detailed and accurate than current commercial ground loop geothermal computer codes. The specific work of this Master's thesis first includes a detailed literature search of GLHE sizing techniques. Secondly, this work contains a detailed description of commercial GLHE sizing codes currently available and compares some results to GEO2D. Additionally, this work has developed a g-function program; a GLHE sizing technique used by many commercial programs, and compared results to GEO2D. Next, this work has developed subroutines to develop a three-dimensional grid system for a horizontal and vertical GLHE. Lasty this work has developed computer code for the boundary conditions and material property allocation used in GEO3D.

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# Nomenclature

|           |                                     |
|-----------|-------------------------------------|
| $g$       | g-function                          |
| $k$       | thermal conductivity                |
| $Q$       | heat flux per unit length           |
| $\alpha$  | thermal diffusivity                 |
| $T$       | temperature                         |
| $H$       | borehole depth                      |
| $R$       | thermal resistance                  |
| $B$       | resistance shape factor coefficient |
| $D$       | diameter                            |
| $h$       | convection coefficient              |
| $Re$      | Reynolds number                     |
| $Pr$      | Prandtl number                      |
| $r$       | radius                              |
| $COP$     | coefficient of performance          |
| $\rho$    | density                             |
| $u$       | velocity                            |
| $c_p$     | specific heat                       |
| $\dot{m}$ | mass flow rate                      |
| $\dot{Q}$ | energy flowing from fluid into soil |
| $U$       | fluid node temperature              |
| $A$       | area                                |
| $x$       | distance between nodes              |
| $t$       | time                                |
| $z$       | axial node index number             |
| $r$       | radial node index number            |
| $\sigma$  | azimuthal node index number         |
| $ncv$     | number of control volumes           |

|            |                                                  |
|------------|--------------------------------------------------|
| $V$        | volume                                           |
| $n_z$      | number of control volumes in axial direction     |
| $n_r$      | number of control volumes in radial direction    |
| $n_\sigma$ | number of control volumes in azimuthal direction |
| $Ri$       | Richardson number                                |
| $D_m$      | neutral stability momentum transfer coefficient  |
| $D_h$      | stability correction                             |

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# **Chapter 1**

## **Introduction**

The popularity of ground loop geothermal systems has increased in the past decade due to their continuously decreasing payback period. Until recently, the initial cost for these systems has stalled their growth. The recent rise in energy price has driven our society to develop alternative energy sources, which at the same time emit less green house gases. Ground loop geothermal systems are still dependent upon electricity, however, they use a ground heat exchanger to extract or reject heat so that their overall efficiency becomes much higher than air-to-air heat pump system or other conventional means of heating and cooling buildings. Various ground loop heat exchanger configurations can be used with a geothermal system. The construction of a ground loop heat exchanger is what causes the initial cost of a geothermal system to be higher than conventional heating and cooling systems. This thesis discusses work that was done to support the development of a computer-modeling tool for GLHE (ground loop heat exchanger) systems. In particular this work looks at the other techniques and computer programs that analyze and size GLHEs. This work also presents the gridding technique used to extend the two-dimensional version of Wright State's GLHE code called GEO2D to three dimensions, which is called GEO3D. The extension to three dimensions adds a number of abilities to the computer program such as more accurately handling vertical loops and including heat transfer effects from the ground-air interface. In addition to developing a three-dimensional grid, work was also done implementing the three-dimensional boundary conditions and setting material properties for the three-dimensional computational domain.

## 1.1 Ground Loop Geothermal System

Geothermal heat pumps are similar to an ordinary heat pump, but instead of using heat from the outside air, they rely on the stable temperature of the earth to provide heating, air conditioning and sometimes hot water. The highest and lowest temperatures recorded in the continental U.S. are 56.6 °C (Death Valley, California) and -56.6 °C (Roger Pass, Montana), respectively. Even during these extreme weather conditions, the ground, just a few feet below the surface, remains a constant uniform temperature. Although the temperatures vary by latitude, at six feet below the surface, temperatures range from 7.2 °C to 23.9 °C (California Energy Commission). This efficient heat sink allows the heat pump to move heat from the earth into the house in the winter, and pull heat from the house and dump it into the ground in the summer. GLHE systems are more efficient than air-to-air heat pumps, which exchange heat with the outside air, due to the stable, moderate temperature of the ground. Studies show that ground loop geothermal systems can have a heating efficiency that is 50 to 70 percent higher than the conventional heating systems and a 20 to 40 percent higher efficiency than the available air conditioners (IGSHPA, 1988). High efficiencies allow the ground loop geothermal system to payback the initial cost for the installation. The initial cost for ground loop geothermal system is a major disadvantage. The cost of GLHE systems differ depending on the loop that is selected.

Ground loop geothermal systems are either open-loop or closed-loop. An open-loop system uses a pump to extract groundwater to the heat pump. A closed-loop system uses a water pump to circulate fluid through pipes buried horizontally, vertically, or, in a pond. These buried closed loop systems are commonly referred to as a ground loop heat exchanger (GLHE). Horizontal loops, vertical loops and pond loops are some basic GLHE that can be installed.

Horizontal loops are usually the most cost effective loops to install. However, since the typical loop requires 75 to 150 meters for each ton of heating and cooling, a sufficient amount of land area is required. Trenchers and backhoes are used to dig

trenches followed by the placement of pipes in the trench. The trench is backfilled, taking care not to allow sharp rocks to damage the pipes. In a closed loop system, fluid flows through the pipe until it reaches the heat pump, where the heat extraction/rejection takes place. Eventually, the fluid enters the horizontal loop and the process is repeated.

Vertical ground loops are used when there is little land area, or in the case for an open loop, where there is a sufficient amount of underground water to extract. For a closed loop, a vertical well is drilled 50 to 150 meters deep and a single loop with a U-bend at the bottom is inserted before the hole is backfilled. A horizontal pipe that carries fluid in a closed system to the heat pump connects a series of these loops. Vertical loops are generally more expensive, due to high drilling costs, but require less pipe material because the earth's temperature is more constant at greater depths. An open loop drills the same vertical well, but only pumps water to the heat pump. From there, the water is dumped in the most eco-friendly manner.

One may only use pond-closed loops when the heat pump is near a body of water that is large enough, such as a large pond or lake. This GLHE is similar to the other closed ground loops, except the fluid circulates through a pipe underwater. Most likely, the pipes are coiled in a "slinky" shape to fit more pipe into a given space. Since the system is a closed loop, there are no adverse effects on the aquatic system.

Regardless of the loop that is selected, one must use an adequate length, separation, and size of pipe for suitable heat extraction/rejection over long periods of time. One can use many heat transfer techniques to estimate these parameters. Due to the lack in accuracy, initial costs increase due to over sizing and decreased efficiencies result in under sizing. With the modern computer processor, one can use a numerical technique to accurately predict the temperature field in the GLHE in order to optimize the system.

## **1.2 Objective of Work**

Over the past few decades, scientist and engineers have developed a number of programs for ground loop geothermal systems. Many of these programs use approximate methods to predict the GLHE size and do not provide detailed outputs. At this point in time we feel that more accurate techniques can be used to design these GLHEs. Since 2010, Wright State University has been developing a 2-D geothermal sizing program called (GEO2D) that uses a transient, finite volume difference technique. GEO2D is a flexible, user-friendly ground loop geothermal system whose main objective is to develop a ground loop heat exchanger sizing program that can model and optimize a system more accurately than most commercial programs available today without extensive computation time.

GEO2D interfaces with a building load calculation developed by the Department of Energy, called EnergyPlus. This highly accurate heating and cooling load calculator outputs hourly loads, which are used to determine the heat pump size. Following the selection of the heat pump, values for flow rate, pipe diameter and pipe length are suggested for the GLHE system. This user-friendly program allows the user to easily model the GLHE. Thermal properties for the fluid, pipe, grout and soil are displayed for the user to select, or the user can define desired thermal properties. Following completion of the GLHE model, FORTRAN is used to execute the heat transfer analysis for the model. FORTRAN was designed for fast computation time. Outputs such as COP, EWT, total pipe heat exchange, hourly loads, weather data, economics and temperature fields are displayed so that the user can optimize the GLHE system.

## **1.3 Literature Survey**

Most of the ground loop geothermal sizing programs available today are variations of two analytical methodologies: Kelvin's line source theory (Kelvin, 1882) and Carslaw and Jaeger's cylinder source solution (Carslaw & Jaeger, 1947). Some programs also use a numerical or combined approach to simulate the GLHE. The use of an analytical

model allows for a quick computation, but reduces the accuracy of the solution; while a numerical model produces a highly accurate solution, but consumes more computation time.

Ingersoll (Ingersoll & Plass, 1948) (Ingersoll, Zobel, & Ingersoll, 1954) applies Kelvin's line source theory (Kelvin, 1882) for obtaining a temperature at any point in an infinite medium. The medium is initially at a uniform temperature in which a line source heat rejection or extraction is applied starting at time zero. Ingersoll's model is valid for a true line source, but can be applied to small pipes after a few hours of operation. For large pipes or small time operation, a "time-to-pipe" ratio ( $\frac{at}{R^2}$ ) must be greater than 20 to meet the error criterion. One of the primary assumptions is that the line source must be infinitely long. Thus, this is a one-dimensional analysis. In addition, this model does not account for thermal interference between boreholes or grouting material. The analysis used by Ingersoll is a rough estimation to the actual heat transfer process, but this approach was modified in the following decades to become a more accurate model.

Hart and Couvillion (1986) also utilized Kelvin's line source theory to estimate continuous time-dependent heat transfer between a line source and the ground. Considering the heat rejected by the line source, they introduced a method to calculate the far-field radius  $r_\infty$ . The method is only approximate since Kelvin's line source would require  $r_\infty$  to be  $\infty$ . Hart and Couvillion developed a standard far-field radius of  $r_\infty = 4\sqrt{at}$ , which assumes the ground temperature beyond this distance to be undisturbed and constant. This technique can be used for multiple borehole configurations by setting  $r_\infty$  equal to the distance between the boreholes. Thermal interference is observed after  $r_\infty$  exceeds the distance between the boreholes, but superposition techniques are used to estimate this interference. Hart and Couvillion's technique introduced a method for calculating more complex ground loop geothermal systems, but still lack the accuracy that can be achieved with the modern computer processor using numerical techniques and precise governing differential equations.

Similar to the line source theory, the cylinder source solution (Carslaw & Jaeger, 1947) uses a number of simplifying assumptions. The most significant assumption is the “equivalent diameter” approximation that treats the U-tube from a vertical borehole as a single pipe. This assumption allows the single pipe and borehole to be modeled as a co-axial so that the cylinder source may be applied. In the following decade, Ingersoll modified this model to size buried heat exchanger (Ingersoll, Zobel, & Ingersoll, 1954). Kavanaugh (1985) furthered this technique to determine the temperature distribution or the heat transfer rate around the pipe. Assumptions made in this technique are: the heat transfer process is of the nature of pure conduction in a perfect ground formation / pipe contact, the pipe is surrounded by an infinite solid with constant properties, and groundwater movements in the earth and thermal interferences between adjacent boreholes are considered negligible. Kavanaugh suggests two methods to correct the thermal interference within the U-tube borehole. The first method calculates the resistance between the fluid, pipe, and ground to estimate the average fluid temperature. The second method is based on Kalman’s work (Kalman, 1980). Kalman developed a general equation for heat transfer from an element of differential length and integrates this equation over the entire length of the coupling.

Analytical models provide a quick and fairly accurate solution to ground loop geothermal systems. Unfortunately, Kelvin’s line source theory and the cylinder source model neglects one very important heat transfer parameter, axial heat flow along the length of the pipe. A model that neglects axial heat flow can be inadequate for analyzing the long-term operation of the ground loop geothermal system (Yang, Cui, & Fang, 2010).

**Table 1.1**

*Development of models and techniques for sizing ground loop geothermal systems*  
(Haberl & Sung, 2008)

| <b>Solution Approach</b>   | <b>Year</b> | <b>Model</b>                                               |
|----------------------------|-------------|------------------------------------------------------------|
| <b>Analytical Solution</b> | 1882        | <b>Lord Kelvin<br/>Kelvin's Line Source Model</b>          |
|                            | 1948        | <b>Ingersoll and Plass<br/>Modified Line Source Model</b>  |
|                            | 1986        | <b>Hart and Couvillion<br/>Enhanced Line Source Model</b>  |
|                            | 1947        | <b>Carslaw and Jaeger<br/>Cylinder Source Model</b>        |
|                            | 1954        | <b>Ingersoll et al.<br/>Modified Cylinder Source Model</b> |
|                            | 1985        | <b>Kavanaugh<br/>Modified Cylinder Source Model</b>        |
| <b>Numerical Solution</b>  | 1985        | <b>Mei and Emerson</b>                                     |
|                            | 1987        | <b>Eskilson</b>                                            |
|                            | 1989        | <b>Hellstrom</b>                                           |
|                            | 1996        | <b>Muraya et al.</b>                                       |
|                            | 1997        | <b>Rottmayer et al.</b>                                    |
|                            |             | <b>Thornton et al.</b>                                     |
|                            | 1999        | <b>Shonder and Beck</b>                                    |
|                            |             | <b>Yavuzturk and Spitler</b>                               |
|                            | 2003        | <b>Zeng et al.</b>                                         |

Numerical models have a significant advantage over analytical models since they can account for short time intervals, complex GLHE geometries, and thermal interference between loops. These numerical models have been developed to research the heat transfer within the GLHE to predict the optimized system. The models discussed below are more complex than the analytical models and have the disadvantage of being computationally more costly. However, the modern computer

processor today eliminates any skepticism in computation time between numerical and analytical models.

Mei and Emerson (1985) were one of the first to develop a numerical model to size horizontal GLHE that can also account for frozen ground formations around the pipe. The model solves three, one-dimensional partial differential equations (radially through the pipe, frozen formation region, and far field region), using an explicit finite difference scheme. These equations were coupled to a fourth one-dimensional partial differential equation representing the flow of heat along the pipe, resulting in a quasi two-dimensional model. The model uses different time steps for the pipe wall, frozen formation region, and a significantly larger time step for the fluid and unfrozen ground formation region (Yavuzturk, Spitler, & Rees, 1999). Mei and Emerson reported comparisons with experimental data over a 48 day simulation period.

Eskilson (1987) developed a hybrid model that uses both analytical and numerical solutions using a g-factor approximation. The use of g-functions allows a program to store predefined g-factors that can be accessed readily to estimate GLHE length given an input heat load. The g-function is specific to a borehole configuration and demonstrates its response to a heat pulse. With this in combination with the principle of superposition, any step change in heat extraction or rejection can be determined. Eskilson's model assumes: homogeneous thermal properties, an evenly distributed heat pulse, and is only accurate for long time steps. Many modifications have been made to Eskilson's g-functions that account for short time steps and the thermal reactions within the fluid, pipe, and grout. A demonstration of the g-function model is discussed and compared in Chapter 2.

Hellström (1989) developed a simulation model for vertical ground heat storage, which uses densely packed ground loop heat exchangers for seasonal thermal energy storage (Yang, Cui, & Fang, 2010). Hellstrom's model is based off a system where heat is stored directly in the ground, otherwise known as a duct ground heat storage system (DST). The model is separated into two regions: the volume that immediately surrounds

a single borehole, and the volume of multiple boreholes. Hellstrom defines these regions as the 'local' and 'global' problems. A third problem Hellstrom explains is the steady-flux problem, which describes the heat pulses around a pipe for a constant rejection or extraction. Like Eskilson, the model is a hybrid that uses a numerical solution within the 'local' and 'global' problems and then superimposes them with an analytical solution from the steady-flux input. The numerical model uses a two-dimensional explicit finite difference technique for the 'global' problem and a one-dimensional radial mesh for the 'local' problem. Hellstrom's model is not ideal for determining long time-step system responses for ground loop geothermal systems since the geometry of the borehole field is assumed to be densely packed, with a minimum surface area to volume ratio (Yavuzturk, Modeling of vertical ground loop heat exchangers for ground source heat pump systems, 1999).

Muraya et al. used a transient two-dimensional finite element model to investigate the thermal interference between the U-tube legs of a borehole (Muraya, O'Neal, & Heffington, 1996). The thermal short-circuiting is investigated by comparing the numerical model to existing analytical solutions from the single line source and the cylindrical-source. The model is validated against two different applications of the cylindrical-source solution using constant temperature and constant flux. In addition, the model examines the effect of different backfill materials on the heat transfer. This allowed Muraya to define an overall thermal effectiveness and backfill effectiveness. Finally, Muraya investigated the coupling of conduction with moisture transport.

Rottmayer et al. (Rottmayer, Beckman, & Mitchell, 1997) developed a numerical simulation for a vertical U-tube heat exchanger using an explicit finite-difference technique. Rottmayer uses a three-dimensional transient heat transfer model that includes lateral heat transfer in the fluid every 3 meters. Conduction in the vertical direction was neglected but each section of the model was coupled via the boundary conditions to a model of flow along the U-tube (Yavuzturk, Modeling of vertical ground loop heat exchangers for ground source heat pump systems, 1999). The program allows

the user to change borehole depth, flow rate, properties of the fluid, ground, and grout, and temperature of the ground and inlet fluid. The model was found to under-predict the heat transfer from the U-tube by approximately 5% when compared to analytical models.

Thornton et al. (1997) used Hellstrom's approach to model the ground loop geothermal system. The model was implemented in TRNSYS as a detailed component model (Klein, 1996). The model was calibrated with an experimental family house unit by adjusting the far-field temperature and the ground formation thermal properties. The model was comparable with measured data.

Shonder and Beck (1999) developed a simple one-dimensional thermal model that describes the temperature field around the borehole. The U-tube pipe is modeled as one, and a thin film may be added to account for the heat capacity of the pipes and fluid. The model assumes one-dimensional transient heat conduction through the film, grout, and soil. These equations are coupled with a time-varying heat flux originating from the film. The far-field radial boundary is assumed to be a constant undisturbed temperature. With this method, ground conductivity can be relatively estimated even though the conditions at the borehole are uncertain (Shonder & Beck, 1999).

Yavuzturk and Spitler (1999) furthered Eskilson's long time-step g-function to account for the thermal properties of the fluid, pipe, and grout. The short time-step model uses a transient, two-dimensional numerical finite volume technique for a vertical GLHE. The numerical model is used to develop a g-function for time intervals as small as three minutes. The parameter estimation method utilizes the downhill simplex minimization algorithm of Nelder and Mead (1965) in conjunction with the numerical model of the borehole to estimate the ground thermal conductivity.

Zeng (2003) developed a quasi-three-dimensional model that accounts for the fluid temperature variation along the borehole depth and its axial convection to determine the thermal resistance inside the borehole analytically. Thermal interference

between a single U-tube pipe and a double U-tube pipe are solved on an analytical basis. These analytical expressions are derived based on the following assumptions: 1) The heat capacity of the materials inside the borehole is neglected; 2) The heat conduction in the axial directions is negligible, and only the conductive heat flow between the borehole wall and the pipes in the transverse cross-section is counted; 3) The borehole wall temperature is constant along its depth; 4) The ground outside the borehole and grout are homogeneous, and all the thermal properties involved are independent of temperature. Zeng limited his research to the thermal resistance inside the borehole so that his model may eventually serve as one of the foundation for future GLHE systems.

# **Chapter 2**

## **G-function Technique**

Eskilson's (1987) long time-step g-factor model laid the foundation for many GLHE sizing programs used today, as described in Chapter 1. Over the past few decades, many modifications have been added to the model to increase accuracy; but for long time periods, Eksilson's unaltered model has been the most widely accepted. Although the model provides a quick and fairly accurate answer, the modern computer processor today can give an even more accurate solution with temperature fields and numerous outputs in seconds. Chapter 2 further explains Eksilson's model and compares some results to GEO2D.

### **2.1 Background**

Eskilson's approach was to obtain formulas for the relation between the heat extraction rate and the required borehole temperature. These formulas are used to acquire dimensioning rules for vertical boreholes. Eskilson uses a two-dimensional numerical calculation that is governed by the heat conduction equation using a finite-difference equation on a radial-axial coordinate system. The solution obtained uses a constant step pulse so that any heat pulse can be considered by summing them (based on the principle of superposition) in time as a series of step pulses. The model assumes homogeneous ground properties with a constant initial temperature. Also, an evenly distributed heat pulse is assumed and capacitance in the pipe and grout are neglected.

The temperature response at the borehole wall is converted to a series of non-dimensional temperatures called g-functions. A simple calculation for a single borehole g-function is defined as

$$g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) = \frac{2\pi k_{soil}}{Q} (T_{borehole} - T_{ground}) \quad (2.1)$$

where g is the g-function value (dimensionless),  $k_{soil}$  is the soil thermal conductivity in  $\left(\frac{W}{m \cdot K}\right)$  or  $\left(\frac{Btu}{h \cdot ft}\right)$ , Q is the flux per unit length in  $\left(\frac{W}{m}\right)$  or  $\left(\frac{Btu}{ft \cdot ^\circ F}\right)$ ,  $T_{borehole}$  is the average temperature at the borehole wall in ( $^\circ C$ ) or ( $^\circ F$ ), and  $T_{ground}$  is the far field temperature of the ground in ( $^\circ C$ ) or ( $^\circ F$ ).  $T_{borehole}$  is calculated at varying times with a numerical or analytical method and requires a significant amount of calculation time. G-functions are dependent on two parameters,  $\frac{t}{t_s}$  and  $\frac{r_b}{H}$ . The g-functions are plotted against the natural log of time over a ‘time-scale’ quantity. The ‘time-scale’ factor is defined as  $t_s$  and can be determined from

$$t_s = \frac{H^2}{9\alpha_{soil}} \quad (2.2)$$

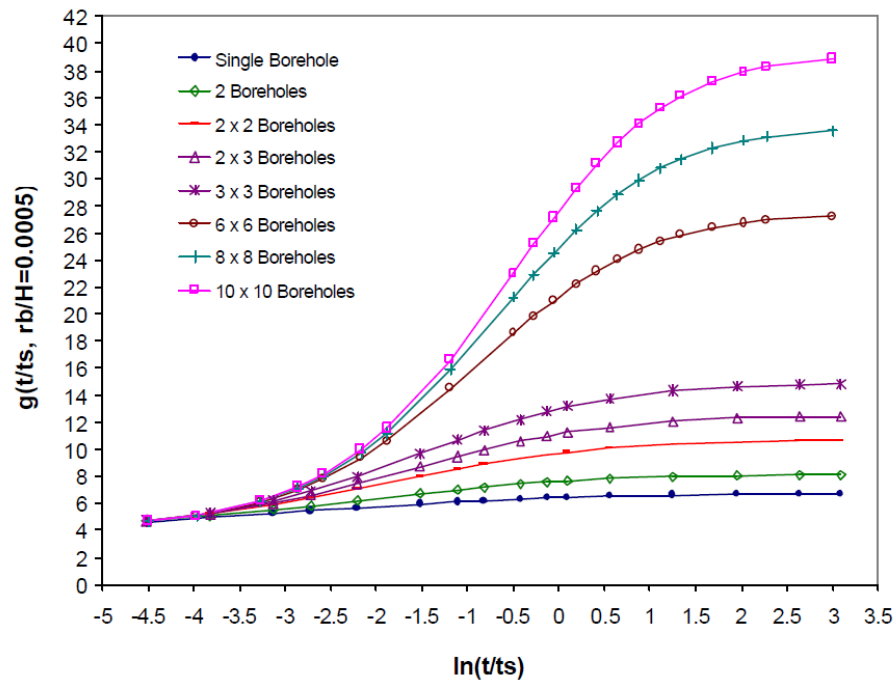
where  $t_s$  is the time scale factor in (s), H is the depth of the borehole in (m) or (ft), and  $\alpha_{soil}$  is the soil thermal diffusivity in  $\left(\frac{m^2}{s}\right)$  or  $\left(\frac{ft^2}{s}\right)$ . The ‘time-scale’ factor is dependent on the depth of the borehole and the soil thermal diffusivity as seen in equation (2.2). Also, the second parameter corrects the g-function according to the borehole radius and borehole depth. The  $\frac{r_b}{H}$  correction factor is relatively minor, since it changes the g-function values by less than one percent (Young, 2004).

G-functions are developed for a variety of borehole geometries for quick calculation time, but this also restricts the GLHE sizing program to specific models. Eskilson’s g-function is only accurate for time periods greater than  $\frac{5r_{borehole}^2}{\alpha}$ , which is equivalent to 3 to 6 hours for a typical borehole. To extend Eskilson’s long time-step model, as well as account for thermal resistance between the pipe wall, grout, and fluid;

Yavuzturk and Spitler (1999) enhanced the long time-step into a short time-step g-function.

## 2.2 Mathematical Model

G-functions are specific to borehole geometries; for this reason, a pre-calculated g-function must be solved before the borehole temperature can be solved. Figure 2.1 shows pre-calculated g-functions for 8 different boreholes geometries with a  $\frac{r_b}{H} = 0.0005$ .

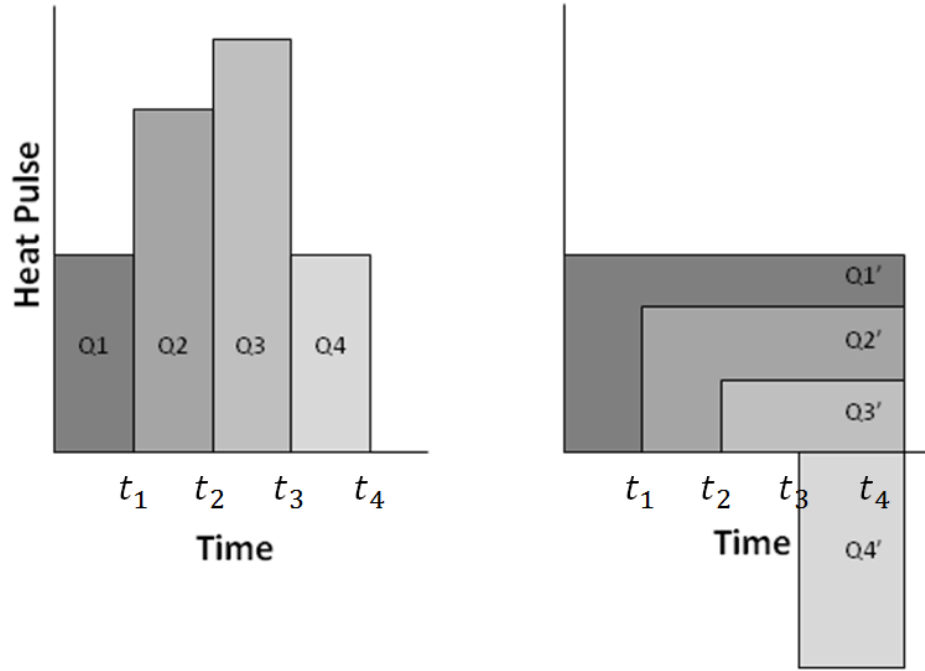


**Figure 2.1:** G-factors for various multiple borehole configurations (Yavuzturk, 1999)

After selection of the borehole configuration, the corresponding g-factor in combination with the principle of superposition can be used to determine the borehole temperature by

$$T_{borehole} = T_{ground} + \sum_{i=1}^n \frac{(Q_i - Q_{i-1})}{2\pi k} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) \quad (2.3)$$

where  $T_{borehole}$  is the average borehole temperature in ( $^{\circ}\text{C}$ ) or ( $^{\circ}\text{F}$ ),  $T_{ground}$  is the undisturbed ground temperature in ( $^{\circ}\text{C}$ ) or ( $^{\circ}\text{F}$ ),  $Q$  is the heat rejection pulse in ( $\frac{W}{m}$ ) or ( $\frac{Btu}{ft \cdot ^{\circ}F}$ ),  $k$  is the ground thermal conductivity in ( $\frac{W}{m \cdot K}$ ) or ( $\frac{Btu}{h \cdot ft}$ ), and  $g$  is the  $g$ -function value which is dimensionless. Devolving the heat rejection/extraction into a series of step functions that are superimposed can be used to solve the response to any heat rejection/extraction regiment.



**Figure 2.2:** Demonstration of superposition for four heat pulses over n number of time periods

The process of superposition of the heat pulses is graphically demonstrated in Figure 2.2 for four periods of heat rejection. The initial heat pulse  $Q_1$ , influences all of the following periods; thus,  $Q_1' = Q_1$  is applied for the entire duration. The second pulse is superimposed as  $Q_2' = Q_2 - Q_1$ , which is considered for  $t_2$ ,  $t_3$ , and  $t_4$ . The third and fourth heat pulse,  $Q_3' = Q_3 - Q_2$  and  $Q_4' = Q_4 - Q_3$ , are effective for  $t_3$  and  $t_4$ , and  $t_4$ ,

respectively. Thus, the borehole wall temperature at any time can be determined by adding the responses of the step function heat pulses up to the time being considered. Mathematically, superposition, as shown in Equation (2.3), gives the borehole temperature at the end of the 4<sup>th</sup> time,

Eskilson's model is only valid for time periods greater than  $\frac{5r_{borehole}^2}{\alpha}$  due to neglecting thermal effects in the fluid, pipe, and grout. Yavuzturk & Spitler (1999) developed a short time step g-function that accounts for time period less than one hour. The numerical model used to calculate the short time-step average borehole temperature is a transient two-dimensional implicit finite volume discretization on a polar grid. A thermal resistive technique within the fluid, pipe, and grout can be expressed as

$$R_{total} = R_{Convection} + R_{PipeConduction} + R_{Grout} \quad (2.4)$$

$$R_{Convection} = \frac{1}{2\pi D_{in} h_{in}} \quad (2.5)$$

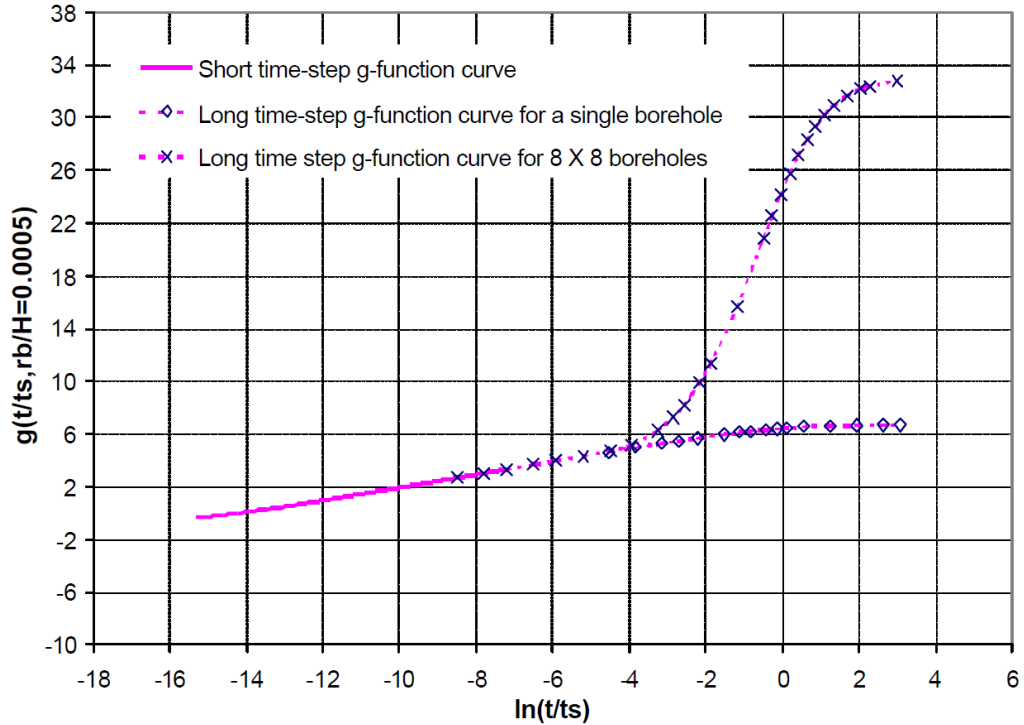
$$R_{PipeConduction} = \frac{\ln\left(\frac{D_{out}}{D_{in}}\right)}{4\pi k_{pipe}} \quad (2.6)$$

$$R_{Grout} = \frac{1}{k_{grout} \beta_0 \left(\frac{D_{Borehole}}{D_{Pipe}}\right)^{\beta_1}} \quad (2.7)$$

where  $\beta_0$  and  $\beta_1$  are resistance shape factor coefficients (Paul, 1996), R is the thermal resistance in  $\left(\frac{K \cdot m}{W}\right)$  or  $\left(\frac{^{\circ}F \cdot hr \cdot ft}{Btu}\right)$ , D is the diameter in (m) or (ft), k is the thermal conductivity in  $\left(\frac{W}{m \cdot K}\right)$  or  $\left(\frac{Btu}{h \cdot ft}\right)$ , and  $h_{in}$  is the convection coefficient determined from the Dittus-Boelter correlation in  $\left(\frac{m^2 \cdot K}{W}\right)$  or  $\left(\frac{hr \cdot ft^2 \cdot ^{\circ}F}{Btu}\right)$ . The total borehole resistance is multiplied by the heat pulse for each time step. The short time-step g-function is defined as

$$g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) = \frac{2\pi k_{soil}}{Q} (T_{borehole} - (R_{Total} \cdot Q) - T_{ground}) \quad (2.8)$$

where  $g$  is the  $g$ -function value which is dimensionless,  $k_{soil}$  is the soil thermal conductivity in  $\left(\frac{W}{m \cdot K}\right)$  or  $\left(\frac{Btu}{h \cdot ft}\right)$ ,  $Q$  is the flux per unit length in  $\left(\frac{W}{m}\right)$  or  $\left(\frac{Btu}{ft \cdot ^\circ F}\right)$ ,  $T_{borehole}$  is the average temperature at the borehole wall in  $(^\circ C)$  or  $(^\circ F)$ ,  $R_{Total}$  is the total borehole thermal resistance in  $\left(\frac{K \cdot m}{W}\right)$  or  $\left(\frac{^\circ F \cdot hr \cdot ft}{Btu}\right)$ , and  $T_{ground}$  is the far field temperature of the ground in  $(^\circ C)$  or  $(^\circ F)$ . Eskilson's long time-step  $g$ -function can be extended to Yavuzturk's short time-step  $g$ -function as shown in Figure 2.3.



**Figure 2.3:** The short time-step  $g$ -function as an extension of the long time- step  $g$ -function for a single borehole and an 8 x 8 borehole configuration (Yavuzturk, 1999).

The short time-step g-functions are valid for time steps between 2 ½ minutes and 200 hours. Likewise, the long time-step g-functions are valid for time step greater than 3 to 6 hours. When overlapping occurs between the short and long time-step g-functions, linear interpolation between the nearest points is used to produce a single g-function.

## 2.3 Results

To compare results between Eskilson's long time-step g-function and GEO2D, a program using the g-function technique to solve the average borehole temperature was developed (see Appendix G). The g-function program that was developed tested and compared to GEO2D using 3 different scenarios. The first involves a direct comparison to Eskilson's results to verify that the long time-step g-function program is correct. The next case uses a constant heat pulse on the long time-step g-function and GEO2D to compare their average fluid temperatures. Finally, the two programs compare their average fluid temperatures to an actual case study with varying heat extractions/rejections.

### 2.3.1 Long Time-Step G-Function Verification

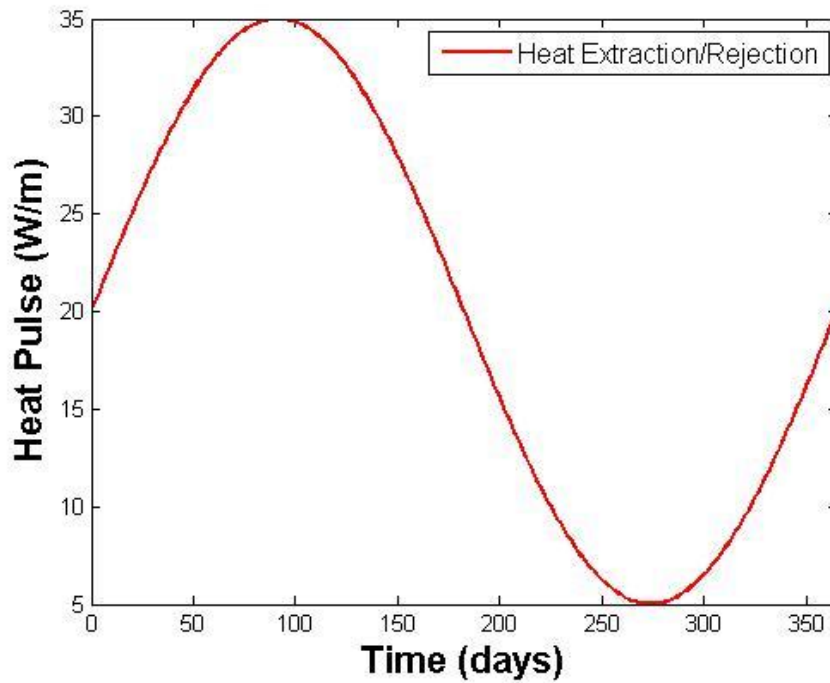
The g-function program uses the simple g-function calculation for a single borehole (Eskilson, 1987) expressed as

$$g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) = \begin{pmatrix} \ln\left(\frac{H}{2r_b}\right) + \frac{1}{2}\ln\left(\frac{t}{t_s}\right) & \text{for } \frac{5r_b^2}{\alpha} < t < t_s \\ \ln\left(\frac{H}{2r_b}\right) & \text{for } t > t_s \end{pmatrix} \quad (2.9)$$

Eskilson discusses a case study that extracts heat in a sinusoidal manner. The heat extraction function can be expressed as

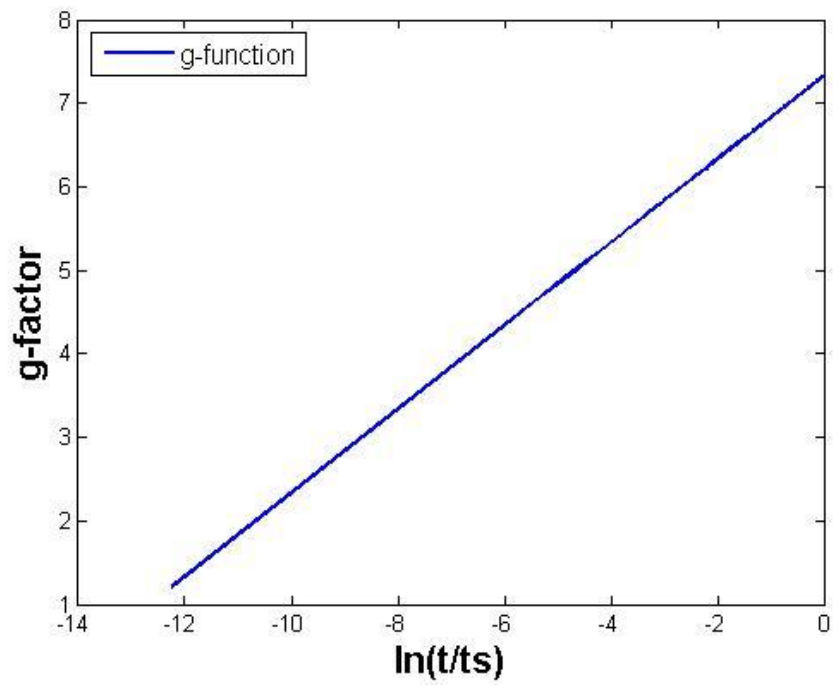
$$q(t) = q_0 + q_p \cdot \sin\left(\frac{2\pi t}{t_p}\right) + q_1 \cdot [H \cdot \exp(t - t_a) - H \cdot \exp(t - t_b)] \quad (2.10)$$

where  $q_0$  is  $20 \left(\frac{W}{m}\right)$ ,  $q_p$  is  $15 \left(\frac{W}{m}\right)$ ,  $t$  is the time in (days),  $t_p$  is 1 year,  $q_1$  is 10 in  $\left(\frac{W}{m}\right)$ ,  $H$  is 110 in (m),  $t_a = \left(n \cdot \frac{5}{24}\right) t_p$ ,  $t_b = \left(n \cdot \frac{7}{24}\right) t_p$ , and  $n$  is the day number. The heat extraction/rejection can be seen in Figure 2.4 and is comparable to Eskilson's case study.

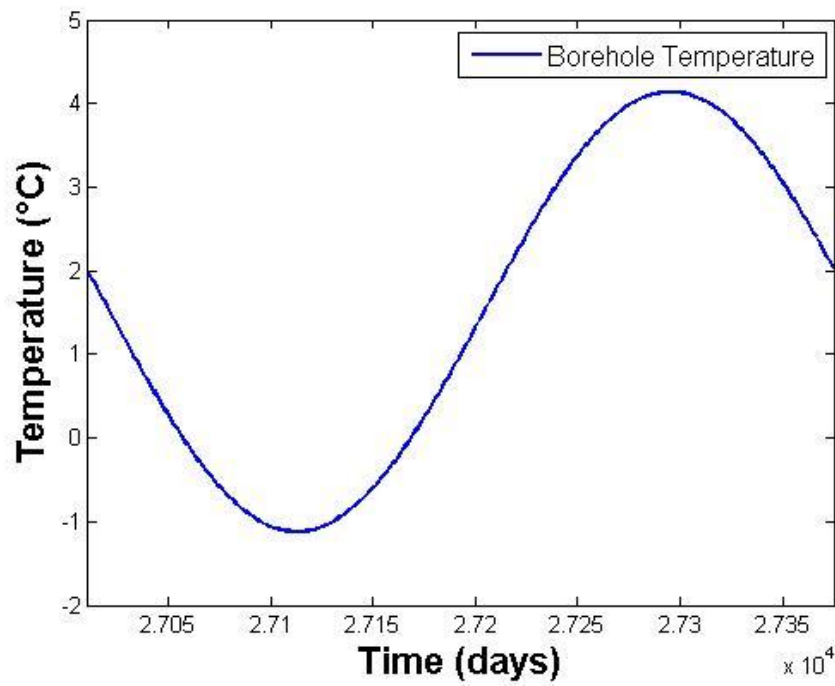


**Figure 2.4:** The heat extraction/rejection function applied to the long time step  $g$ -function.

The  $g$ -function obtained when using the suggested inputs produces a  $g$ -function that is equivalent to Eskilson's asymptotic approximation as shown in Figure 2.5. Finally, a comparison between Eskilson's average borehole temperature and the programmed long time-step  $g$ -function was completed with minimum error. The model was computed for a time period of 75 years as shown in Figure 2.6.



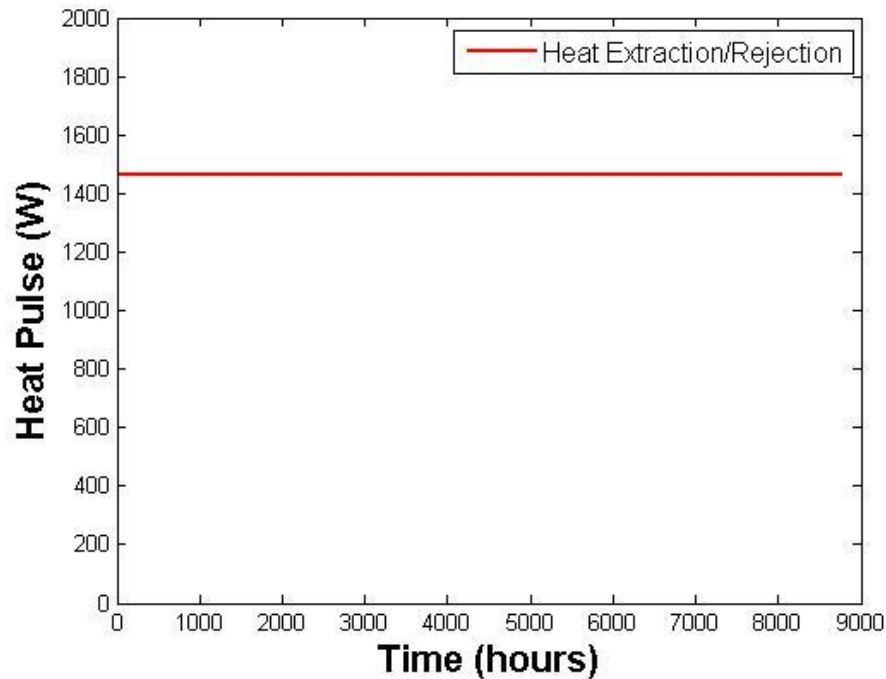
**Figure 2.5:** *G-function as suggested by Eskilson's asymptotic approximation.*



**Figure 2.6:** *The average borehole temperature at 75 years.*

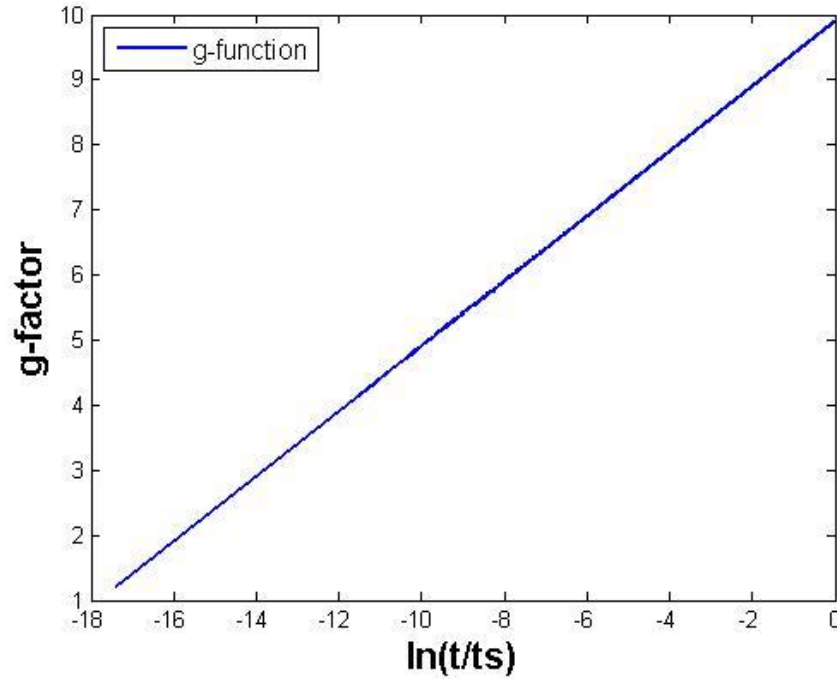
### 2.3.2 Constant Heat Rate Comparison

A model using constant heat rejection/extraction was used to compare the average fluid temperatures between GEO2D and the long time-step g-function. To compare the results between the two programs, certain parameters in GEO2D must be altered to equate the models. First, a thermal conductivity of  $1.5 \left( \frac{W}{m \cdot K} \right)$  and a thermal diffusivity of  $0.3 \left( \frac{m^2}{hr} \right)$  was used for the soil in the long time-step g-function and used for the soil and pipe in GEO2D. The borehole radius and inner pipe radius was 15 (mm) for the long time-step g-function and GEO2D, respectively. Also, GEO2D used a pipe length of 600 (m) and the long time-step g-function used a borehole depth of 600 (m). Finally, the entering and exiting bulk fluid temperatures were averaged in GEO2D to compare with the average fluid temperature produced by the long time-step g-function.



**Figure 2.7:** Heat extraction/rejection used to compare GEO2D and the long time-step g-function.

The heat extraction/rejection used for each model was 1464 (W) over a time period of 1 year, as seen in Figure 2.7. The g-function obtained using Equation (2.9) can be seen in Figure 2.78.

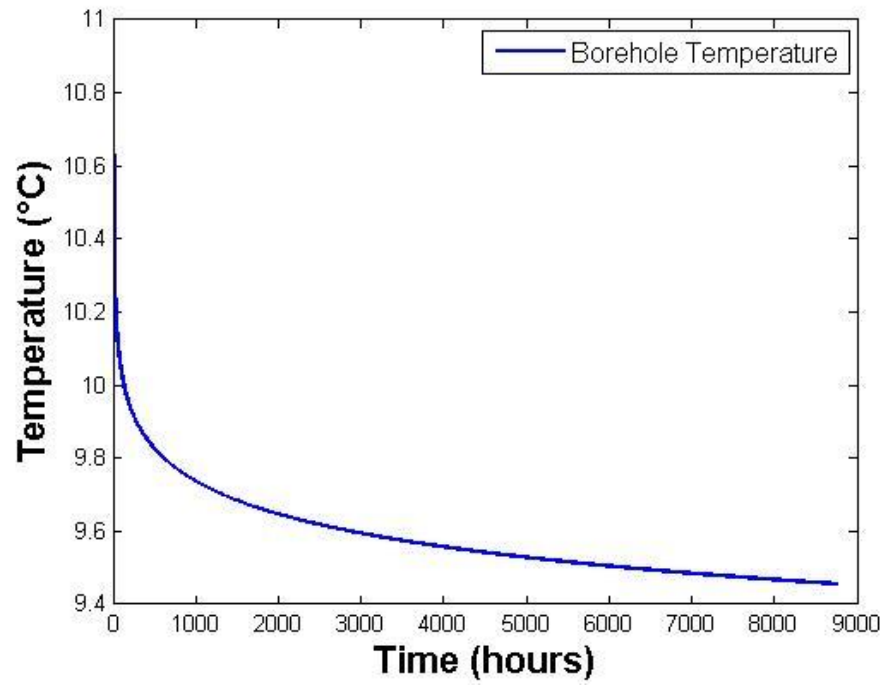


**Figure 2.8:** The g-function obtained from the long time-step g-function

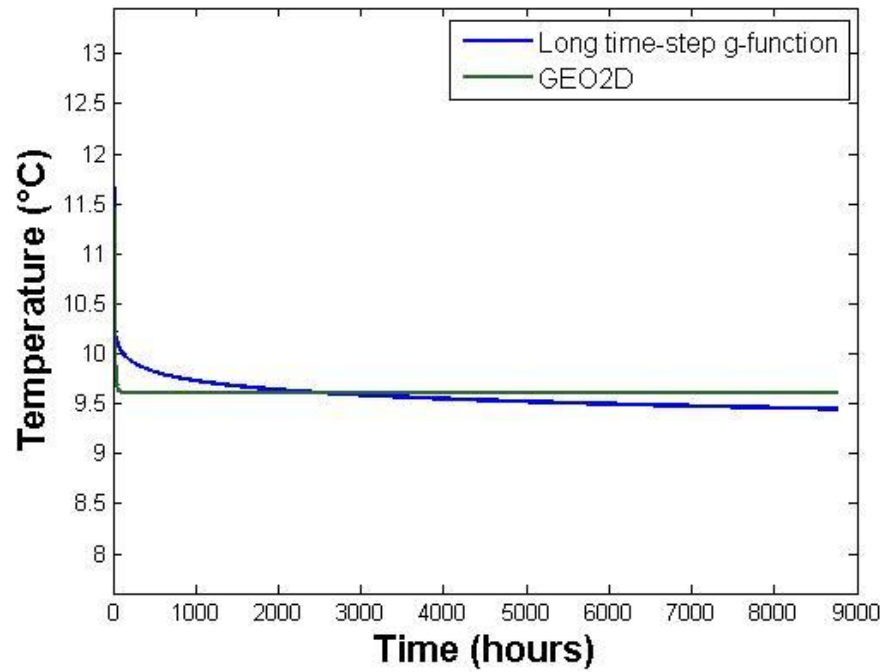
Figure 2.9 shows that the average borehole temperature decreases quickly and begins to reach a steady state temperature of 9.434 (°C) due to constant heat extraction. The average fluid temperature can be calculated by

$$T_{fluid} = T_{borehole} + R_{convection} \cdot Q \quad (2.11)$$

where  $T_{fluid}$  is the average fluid temperature in (°C) or (°F),  $T_{borehole}$  is the average borehole temperature in (°C) or (°F),  $R_{convection}$  is the convective thermal resistance in the fluid in  $\left(\frac{^{\circ}\text{C}}{\text{W}}\right)$  or  $\left(\frac{^{\circ}\text{F}}{\text{Btu}}\right)$ , and  $Q$  is the heat extraction/rejection step in  $\left(\frac{\text{W}}{\text{m}}\right)$  or (Btu).



**Figure 2.9:** The average borehole temperature using the long time-step g-function

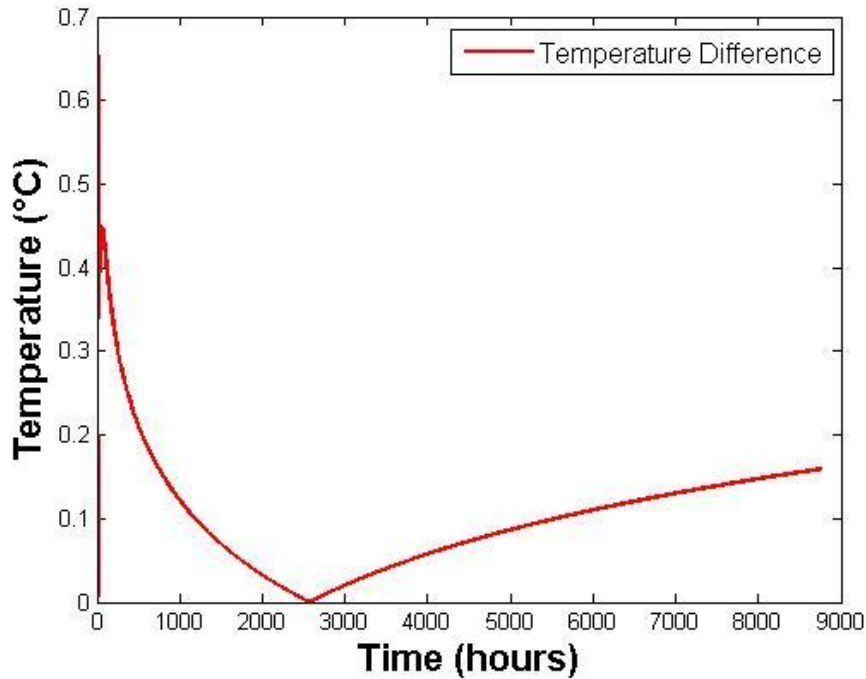


**Figure 2.10:** Comparison of the average fluid temperature between GEO2D and the long time-step g-function.

The thermal resistance in the fluid can be calculated using Equation (2.5). The convection coefficient is determined with the Dittus-Boelter correlation

$$h_{in} = \frac{0.023Re^{0.8}Pr^{0.35}k_{fluid}}{2r_{in}} \quad (2.12)$$

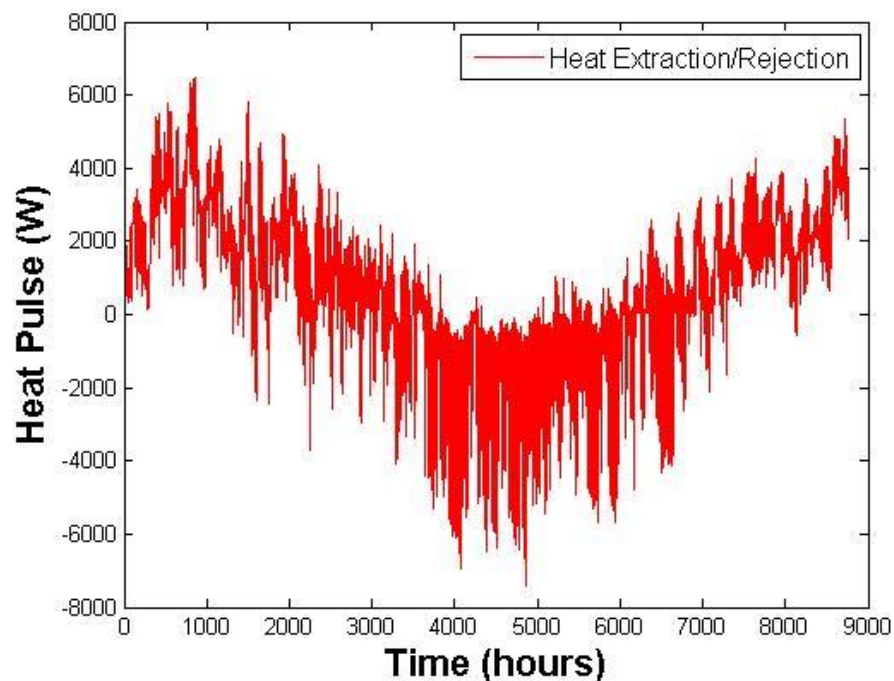
Figure 2.10 compares the fluid temperature between the two programs. GEO2D quickly reaches a steady state fluid temperature of 10.05 (°C) while the g-function slowly reaches a steady state fluid temperature of about 9.3 (°C). The temperature difference between the programs stays below 0.7 (°C), as shown in Figure 2.11. The considerable difference between the programs could be due to g-function program neglecting the capacitance in the fluid and pipe.



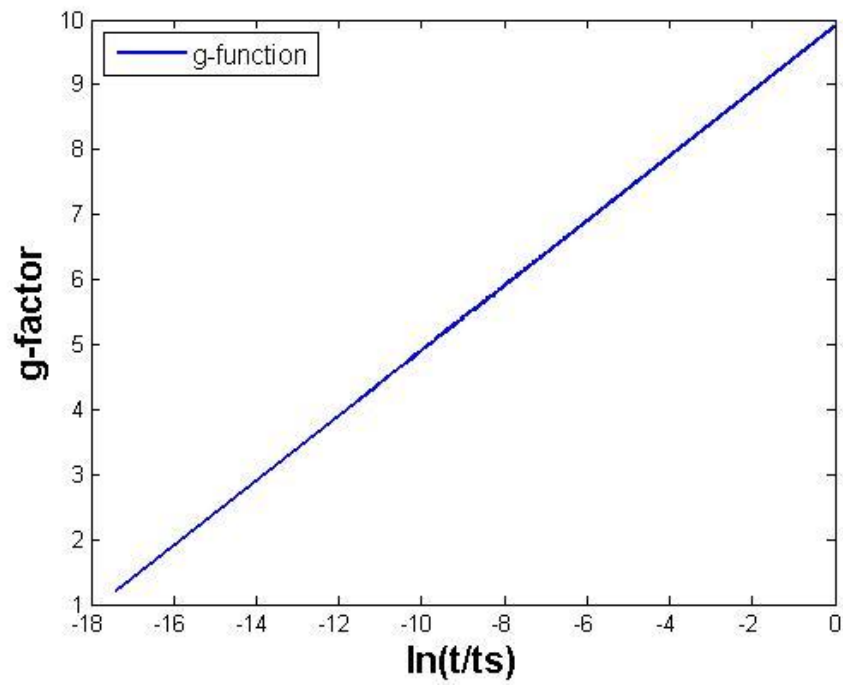
**Figure 2.11:** The fluid temperature difference between GEO2D and the long time-step g-function.

### 2.3.3 Varying Heat Pulse Comparison

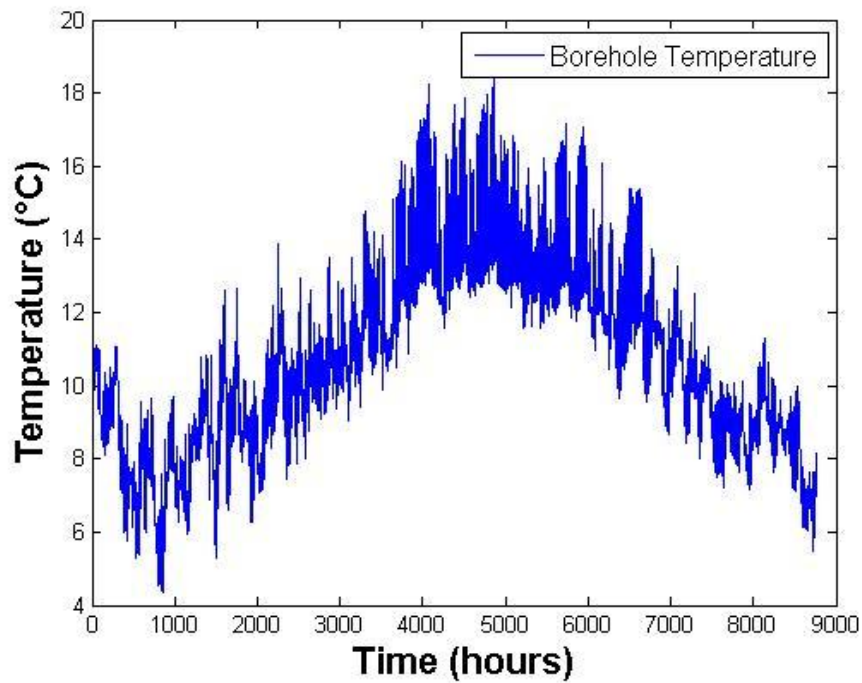
Comparing the average fluid temperature for an actual residential home was completed using heat extraction/rejection inputs that are determined from GEO2D. The EnergyPlus program that is coupled with GEO2D outputs hourly heating and cooling loads from a house. These loads are used in GEO2D's heat transfer analysis in combination with a heat pump model to produce hourly heat rates from the fluid. These heat rates are then used in the long time-step g-function to compare the two programs. The heat extraction/rejection used in the comparison can be seen in Figure 2.12. The g-function obtained is identical to the g-function found in section 2.3.2 since the GLHE models are the same as shown in Figure 2.13.



**Figure 2.12:** GEO2D's heat extraction/rejection for a residential sized GLHE in Dayton, OH

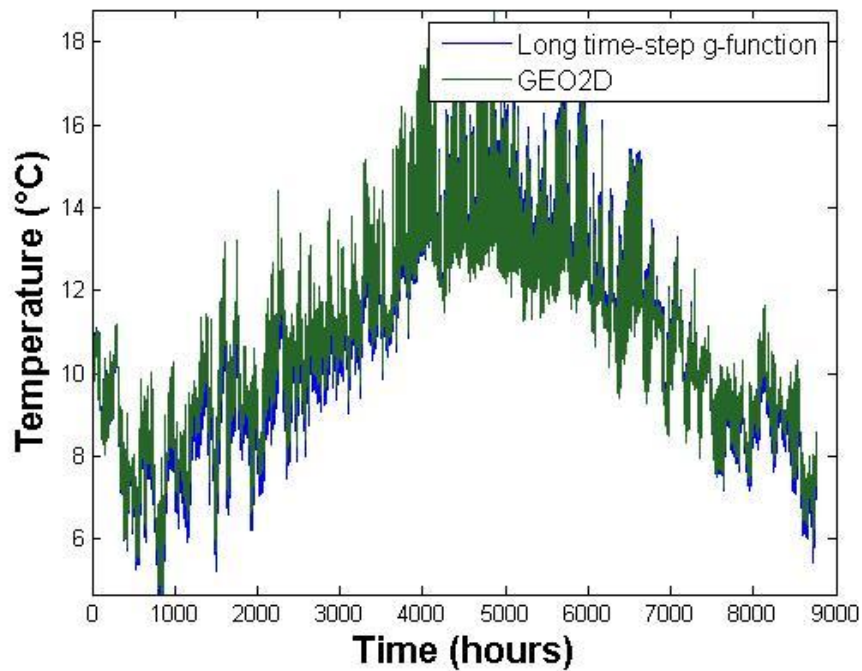


**Figure 2.13:** The  $g$ -function obtained for  $a \frac{r_b}{H} = 0.00005$ .

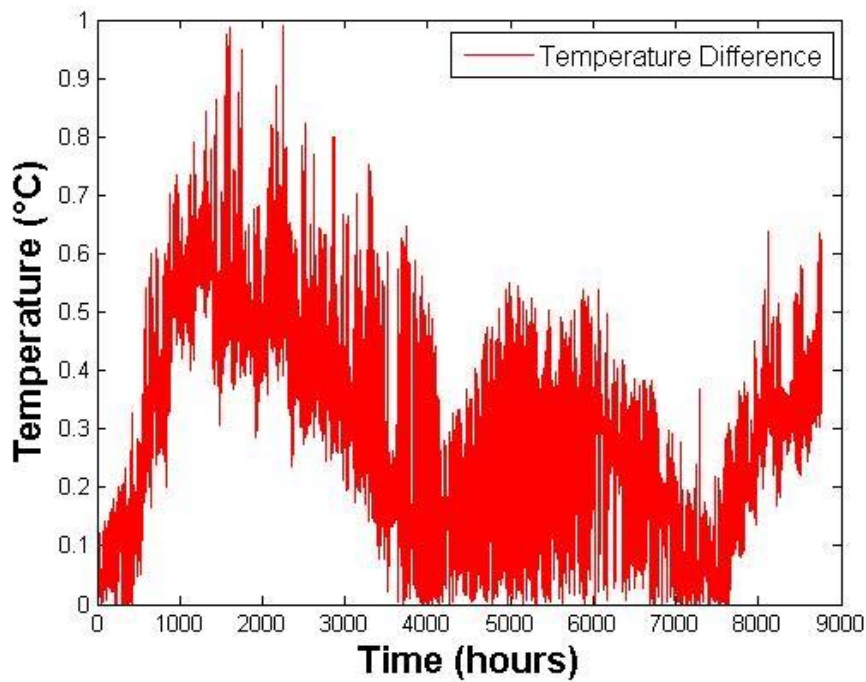


**Figure 2.14:** Temperature of the borehole from the long time-step  $g$ -function

The borehole temperature calculated from the g-function program is shown in Figure 2.14. Like section 2.3.2, the average fluid temperature can be calculated using Equation (2.11). The average fluid temperature between the two programs can be seen in Figure 2.15. The programs follow the same trend, and accounts for the peak heating and cooling loads similarly. However, some differences can be observed between the programs. These differences can be from the g-function program neglecting the thermal capacitance in the fluid and pipe. Nevertheless, a difference of 1 (°C) can lead to significant over sizing or under sizing, since the temperature range that a typical GLHE system operates on is between 0 and 20 (°C).



**Figure 2.15:** The average fluid temperature from GEO2D and the g-function program.



**Figure 2.16:** *The fluid temperature difference between GEO2D and the long time-step g-function.*

## 2.4 Conclusion

To compare results between GEO2D and Eskilson's long time-step g-function, a working program using the g-function technique was required. The long time-step g-function developed used Eskilson's approximate g-function for a single borehole and was verified by comparing results to Eskilson's test case. Next, GEO2D and the long time-step g-function were compared with a constant heat pulse over a time period of 8760 hours. The results gave a maximum difference of 0.7 (°C). Finally, an actual residential home with varying heating and cooling loads was modeled to compare the programs. The difference between the two programs created a fluid temperature difference no greater than 1 (°C). This error although small, can sometimes cause an over or under sized GLHE system. The difference could be due to the assumptions within the g-function method or the more accurate calculation in GEO2D. Note that the

analysis technique used in GEO2D is good for short time frames, as well as long time frames.

Eskilson's long time-step g-function model calculates a fairly accurate solution to borehole temperature in a short period of time. However, a small difference still exists between the g-function and the actual solution. This can lead to over sizing or under sizing a GLHE, causing an increased payback period or additional cost for adding pipe to the GLHE. GEO2D provides a two-dimensional heat transfer analysis that accounts for axial heat flow and fluid flow within the pipe; GEO2D also outputs temperature fields throughout the fluid, pipe, and soil. With computer processors available today, a detailed, physical precise heat transfer analysis as performed in GEO2D can be solved in seconds; nearly eliminating the difference between the computational times difference between GEO2D and other commercial programs.

# **Chapter 3**

## **Available Commercial Codes**

Commercial programs available today offer a variety of methods to analyze a GLHE. Most of the programs use the g-function method, which limits the borehole geometry and can generate a significant error, as discussed in Chapter 2. On the other hand, some programs use a numerical heat transfer calculation, like GEO2D; however, some of these programs lack the outputs necessary to optimize the system. Chapter 3 discusses the heat transfer techniques used, advantages and disadvantages, and outputs from the following programs: RETScreen, TRNSYS, GLHEPRO, GLD2000, Earth Energy Designer and GS2000. Additionally, results from some of the programs will be compared to GEO2D.

### **3.1 RETScreen**

RETScreen is a program developed by CanmetENERGY and a number of other governmental and nongovernmental organizations. The program is used to evaluate the energy production, savings, costs, emission reductions, financial viability and risk for various types of renewable energy systems. The RETScreen Ground-Source Heat Pump (GSHP) Project Model can be used to evaluate horizontal loops, vertical closed-loops, and vertical open-loops, from large-scale commercial applications to small residential systems. The GSHP systems in RETScreen provide six worksheets in Microsoft Excel to solve and analyze the system through an energy model, heating and cooling load calculation, cost analysis, greenhouse gas emission reduction analysis, financial summary, and sensitivity and risk analysis.

The methodology used in the RETScreen's GSHP Project Model present many limitations. In some instances, the model cannot capture complex building usage profiles. Additionally, the long-term thermal imbalances are not included in the GLHE calculations. The horizontal GLHE is restricted to a stacked pipe system with a 31.8 (mm) pipe buried at 1.8 (m) and 1.2 (m) below the surface. Likewise, the vertical GLHE configuration is limited to one 31.8 (mm) U-tube per borehole. Finally, the building's heating and cooling energy consumption and peak loads are evaluated using a simplified version of ASHRAE's modified bin method (ASHRAE, Handbook Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1985) with an interior set point temperature at a constant 23 (°C).

A detailed analysis for a GLHE usually requires a dynamic time and temperature model that uses short time-steps. The GSHP model in RETScreen uses a simplified approach, which only uses outside temperature as the critical variable. This approach, called the bin method, distributes the hourly temperature occurrences into the associated temperature bins. The bin method uses temperature and weather data to calculate the building load for each temperature bin. The temperature data is also used to calculate the minimum and maximum ground temperature using (IGSHPA, 1988)

$$T_{ground,min} = T_{ground} - A_S \exp\left(-X_s \sqrt{\frac{\pi}{365\alpha}}\right) \quad (3.1)$$

and

$$T_{ground,max} = T_{ground} + A_S \exp\left(-X_s \sqrt{\frac{\pi}{365\alpha}}\right) \quad (3.2)$$

where  $T_{ground,min}$  is the minimum ground temperature in (°C) or (°F),  $T_{ground,max}$  is the maximum ground temperature in (°C) or (°F),  $T_{ground}$  is the mean annual surface soil temperature in (°C) or (°F),  $A_S$  is the annual surface temperature amplitude in (°C) or

(°F),  $X_s$  is the soil depth in (m) or (ft), and  $\alpha$  is the soil thermal diffusivity in  $\left(\frac{m^2}{s}\right)$  or  $\left(\frac{ft^2}{s}\right)$ .

There are two options to calculate the load of the building in RETScreen's GSHP Project Model. Either the user can use the descriptive data method or the energy use method. The descriptive data method requires the user to enter the physical characteristics of the building. While the energy use method requires the user to enter the design loads and typical energy use of the building. The descriptive data method accounts for: transmission losses (conductive and convective), solar gains (sensible), fresh air loads (latent and sensible), internal gains (latent and sensible), and occupant loads (latent and sensible). The building loads are calculated for the hourly bin temperatures that occur throughout the year.

The maximum and minimum design entering water temperatures are estimates based off of a literature review by ASHRAE, Kavanaugh and IGSHPA and can be expressed as (ASHRAE, 1995), (Kavanaugh & Rafferty, 1997), and (IGSHPA, 1988)

$$T_{ewt,min} = T_{g,min} - 15^{\circ}\text{F} \quad (3.3)$$

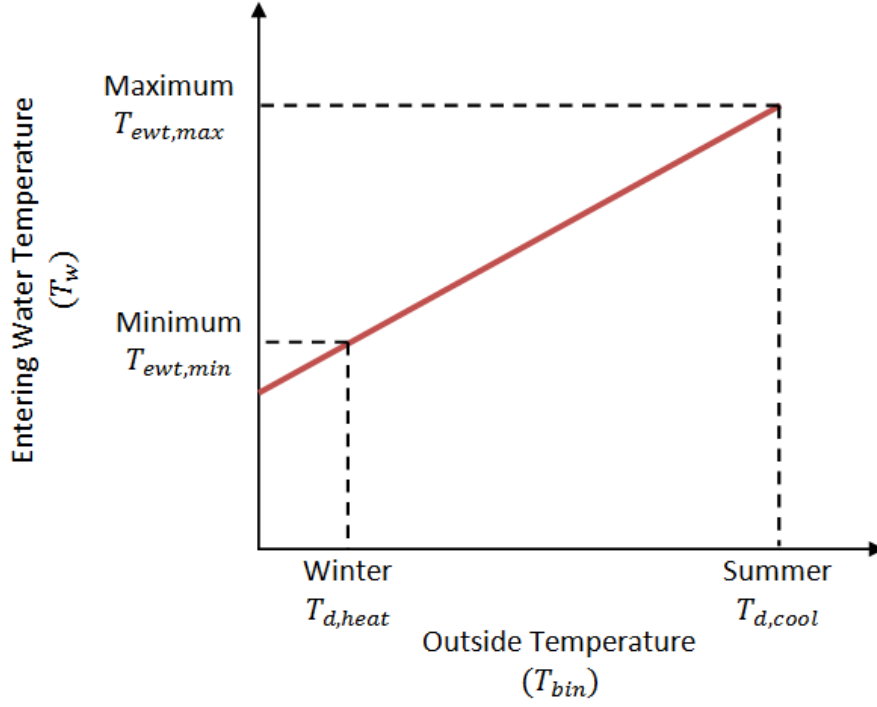
and

$$T_{ewt,max} = \min (T_{g,max} + 20^{\circ}\text{F}, 110^{\circ}\text{F}) \quad (3.4)$$

The heating design temperature,  $T_{d,heat}$ , and the cooling design temperature,  $T_{d,cool}$ , are specified by the user in the heating and cooling load worksheet. From there the temperature of the water entering the heat pump can be calculated by

$$T_w = T_{min} + \left( \frac{T_{ewt,max} - T_{ewt,min}}{T_{d,cool} - T_{d,heat}} \right) (T_{bin,i} - T_{d,heat}) \quad (3.5)$$

This function is shown in Figure 3.1 where  $T_{min}$  represents the point where the curve crosses the y-axis.



**Figure 3.1:** RETScreen's method for determining entering water temperature as a function of outside temperature.

Once a function for entering water temperature is determined, the coefficient of performance is calculated by

$$COP_{actual} = COP_{baseline}(k_0 + k_1 T_{ewt} + k_2 T_{ewt}^2) \quad (3.6)$$

where  $COP_{actual}$  is the actual COP of the heat pump,  $COP_{baseline}$  is the nominal COP of the heat pump,  $T_{ewt}$  is the entering water temperature for the heat pump in ( $^{\circ}\text{C}$ ) or ( $^{\circ}\text{F}$ ), and  $k_i$  are the correlation coefficients. For cooling,  $k_0$  is 1.53105836,  $k_1$  is  $-2.296095 \times 10^{-2}$ , and  $k_2$  is  $6.87440 \times 10^{-5}$ . For heating,  $k_0$  is 1.0000,  $k_1$  is  $1. \times 10^{-2}$ , and  $k_2$  is  $-1.59310 \times 10^{-4}$ .

Finally, sizing of the GLHE is completed using a method developed by IGSHPA (1988). The required length based on heating requirements is calculated by

$$L_h = q_{d,heat} \left[ \frac{\frac{(COP_h - 1)}{COP_h} (R_p + R_s F_h)}{T_{g,min} - T_{ewt,min}} \right] \quad (3.7)$$

where  $L_h$  is the length required in (m) or (ft),  $q_{d,heat}$  is the design heating load in (kW) or (Btu),  $COP_h$  is the design heating coefficient of performance,  $R_p$  is the pipe thermal resistance in  $\left(\frac{^\circ\text{C}}{\text{W}}\right)$  or  $\left(\frac{^\circ\text{F}}{\text{Btu}}\right)$ ,  $R_s$  is the soil field thermal resistance in  $\left(\frac{^\circ\text{C}}{\text{W}}\right)$  or  $\left(\frac{^\circ\text{F}}{\text{Btu}}\right)$ ,  $F_h$  is the ground heat exchanger part load factor for heating,  $T_{g,min}$  is the minimum undisturbed ground temperature in ( $^\circ\text{C}$ ) or ( $^\circ\text{F}$ ), and  $T_{ewt,min}$  is the minimum design entering water temperature in ( $^\circ\text{C}$ ) or ( $^\circ\text{F}$ ). Similarly, the required length based on cooling loads can be calculated by

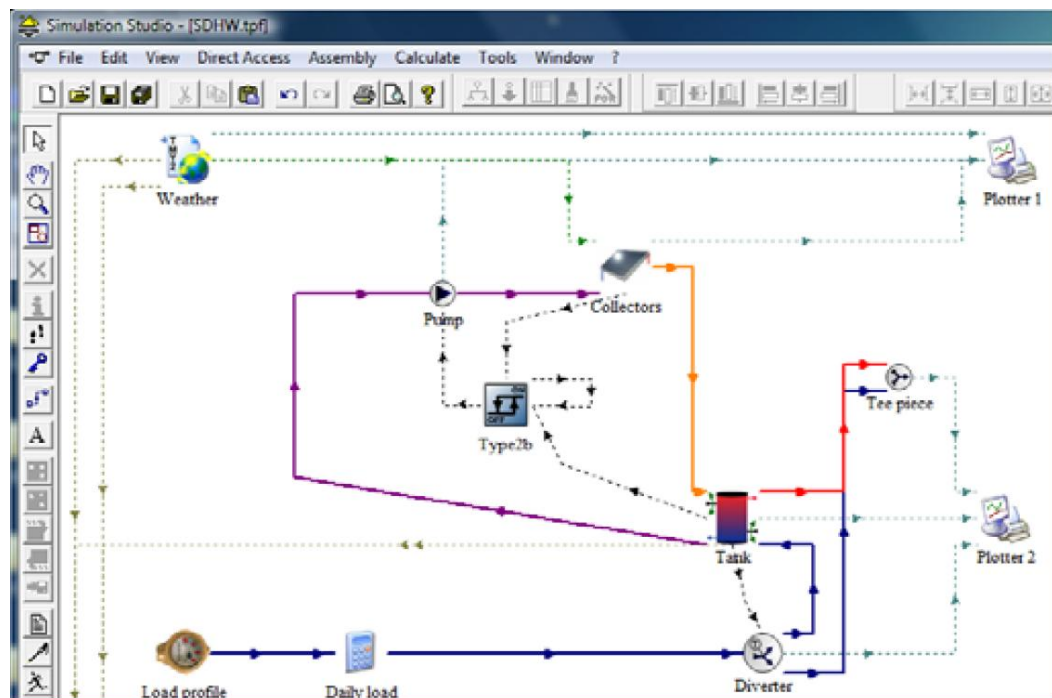
$$L_c = q_{d,cool} \left[ \frac{\frac{(COP_c+1)}{COP_c}(R_p+R_sF_c)}{T_{ewt,max}-T_{g,max}} \right] \quad (3.8)$$

where  $L_c$  is the length required (m) or (ft),  $q_{d,cool}$  is the design cooling load in (kW) or (Btu),  $COP_c$  is the design cooling coefficient of performance,  $R_p$  is the pipe thermal resistance in  $\left(\frac{^\circ\text{C}}{\text{W}}\right)$  or  $\left(\frac{^\circ\text{F}}{\text{Btu}}\right)$ ,  $R_s$  is the soil field thermal resistance in  $\left(\frac{^\circ\text{C}}{\text{W}}\right)$  or  $\left(\frac{^\circ\text{F}}{\text{Btu}}\right)$ ,  $F_h$  is the ground heat exchanger part load factor for cooling,  $T_{ewt,max}$  is the maximum design entering water temperature at the heat pump in ( $^\circ\text{C}$ ) or ( $^\circ\text{F}$ ), and  $T_{g,max}$  is the maximum undisturbed ground temperature in ( $^\circ\text{C}$ ) or ( $^\circ\text{F}$ ). The soil thermal resistance is determined from geometrical and physical considerations shown by IGSHA (1988).

The methodology used by RETScreen provides a quick estimate for sizing a GLHE. When compared to other commercial programs, RETScreen oversized their models by 23%, resulting in a higher initial cost (CANMET, 2005). For purposes of a ballpark solution on a variety of renewable energy systems with an economical analysis, RETScreen is acceptable; however, for a detailed geothermal analysis, RETScreen lacks the accuracy and outputs information.

## 3.2 TRNSYS

TRNSYS is an extremely flexible, graphical based, commercial, simulation program package developed at the University of Wisconsin that simulates the behavior of transient systems, including renewable energy systems. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their components, including strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems, etc.) (TRNSYS, 2009). Using the short time-step g-function technique and a 3-D conduction model, several TRNSYS component models for numerous GLHE were developed. These models include a vertical U-tube borehole, a horizontal single buried pipe, a horizontal twin buried pipe, and a horizontal multi-level pipe. TRNSYS provides a graphical interface, a simulation engine, and a library of components that are standard for HVAC equipment. The simulation package used in TRNSYS is Simulation Studio and can be seen in Figure 3.2.

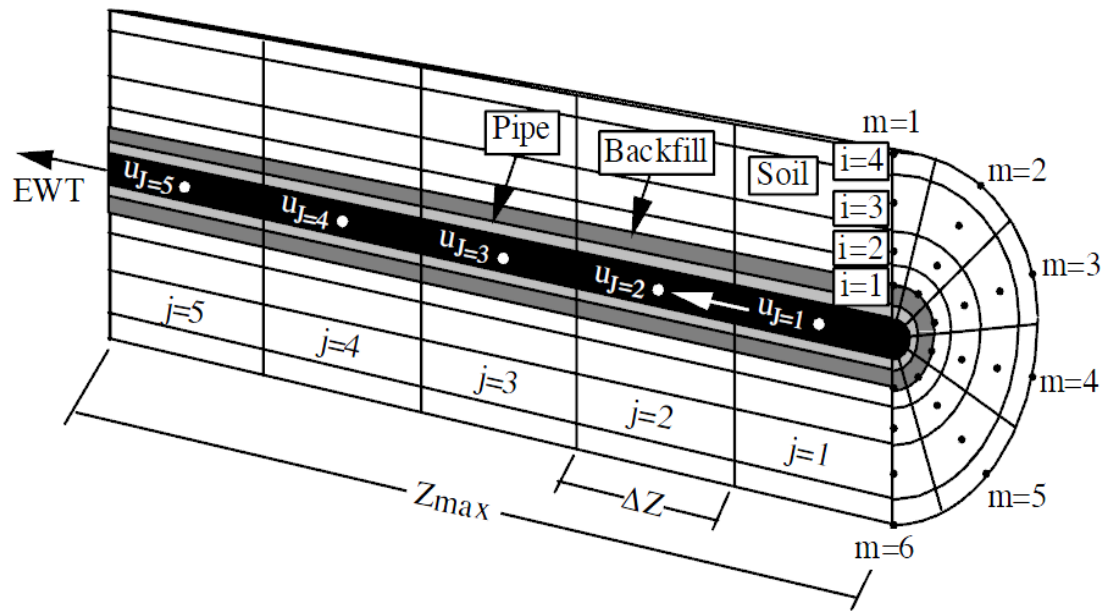


**Figure 3.2:** Example project in TRNSYS Simulation Studio (TRNSYS, 2009)

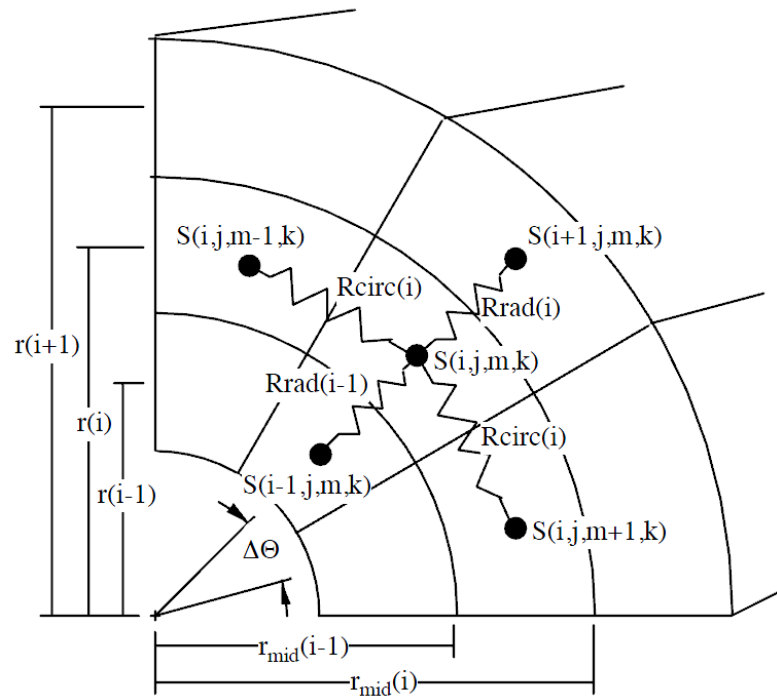
The vertical U-tube GLHE is modeled in TRNSYS is called 'type 557' and is solved using Hellstrom's Duct Storage Model (DST) (Hellström, 1989). Yavuzturk and Spitler (Yavuzturk & Spitler, 1999) also incorporated their short time-step g-function model into TRNSYS. The model assumes that the boreholes are placed uniformly throughout the ground. Also, the model accounts for convective heat transfer within the pipes and conductive heat transfer throughout the ground. As described in Chapter 1, the model is separated into two regions: the ground that immediately surrounds a single borehole (local region) and the ground that surrounds multiple boreholes (global region). The global and local regions are solved using an explicit finite-difference technique, while the steady-flux solution is obtained analytically.

The horizontal single buried pipe (type 952), horizontal twin buried pipe (type 951), and horizontal multi-level pipe (type 997) are all solved using a three-dimensional finite difference method. The model from Oak Ridge National Lab (ORNL) for GLHE is used as the basis for the horizontal models in TRNSYS. ORNL models a buried pipe within the ground, where the heat transfer is solved radially and circumferentially. Temperatures along the outer radius are assumed undisturbed by the heat transfer of the pipe and the soil properties are assumed to be homogeneous. Also, there are no moisture migrations or soil freezing within the model.

The model simulates a pipe located in the center of a large volume of soil with homogeneous thermal properties. The heat transfer is symmetric along the 'z' by 'i' plane, so only half the cylinder is needed. The model accounts for heat transfer in the radial and circumference direction, but not in the axial direction. Figure 3.3 illustrates a sample grid layout, where the section, radius, and rotation from the top are indicated by j, i, and m, respectively. The fluid temperature is saved in a matrix  $U(j, k)$ . Similarly, The ground temperatures are saved in a matrix  $S(i, j, m, k)$ , where k marks the updated node. TRNSYS users may select minute or hourly time-steps.



**Figure 3.3:** The finite difference model for a single buried pipe in TRNSYS (Giardina, 1995)



**Figure 3.4:** TRNSYS's thermal resistance approach for the heat transfer analysis (Giardina, 1995)

For ease, TRNSYS uses a simplistic thermal resistance approach for solving the heat transfer problems. The temperature of the soil node  $S(i, j, m, k)$ , is determined by

$$(\rho V(i) c_p)_{soil} \frac{(S(i, j, m, k + 1) - S(i, j, m, k))}{dt} = \frac{(S(i + 1, j, m, k) - S(i, j, m, k))}{R_{rad}(i)} + \frac{(S(i - 1, j, m, k) - S(i, j, m, k))}{R_{rad}(i - 1)} + \frac{(S(i, j, m + 1, k) - S(i, j, m, k))}{R_{circ}(i)} + \frac{(S(i, j, m - 1, k) - S(i, j, m, k))}{R_{circ}(i)} \quad (3.9)$$

and

$$R_{circ}(i) = \frac{r(i) * \Delta \theta}{k_{soil} * (r_{mid}(j) - r_{mid}(j - 1)) * \Delta Z} \quad (3.10)$$

$$R_{rad}(i) = \frac{\ln \left( \frac{r(i+1)}{r(i)} \right)}{\Delta \theta * k_{soil} * \Delta Z} \quad (3.11)$$

TRNSYS also accounts for the convective heat transfer from the fluid, followed by the conductive heat transfer through the pipe and backfill. The energy transfer in the fluid can be solved by

$$U(j, k + 1) = U(j, k) + \frac{\dot{m} dt}{(\rho V)_{fluid}} (U(j - 1, k) - U(j, k)) - \frac{dt}{(\rho c_p V)_{fluid}} \dot{Q}_{out} \quad (3.12)$$

where  $U$  is the fluid node temperature and the energy transfer from the fluid to the ground,  $\dot{Q}_{out}$ , is determined by

$$\dot{Q}_{out} = \frac{(U(j, k) - avg S_j)}{R_{total}} \quad (3.13)$$

where

$$R_{total} = R_{fluid} + R_{pipe} + R_{backfill} \quad (3.14)$$

And the average temperature of the inner soil ring is calculated by

$$avg S_j = \frac{\sum_{m=1}^{m_{max}} S(i,j,m,k)}{m_{max}} \quad (3.15)$$

and

$$R_{fluid} = \frac{1}{h_{conv} * A} \quad (3.16)$$

$$R_{pipe} = \frac{\ln\left(\frac{r_{pipe,out}}{r_{pipe,in}}\right)}{\pi * k_{pipe} * \Delta Z} \quad (3.17)$$

$$R_{backfill} = \frac{\ln\left(\frac{r_{backfill,out}}{r_{backfill,in}}\right)}{\pi * k_{backfill} * \Delta Z} \quad (3.18)$$

TRNSYS provides an accurate simulation of the GLHE, as well as an advanced and very flexible graphical user interface. However, the user must have detailed information about the system, such as, building design, heat pump coefficients, and values for the thermal properties throughout the GLHE. Most of these inputs are not assumed or suggested in TRNSYS, and therefore makes the program complicated for the common user. Due to its high cost, stiff learning curve, and significant computation time, TRNSYS is not used frequently (Liu & Hellstrom, 2006).

### 3.3 GLHEPRO

GLHEPRO was developed as an aid in the design of vertical GLHE, typically for commercial sized systems, though GLHEPRO may be used for sizing residential systems. GLHEPRO is composed of numerous borehole configurations and performs three tasks. First, it allows the user to perform a simulation period, up to 100 years, and determines the monthly peak and average entering fluid temperature, the power consumed by the heat pump, and the heat extraction rate per unit length. Second, GLHEPRO determines the required depth of the borehole(s), to meet the user specified minimum and

maximum entering fluid temperature into the heat pump. Third, the program sizes hybrid ground source heat pump systems by determining the required depth of the borehole(s) after the user designs a supplemental cooling tower and/or boiler system. The g-function method, developed by Eskilson (Eskilson, 1987) , is implemented in the GLHEPRO program. Eskilson's g-function technique is explained in Chapter 2.

There are 307 pre-computed g-function configurations included in GLHEPRO, as of 2007. Additionally, functions have been developed that approximate larger rectangular borehole fields, with a reasonable degree of accuracy (GLHEPRO 4.0 for Windows, 2007). GLHEPRO is limited to modeling vertical closed-loop heat exchangers. Also, GLHEPRO requires an outside heating and cooling load program to determine monthly loads and monthly peaks.

### **3.4 Ground Loop Design**

Ground Loop Design (GLD) is a prestigious geothermal sizing program developed by Gaia Geothermal. The program provides heating and cooling loads for a building designed by the user and determines lengths for vertical, horizontal and surface water GLHE. Additionally, the coefficient of performance (COP) can be determined from a heat pump model to let the user know how efficiently the system is operating. One major advantage of GLD is the internationalization. Not only does that program provide an option for metric or English units, the program is also capable of communicating in multiple languages.

Ground Loop Design uses two methods to solve the heat transfer problem for a vertical borehole GLHE. The first method is based on the cylindrical source method, while the second is based on Eskilson's g-function technique. The first method uses Ingersoll's (Ingersoll & Plass, 1948) modification to Carslaw and Jaeger's (1947) cylinder buried in the earth model to size GLHE. Additionally, the model uses Kavanaugh and Deerman's (1991) method to account for the U-tube arrangement and hourly time steps. It also accounts for the borehole resistance, such as: pipe placement, grout

conductivity, and borehole size, as suggested by Remund and Paul (1996). The second method uses Eskilson's (1987) g-function as discussed in Chapter 2.

The two vertical GLHE models do not always agree, but both are available for the user to compare the results. Additionally, the program calculates the energy extracted or rejected into the ground based on the load information and heat pump model chosen. The two methods calculate the long-term condition of the borehole. The system is then optimized to allow for acceptable heat extraction/rejection from the earth.

The horizontal GLHE heat transfer analysis used in Ground Loop Design uses a combination of Carslaw and Jaeger's cylindrical buried in the earth and the multiple pipe methodology developed by Parker et al. (1985). The model includes modifications suggested by Kavanaugh and Deerman that accounts for the physical arrangement and an hourly heat variation. The slinky loop option in GLD provides a theoretical approximation to the pipe length. The loop models a 36" diameter slinky coil that assumes it to be a single U-tube buried pipe in a horizontal configuration. The heat transfer analysis performed is identical to the cylindrical source method used in the vertical borehole model. The calculated length is then divided by 250 ft and multiplied by a factor determined from both the run fraction and the slinky pitch (distance between adjoining loops).

The surface water heat exchanger used in GLD is based off experiments performed by Kavanaugh and Rafferty (1997) for different sized pipes in coiled and slinky configurations. A polynomial fit of this experimental data is used to determine the amount of pipe necessary for a given heating and cooling load.

Ground Loop Design offers a fairly accurate solution for a GLHE, while maintaining a certain degree of user friendliness. The heat transfer techniques used to solve the vertical, horizontal and surface water heat exchangers have been used for the past few decades and give a fairly good solution for a short computation time.

However, a more accurate numerical heat transfer analysis can be solved with little additional computational time in exchange for a more accurate GLHE.

### 3.5 Earth Energy Designer

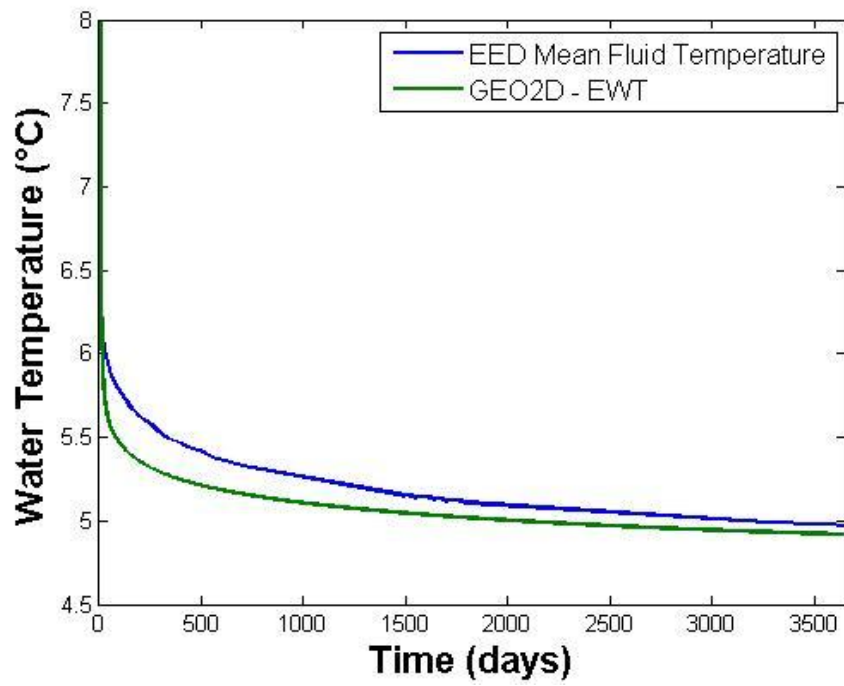
Earth Energy Designer (EED) is a GLHE program that is easy to use and provides a quick solution to GLHE problem providing the average fluid temperature. EED was designed for commercial buildings, but residential houses can be modeled with this program, as well. The methods used to solve the heat transfer problem for a GLHE are g-function techniques developed by Eskilson (1987) and Hellstrom (1989). Only vertical GLHE can be modeled in EED. EED contains g-functions for 798 different borehole configurations, which vary from vertical lines, L-shapes, U-shapes and rectangles. The pipe selections available are coaxial (one tube inside another), single U-tube, double U-tube and triple U-tube per borehole.

As discussed in Chapter 2, heat extraction/rejection over a time period is required when using the g-function technique. EED uses monthly, average heating and cooling loads with an additional heating and cooling pulse to solve the average, monthly fluid temperature. Calculating the borehole thermal resistance using the borehole geometry, grout material properties and pipe material properties solves the fluid temperature. For a simulation of 20 years (EED does a maximum of 25 years), the output from EED include: design data entered, required length of boreholes, average monthly specific heat extraction rate, end of the month mean fluid temperature for years 1, 2, 5, 10 and 20, and minimum and maximum mean fluid temperature with month of occurrence for the final year of simulation.

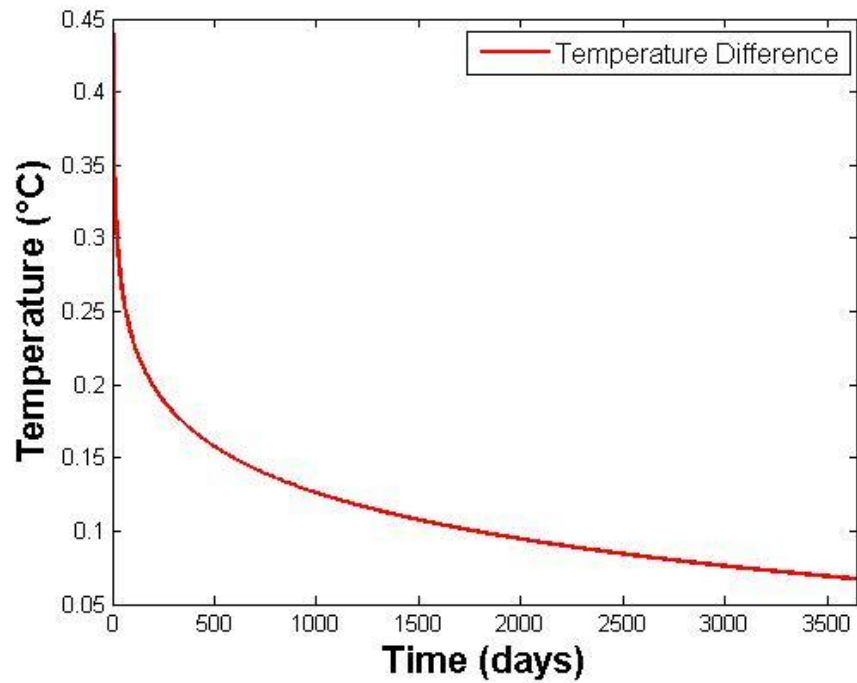
When making comparisons between GEO2D to the demo version of EED, certain modeling constraints has to be made. First, EED's demo version has limited ground properties. The demo version of EED uses a thermal conductivity, volumetric heat capacity, ground surface temperature, and geothermal heat flux set to  $3.5 \left( \frac{W}{m \cdot K} \right)$ , 2.16

$\left(\frac{MJ}{m^3 \cdot K}\right)$ , 8.0 ( $^{\circ}C$ ) and 0.06  $\left(\frac{W}{m^2}\right)$ , respectively. To replicate EED's properties, the properties entered into GEO2D are a soil thermal conductivity of 3.5  $\left(\frac{W}{m \cdot K}\right)$ , the soil heat capacity of 0.8247  $\left(\frac{kJ}{kg \cdot K}\right)$  and the soil density of 2619  $\left(\frac{kg}{m^3}\right)$ . Secondly, to model the same GLHE, the borehole diameter in EED was simulated as 10 (m) and was filled with a grout with a thermal conductivity equal to that of the ground. The U-tube pipe was then modeled with a shank spacing that places the inlet and outlet pipe at the edge of either side of the borehole, with the intention of virtually eliminating the thermal interference between U-tube. The fluid properties used in both programs are a dynamic viscosity of 0.00131  $\left(\frac{N \cdot s}{m^2}\right)$ , a heat capacity of 4.194  $\left(\frac{kJ}{kg \cdot K}\right)$  and a density of 999.7  $\left(\frac{kg}{m^3}\right)$ .

Comparison of results from the two programs was completed using two methods. The first method assumed a constant extraction of 2070 (W) every hour, while the second method used heating and cooling data from a home located in Dayton, OH. Since EED only produces average monthly fluid temperatures, the program does not accurately account for the peak heating and cooling loads, even with the hourly heating and cooling input for each month. A comparison of EED's average monthly fluid temperature and GEO2D's daily entering water temperature can be seen in Figure 3.5. Results from the two programs have the same trend and are comparable in magnitude with differences less than 0.5 ( $^{\circ}C$ ) temperature difference between the two programs results may not seem like much, it has to be remembered that GLHEs only operate with temperature differences that run from 0 ( $^{\circ}C$ ) to about 20 ( $^{\circ}C$ ).

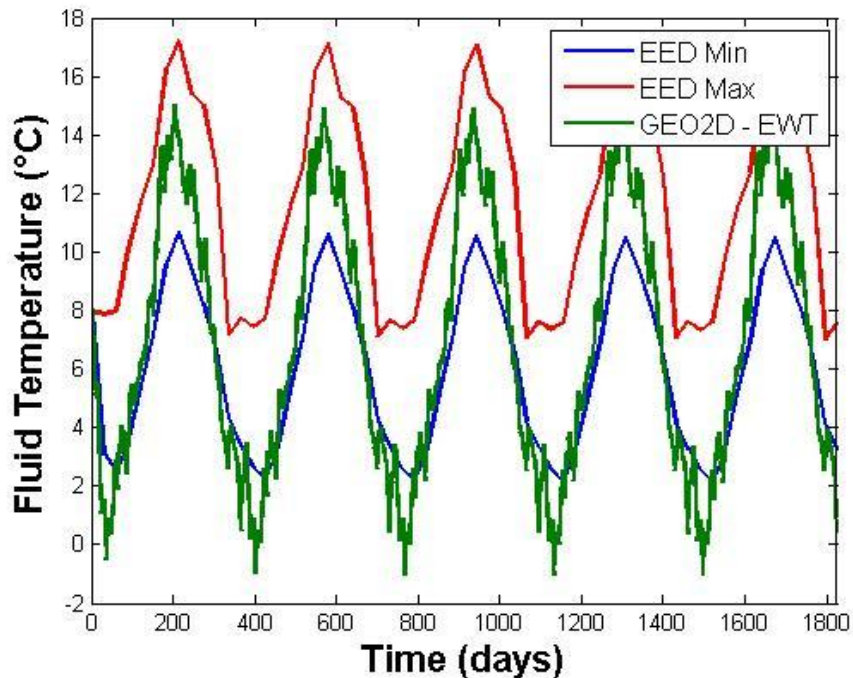


**Figure 3.5:** The average fluid temperature from GEO2D and Earth Energy Designer.

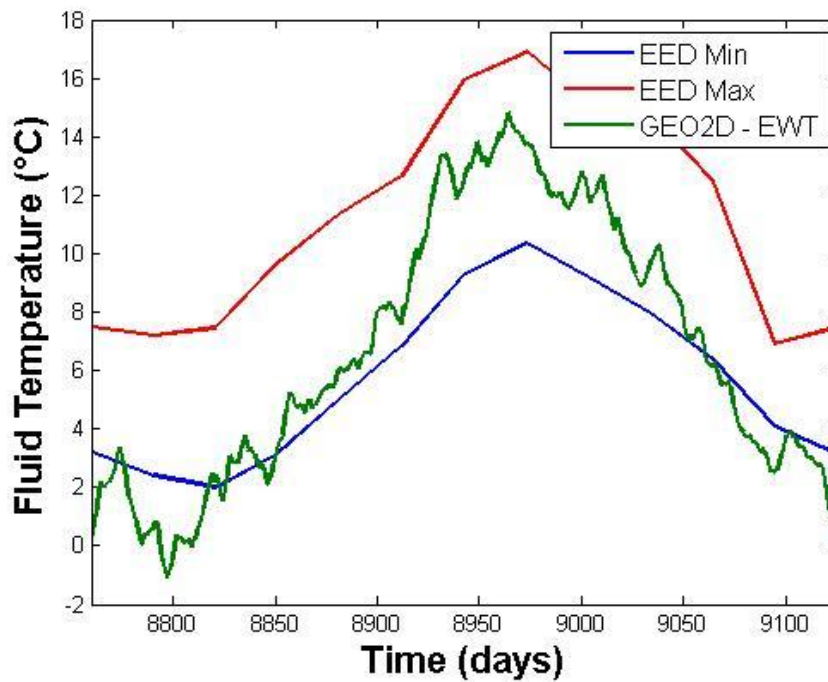


**Figure 3.6:** The average fluid temperature difference between GEO2D and Earth Energy Designer.

In order to simulate the same GLHE model for an actual case study in Dayton, OH, GEO2D was run for a home with weather data from Dayton, OH. Once completed, the hourly home heating and cooling load was added for each month, keeping track of the hourly peak load. The base loads and peak loads were entered into EED for comparison. Based on the monthly peak loads, EED yields maximum and minimum average monthly fluid temperatures as seen in Figure 3.7 for a 5 year simulation and Figure 3.8 for a 25 year simulation. Also shown in these figures are the daily entering fluid temperatures from GEO2D. The entering water temperature from GEO2D follows the same trend as EED, but shows a more rapid variation because of its much finer time steps. In general, GEO2D predicts fluid temperatures that lie between the minimum and maximum values predicted by EED except for the coldest temperatures. It should be noticed that the temperature difference predicted by GEO2D and EED are significant in the case. The temperature differences can be 2 to 4 ( $^{\circ}\text{C}$ ).



**Figure 3.7:** The minimum and maximum average fluid temperature for EED and the daily entering water temperature for GEO2D, for a 5 year simulation.



**Figure 3.8:** The minimum and maximum average fluid temperature for EED and the daily entering water temperature for GEO2D, for 25<sup>th</sup> year.

Overall the GLHE program EED provides a quick calculation for the average fluid temperature in the ground loop, but lacks accuracy due to the large time step used in the heat transfer analysis. To account for the peak loads for a GLHE system, a model needs more than just a single hourly peak heating load and single hourly peak cooling load during each month. Furthermore, a GLHE sizing program also needs an option for both horizontal and vertical GLHE. The user friendliness of EED allows for a quick learning curve, but lacks accuracy, generality and useful outputs.

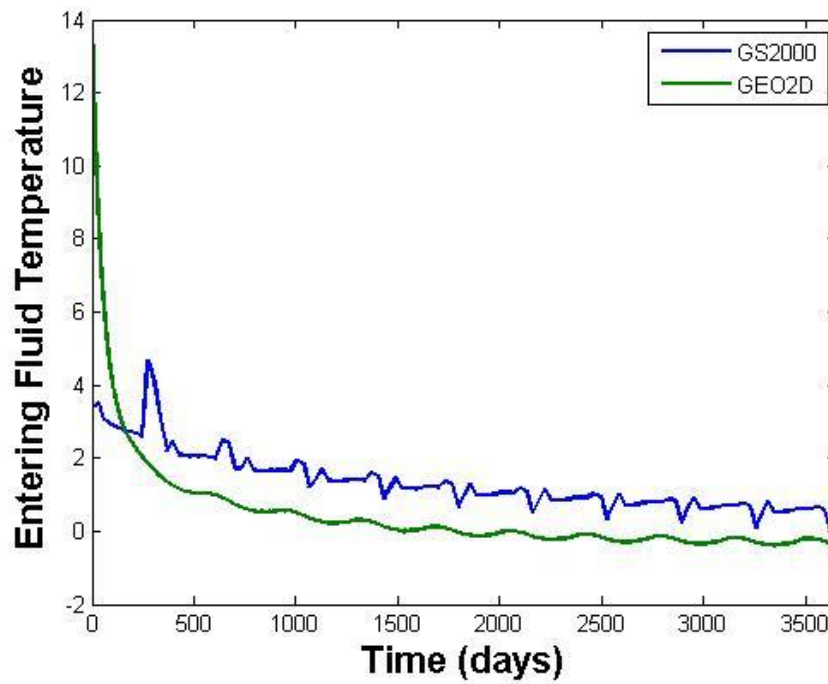
### 3.6 GS2000

GS2000 was first developed in 1995 by Caneta Incorporated for CETC-Ottawa as a GLHE sizing program. A simple GUI allows the user to select soil properties, fluid properties, pipe properties, and heat pump design information to easily design a GLHE. The program can model 34 different loop configurations consisting of horizontal and

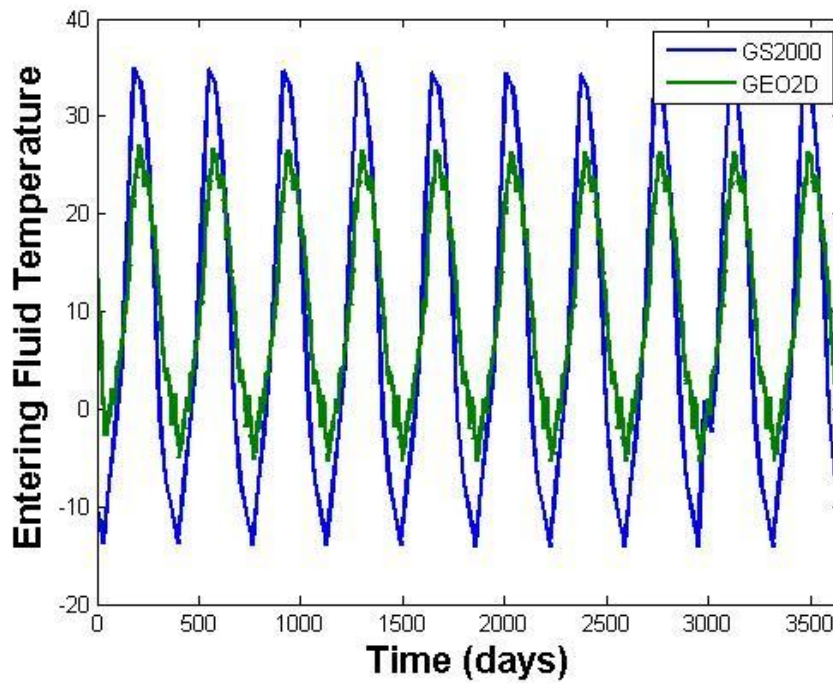
vertical GLHE. Ground temperature data from 129 locations in the United States and Canada are available for selection. Once a design of the GLHE is complete and heating and cooling loads are entered, the program runs a single year or multi-year analysis (up to 25 years). GS2000 recommends a length or depth of the GLHE. Also, the fluid entering water temperature is provided for the user on a monthly basis.

The heat transfer analysis used in GS2000 is the cylinder and line source method developed by Carslaw and Jaeger (1947), as discussed in Chapter 1. The line source analysis is performed on a single pipe and the results are superimposed for a multi-pipe GLHE (Purdy & Morrison, 2003). During heating season, the freezing soil is modeled as an ice ring, with an estimated diameter and assumes the outside temperature of the ring remains a constant 0 °C. This does not accurately model the latent energy in the soil, but provides a reasonable solution to the fluid temperature.

To compare results from GS2000 and GEO2D two cases were considered. First, a constant heat extraction was performed; followed by a varying heating and cooling load. The fluid selected for both programs was water with a velocity of  $3.166 \text{ (m/s)}$  and a dynamic viscosity, thermal conductivity, heat capacity and density of  $0.00131 \left(\frac{\text{N}\cdot\text{s}}{\text{m}^2}\right)$ ,  $0.58 \left(\frac{\text{W}}{\text{m}\cdot\text{K}}\right)$ ,  $4.194 \left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)$  and  $999.7 \left(\frac{\text{kg}}{\text{m}^3}\right)$ , respectively. A thermal conductivity of  $0.391 \left(\frac{\text{W}}{\text{m}\cdot\text{K}}\right)$ , heat capacity of  $0.32 \left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)$  and a density of  $58.74 \left(\frac{\text{kg}}{\text{m}^3}\right)$  was selected for a pipe of  $26.67 \text{ (mm)}$  diameter and thickness of  $2.87 \text{ (mm)}$ . The soil thermal properties consisted of  $1.3 \left(\frac{\text{W}}{\text{m}\cdot\text{K}}\right)$  for the thermal conductivity,  $1.814 \left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)$  for the heat capacity and  $1280 \left(\frac{\text{kg}}{\text{m}^3}\right)$  for the density. Finally, a constant building heat load of  $1500 \text{ (W)}$  every hour was used for a GLHE located in Dayton, Ohio. Results from the two programs can be seen in Figure 3.9. Since GS2000 first outputs a recommended pipe length, GEO2D was executed after the recommended length was found from GS2000, so that the GLHE same GLHE length was used in each simulation.



**Figure 3.9:** GS2000 and GEO2D entering water temperature comparison for 10 years of simulation.



**Figure 3.10:** Entering water temperature from a GLHE simulation in Dayton, Ohio

From Figure 3.9 it can be seen that the difference between the two programs is about 1.5 (°C). This could be a result of the long, monthly time steps that GS2000 uses or the inaccuracy of the heat transfer method used by GS2000. Regardless, a GLHE following the results from GS2000 would be undersized and cause a longer payback period.

Next a varying heating and cooling load comparison is performed using the same GLHE used with the constant heat extraction comparison, with the exception of the length of pipe. This was taken from GS2000 after the program gave a recommended length. The heating and cooling loads were taken from GEO2D and the loads were summed to obtain a monthly value and then entered into GS2000. The entering water temperature results are shown in Figure 3.10. Entering water temperature results from GS2000 and GEO2D follow the same pattern, but GS2000 calculates a higher entering water temperature during peak heating and a lower entering water temperature during peak cooling. Again, this could be from the long monthly time steps or the inaccuracy of the heat transfer analysis. A system modeled by GS2000 would be considerably oversized, causing a higher initial cost, thus, a longer payback period.

For comparison, the six commercial programs and GEO2D are analyzed under five main points of interest. First, the user-friendliness determined the type of user. For instance, TRNSYS requires a high learning curve, but produces an accurate GLHE solution. For this reason, TRNSYS appeals to researchers rather than the typical GLHE installers. Secondly, the program's heat load calculation methods are compared, as shown in Table . The heating and cooling load calculations play a significant role in determining the optimized size for a GLHE. An accurate hourly heating and cooling prediction, such as those used in TRNSYS, GLD2000 and GEO2D, account for peak loads accurately. Next, the loops capable of sizing are compared for each program. A program limited to sizing vertical GLHE eliminates the option for installers to simulate a horizontal GLHE, which overall, is less expensive to install. The heat transfer analysis

technique used by each program presents the most important aspect of each program. A more accurate technique, such as those used by GEO2D and TRNSYS, provides a more accurate simulation, but require more computation time. On the other hand, programs such as GS2000, RETScreen, GLHEPRO and EED give quick solution, but lack accuracy. Whether the programs offered a cost analysis was the final point of interest to analyze. The programs that provide a cost analysis are shown in Table . These programs estimate the cost for the modeled GLHE and also give an estimated payback period compared to conventional HVAC systems. It should be noted that the major factor in motivating costumers to install a GLHE is the payback period.

**Table 3.1**

*A brief description of 6 commercial GLHE programs available today in comparison to GEO2D.*

|                    | User Friendly | Heat Load Calculation Method      | Loops Capable of Modeling | Heat Transfer Technique                      | Cost Analysis |
|--------------------|---------------|-----------------------------------|---------------------------|----------------------------------------------|---------------|
| GS 2000            | Yes           | Monthly averaged loads            | Horizontal and Vertical   | Cylinder & line source method and g-function | No            |
| RETScreen          | No            | Built in                          | Horizontal and Vertical   | Bin Method                                   | Yes           |
| TRNSYS             | No            | TRNBuild                          | Horizontal and Vertical   | Multiple methods                             | Yes           |
| EED                | Yes           | Monthly averaged loads (built in) | Vertical                  | g-function                                   | No            |
| GLHEPRO            | Yes           | User Supplied                     | Vertical                  | g-function                                   | No            |
| Ground Loop Design | No            | LEADPlus                          | Horizontal and Vertical   | Cylinder & line source method and g-function | Yes           |
| GEO2D              | Yes           | EnergyPlus                        | Horizontal                | 2-D, Unsteady Finite Volume                  | Yes           |

# **Chapter 4**

## **3D Grid Development**

At the present time Wright State has developed a transient, two-dimensional GLHE computer program called GEO2D. This program is working and is producing very good results. A number of results from GEO2D have been presented in this thesis. Because of some complex geometry issues involved in vertical GLHEs and a desire to include ground surface heat transfer, it was essential to develop a transient, three-dimensional GLHE program. This program is called GEO3D. This chapter describes the gridding scheme used in GEO3D.

### **4.1 Governing Differential Equations**

The governing differential equations used to solve for the heat transfer and temperature field in a GLHE problem for both GEO2D and GEO3D comes from the first law of thermodynamics. The first law of thermodynamics is nothing more than a statement that says energy is conserved. The first law of thermodynamics can be written in many forms depending on the energy mechanisms involved. For a GLHE there are two energy flow mechanisms and one storage energy mechanisms. The energy flow mechanisms are conduction and advection. The energy storage mechanism is thermal energy storage. All three of these energy mechanisms are included in the governing differential equations presented below.

For GEO2D changes in the temporal direction and both the radial and axial spatial directions are included. This is more than most commercial programs do, which generally consider a GLHE to be essentially a one dimensional, unsteady problem. The

governing differential equation solved by GEO2D for the two-dimensional unsteady heat transfer occurring is

$$\rho C_p \frac{\partial T}{\partial t} + \frac{\partial(\rho u C_p T)}{\partial z} = \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) \quad (4.1)$$

where  $\rho$  is the density in  $\left(\frac{kg}{m^3}\right)$  or  $\left(\frac{lbm}{ft^3}\right)$ ,  $C_p$  is the specific heat in  $\left(\frac{J}{kg \cdot K}\right)$  or  $\left(\frac{Btu}{lbm \cdot R}\right)$ ,  $T$  is the temperature in  $(K)$  or  $(R)$ ,  $t$  is the time in  $(sec)$ ,  $u$  is the velocity in  $\left(\frac{m}{s}\right)$  or  $\left(\frac{ft}{s}\right)$ ,  $k$  is the thermal conductivity in  $\left(\frac{W}{m \cdot K}\right)$  or  $\left(\frac{Btu}{hr \cdot ft \cdot R}\right)$ , and  $z$  and  $r$  are the radial and axial positions in  $(m)$  or  $(ft)$ .

Even though GEO2D is a very good program for GLHE, only accounting for heat transfer in 2 dimensions causes some limitations. GEO2D does not account for the ground surface temperature for a horizontal GLHE. Additionally, for a vertical GLHE, the symmetry for a U-tube pipe requires a 3-dimensional heat transfer analysis. For these reasons, Wright State University is presently furthering its GEO2D program to three-dimensions. The three-dimensional form of GEO2D is called GEO3D.

GEO3D uses a third spatial dimension, the azimuthal direction, to account for the ground surface heat transfer and the thermal interference between the U-tube pipes within a vertical borehole. The third dimension adds physical detail to the model, but increases the computation time as well. The governing differential equation used to solve the heat transfer in GEO3D is

$$\frac{\partial(\rho C_p T)}{\partial t} + \frac{\partial(\rho u C_p T)}{\partial z} = \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( k r^2 \frac{\partial T}{\partial \theta} \right) \quad (4.2)$$

where the meaning of the symbols used are the same as used in Equation (4.1) and  $\theta$  is the azimuthal coordinate in radians. Thus only one term has been added to Equation (4.1) to obtain Equation (4.2). This is the last term on the right-hand side of Equation (4.2) and it accounts for heat conduction in the azimuthal direction. This adds a

considerable amount of complexity to the solution of the governing differential equation.

Neither Equation (4.1) or (4.2) can be solved analytically. Thus a finite volume numerical representation is used for both of these equations. Numerical models are developed by replacing the differential equations, with a set of algebraic equations. In the case of the finite volume method, this is done by writing algebraic representations of the differential equations over a large number of small volumes which subdivide the overall computational domain. The center point of these control volumes is called a grid point (Cengel, 2007). The collection of these grid points and control volumes will be called the grid. It is this grid that is developed as part of thesis work for the GEO3D. This is the topic being discussed in this chapter. Since this grid is different for both the horizontal GLHE and the vertical GLHE each will be discussed in its own section.

## 4.2 Horizontal GLHE Grid

The graphical user interface allows the user to input grid parameters such as: number of nodes in the fluid, pipe, grout and soil along the radial, axial and azimuthal axis as shown in Appendix A. Additionally, an exponential can be entered for each grid parameter to distribute the nodes in a more efficient and accurate way. The input file provided by Matlab describes the modeler's desired loop, as seen in Appendix D. FORTRAN uses this input file to construct a three-dimensional grid with material properties located in the proper region. This gridding scheme allows non-uniform grid spacing in each of the different material regions. First, the control volumes in the fluid, pipe, grout and soil are summed to find the total number of nodes in the axial, radial and azimuthal direction. These quantities are noted as  $n_z$ ,  $n_r$  and  $n_\theta$  and for a horizontal GLHE are determined by

$$n_z = ncv_z + 2 \quad (4.3)$$

and

$$n_r = ncv_{r,fluid} + ncv_{r,y+} + ncv_{r,wall} + ncv_{r,earth} + 2 \quad (4.4)$$

and

$$n_\theta = ncv_\theta + 2 \quad (4.5)$$

The number of control volumes, ' $ncv$ ' in each material region is determined by the modeler in their respective directions. Next, the grid locations are calculated and stored in an array to be called in a later subroutine. The grid face locations for a horizontal GLHE along the axial direction is calculated by

$$zf_i = zf_2 + (zf_{n_z} - zf_2)((i - 2)/ncv_z)^{exp_z} \quad (4.6)$$

where  $zf_i$  is the grid face location at location  $i$ ,  $zf_2$  is 0,  $zf_{n_z}$  is the axial length of the tube,  $i$  is the grid index number,  $ncv_z$  is the number of control volumes in the axial direction, and  $exp_z$  is the axial grid exponent. Equation (4.6) uses a 'DO' loop that cycles from  $i = 3$  to  $i = n_z$ . The grid location can then be found by

$$z_i = 0.5 * (zf_{i+1} + zf_i) \quad (4.7)$$

where  $z$  is the grid location at location  $i$ . Equation (4.7) requires 'DO' loop from  $i = 2$  to  $i = n_z - 1$ . Similar formulas are used to construct the grids in the radial direction. The grid face locations for a horizontal GLHE in the radial direction is calculated by

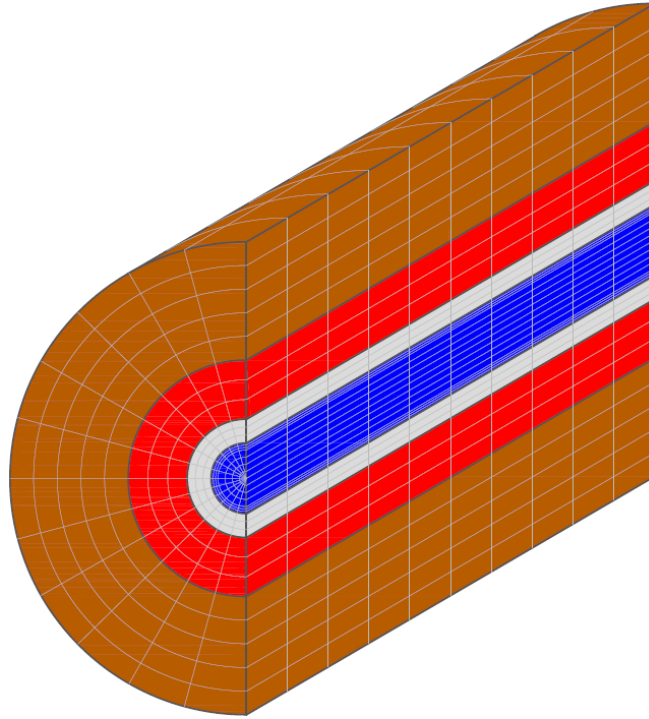
$$rf_j = rf_2 + (rf_{n_{r,fluid}} - rf_2) \left( \frac{(j-2)}{(n_{r,fluid}-2)} \right)^{exp_{r,fluid}} \quad (4.8)$$

where  $rf_i$  is the grid face location at location  $i$ ,  $rf_2$  is 0,  $rf_{n_{r,fluid}}$  is the radius of the inner tube,  $i$  is the grid index number and  $exp_{r,fluid}$  is the radial grid exponent. Equation (4.8) uses a 'DO' loop from  $j = 3$  to  $j = ncv_{r,fluid}$ . Equation (4.8) illustrates the grid face location in the fluid region. A similar equation is used for the  $y_{plus}$ , pipe, grout and soil region. The grid locations for the entire radial direction are found by

using Equation (4.7), but with the radial face locations. The grid locations in the azimuthal direction for a horizontal GLHE are calculated by

$$\theta f_k = \theta f_2 + (\theta f_{n_\theta} - \theta f_2) \left( \frac{(k-2)}{ncv_\theta} \right)^{exp_\theta} \quad (4.9)$$

where  $\theta f_k$  is the grid face location at location  $k$ ,  $\theta f_2$  is 0,  $\theta f_{n_\theta}$  is  $\pi$ ,  $k$  is the grid index number,  $ncv_\theta$  is the number of control volumes in the azimuthal direction, and  $exp_\theta$  is the azimuthal grid exponent. Equation (4.9) uses a 'DO' loop that ranges from  $k = 3$  to  $k = n_\theta$ . The azimuthal grid locations are found using Equation (4.7), but with the azimuthal face locations.

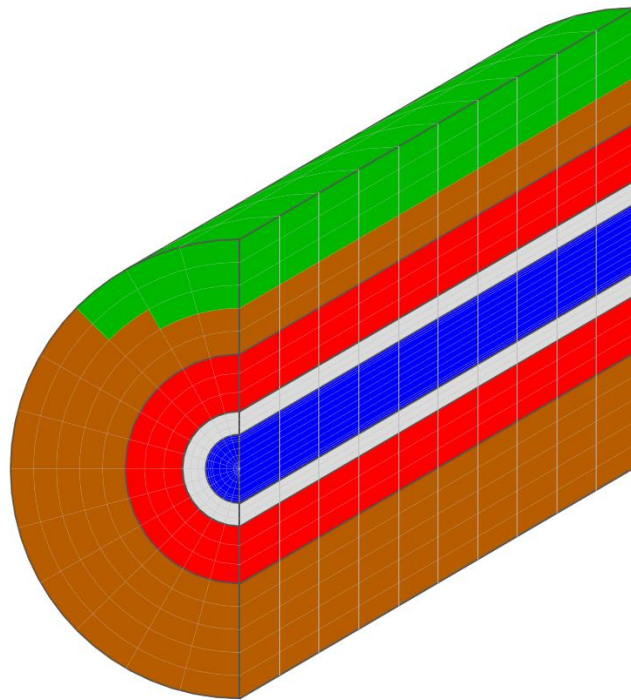


**Figure 4.1:** The grid system used for a horizontal GLHE in GEO3D.

From this, a 3-dimensional grid is developed that is used to solve the governing differential equations (see Equations (4.1) and (4.2)). In order to increase the computation time, symmetry was used to dissect the model along the axial direction.

Since a horizontal GLHE acts the same when divided as such, only half of the model needs to be analyzed as shown in Figure 4.1.

The model in Figure 4.1 uses 10 nodes in the axial direction, 10 nodes in the azimuthal direction, 4 nodes in the fluid radial direction, 4 nodes in the  $y_{plus}$  radial direction, 3 nodes in the pipe radial direction, 3 nodes in the grout radial direction and 5 nodes in the soil radial direction. Suggested numbers of nodes are given in the GUI and are based on heating and cooling loads, thermal conductivity of the soil and time of simulation. The number of nodes advised is based on a study for the fewest number of nodes to return a 1% error from the actual solution (Gross, 2011). This study was performed to reduce computation time while maintaining an accurate solution.

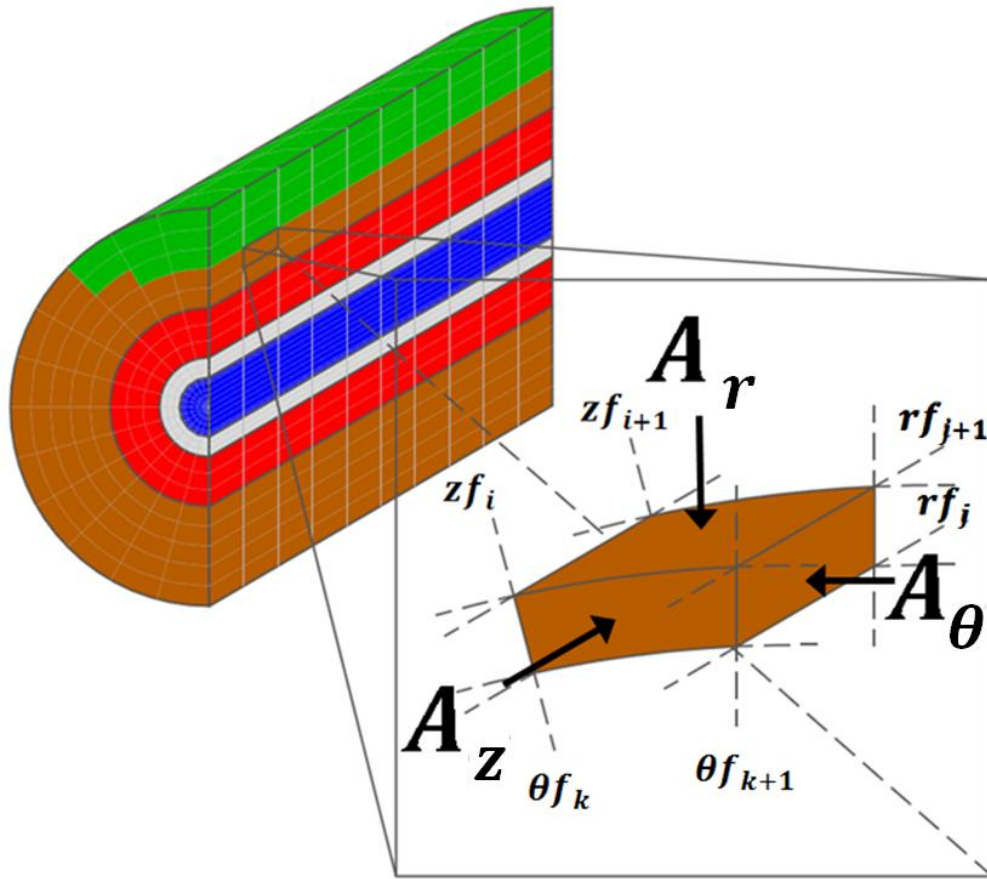


**Figure 4.2:** The grid system used for a horizontal GLHE in GEO3D with interaction from the surface.

To account for the surface temperature, the grids along the top of the soil take on thermal properties that allow the convective surface boundary condition to move

into the circular computational domain to the appropriate location, as shown in Figure 4.3. This is discussed in Chapter 5.

Immediately following the 3-D grid geometry, memory is allocated for nodes, areas, volumes, thermal properties and velocities. First, axial, radial and azimuthal locations are calculated from node quantities and GLHE geometries. The node locations are then used to find the area of the face for the respective node as illustrated in Figure 4.3.



**Figure 4.3:** Cutout of a single soil node in GEO3D.

The area for each face can be calculated by

$$A_r = (z_{f_{i+1}} - z_{f_i}) \left( (\theta_{f_{k+1}} - \theta_{f_k}) r_{f_j} \right) \quad (4.10)$$

$$A_{\theta} = (zf_{i+1} - zf_i)(rf_{j+1} - rf_j) \quad (4.11)$$

$$A_z = \left( \frac{\theta f_{k+1} - \theta f_k}{2} \right) (rf_{j+1}^2 - rf_j^2) \quad (4.12)$$

Finally, the volume of each node can be calculated by

$$V = \left[ \left( \left( \frac{\theta f_{k+1} - \theta f_k}{2} \right) rf_{j+1} \right) - \left( \left( \frac{\theta f_{k+1} - \theta f_k}{2} \right) rf_j \right) \right] (zf_{i+1} - zf_i) \quad (4.13)$$

The area and volume results are stored in a three-dimensional matrix and are used in later subroutines for heat transfer analysis.

### 4.3 Vertical GLHE Grid

Like the horizontal GLHE, the vertical GLHE receives the dimensions, number of nodes and grid exponents for the GUI. This again allows FORTRAN to develop several matrices to model the specified vertical GLHE. The number of nodes in the axial, radial and azimuthal directions is determined by

$$n_z = ncv_z + 2 \quad (4.14)$$

and

$$\begin{aligned} n_r = & ncv_{r,shank} + 2 \cdot ncv_{r,y+} + 2 \cdot ncv_{r,wall} \\ & + ncv_{r,fluid} + ncv_{r,grout} + ncv_{r,earth} + 2 \end{aligned} \quad (4.15)$$

and

$$n_{\theta} = 2 \cdot (ncv_{\theta,fluid} + ncv_{\theta,y+} + ncv_{\theta,wall} + ncv_{\theta,grout}) + 2 \quad (4.16)$$

From there, the grid locations in the axial direction are calculated using Equations (4.6) and (4.7). The grid face locations in the radial direction are calculated using Equation

(4.8), but with regions including the inner grout, inner pipe, inner  $y_{plus}$ , fluid, outer  $y_{plus}$ , outer pipe, outer grout and soil. The azimuthal grid locations are calculated by

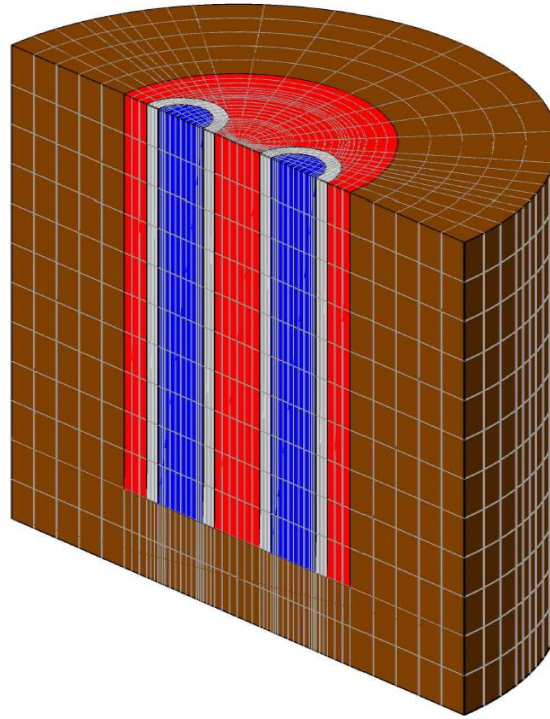
$$\theta f_k = \theta f_2 + \left( \theta f_{nf_{\theta, fluid}} - \theta f_2 \right) \left( \frac{(k-2)}{(nf_{\theta, fluid}-2)} \right)^{exp_{\theta, fluid}} \quad (4.17)$$

where  $\theta f_k$  is the grid face location at location  $k$ ,  $\theta f_2$  is 0,  $\theta f_{nf_{\theta, fluid}}$  is the angle of the inner tube,  $k$  is the grid index number and  $exp_{\theta, fluid}$  is the azimuthal fluid grid exponent. Equation (4.17) uses a 'DO' loop from  $k = 3$  to  $k = nc_{v_{\theta, fluid}}$ . Equation (4.17) illustrates the grid face location in the azimuthal fluid region. A similar equation is used for the  $y_{plus}$ , pipe and grout region. The grid locations for the entire radial direction are found by using Equation (4.7), but with the azimuthal face locations.

The node's face areas and volumes are then calculated using Equations (4.10) through (4.13). For an increase computation time, the vertical GLHE is divided along the axial direction and the 0<sup>th</sup> degree in the azimuthal direction, as shown in Figure 4.4. Since the GLHE acts the same on either side, a single half can be simulated and produce the same results as a whole model would. On the other hand, the zeroth radius is taken between the U-tube pipe, causing some inaccuracies as the radius increases, specifically within the fluid. Because a three-dimensional cylindrical gridding system is used the round cross section of the U-tube are modeled with a stepping routine. Thus, the circular tubes are replaced with jagged edge circular control volumes as shown in Figure 4.5. This is not a perfect way to perform this modeling, but is very satisfactory. This model can be fixed by adding additional nodes in the fluid and pipe.

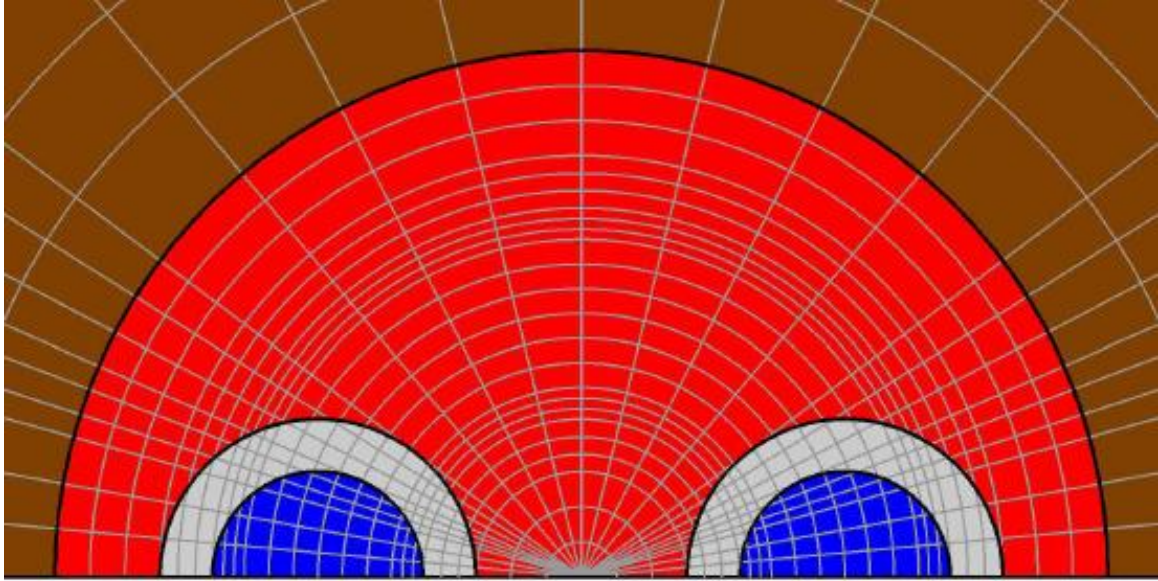
GEO3D calculates the heat transfer within the fluid unlike any other commercial program available. Heat transfer in the fluid is calculated by finding the frictional velocities, eddy momentum and effective thermal conductivity in the fluid. Most importantly, this method uses a  $y^+$  region, which is the fluid region closest to the pipe wall. To model this correctly, a minimum of 3 nodes must be in the  $y^+$  region (Gross,

2011). Therefore, additional nodes are added to the fluid in the azimuthal and radial direction.



**Figure 4.4:** *The grid system used for a vertical GLHE in GEO3D.*

Figure 4.5 shows the zoomed in view of the grids being modeled in the grout region of a vertical GLHE. The important region to notice is the  $y_{plus}$  region located on the inside of the pipe. The  $y_{plus}$  region of the fluid gives a very low effective thermal conductivity as discussed by Gross (2011). A model that lacks the number of nodes in the  $y_{plus}$  region can produce an erroneous solution.



**Figure 4.5:** *The grid system in GEO3D for a vertical GLHE with additional nodes to account for the  $y^+$  region in the fluid.*

#### 4.4 Comments on GEO3D

GEO3D offers some significant advantages over GEO2D and many other commercial GLHE sizing programs available. The added dimension in the azimuthal direction increases the overall accuracy of a horizontal GLHE by incorporating the surface temperature. The vertical GLHE in GEO3D gives an accurate numerical solution, while other commercial programs use a combined analytical and numerical solution. Alternatively, GEO3D presents 3 noteworthy problems: GEO3D requires more computation time, GEO3D cannot model adjacent pipe in a horizontal GLHE system and it is difficult to get a precise representation of a round tube in GEO3D since the centerline of the tube does not lie on the axis of symmetry of the computational domain. For issue number one, a number of steps are being taken in GEO3D to reduce the computational time to a reasonable value. Of course the computational time required by GEO3D will be higher than GEO2D. For issue two, while GEO2D or GEO3D are not capable of modeling multiple GLHEs that interact with one another, the distance required between adjacent loops so they do not interact can be determined since

GEO3D displays the temperature fields. Issue three can be alleviated by adding additional grid points in the radial and azimuthal directions. All in all GEO3D will offer an even more accurate simulation of a GLHE than GEO2D and more so than any of the commercial codes described in Chapter 3. Hopefully this will decrease the installation cost of GLHEs or increase their operational efficiency.

# **Chapter 5**

## **3D Properties and Boundary Development**

In this chapter the allocation of material properties and velocities to the three-dimensional grid discussed in the previous chapter and the allocation of boundary conditions to the grids are discussed. As mentioned in Chapter 4, a number of regions or different materials exist in the computational domain. Each of these regions has different material properties. Because of the shape of some of these regions allocating properties is difficult. This is especially true for the vertical GLHE configuration. Since fluid velocities are determined with analytical equations and not by solving the Navier Stokes equations, they need to be allocated like the material properties.

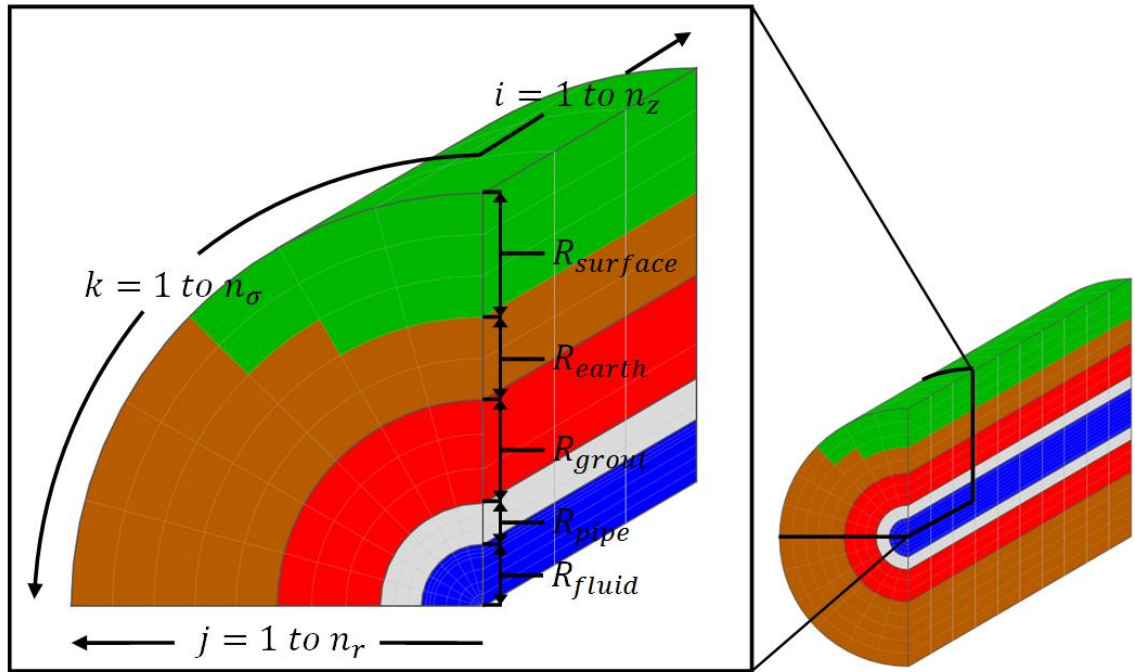
### **5.1 Property Allocation**

The material properties that need to be allocated are density, specific heat, and thermal conductivity, as can be seen in the governing differential equations shown in Equations (4.1) and (4.2). For the fluid region two types of thermal conductivity are required. They are the material thermal conductivity of the fluid and the turbulent thermal conductivity. The actual determination of the turbulent thermal conductivity is not within the scope of this work and has been covered in the work of Gross (2011). The purpose of thesis work is to allocate these properties to the correct grid point. GEO3D allows these properties to be a function of position, which they must be if different materials are involved. They can even vary within a single material. It should be noted

that GOE3D does not adjust material properties as a function of temperature. This is not needed because the temperature variations are relatively small. To implement temperature dependent material properties would make the computational time for GEO3D excessive. Only the axial flow fluid velocities need to be allocated, there are no velocity components in the radial or azimuthal direction.

### 5.1.1 Horizontal GLHE Properties

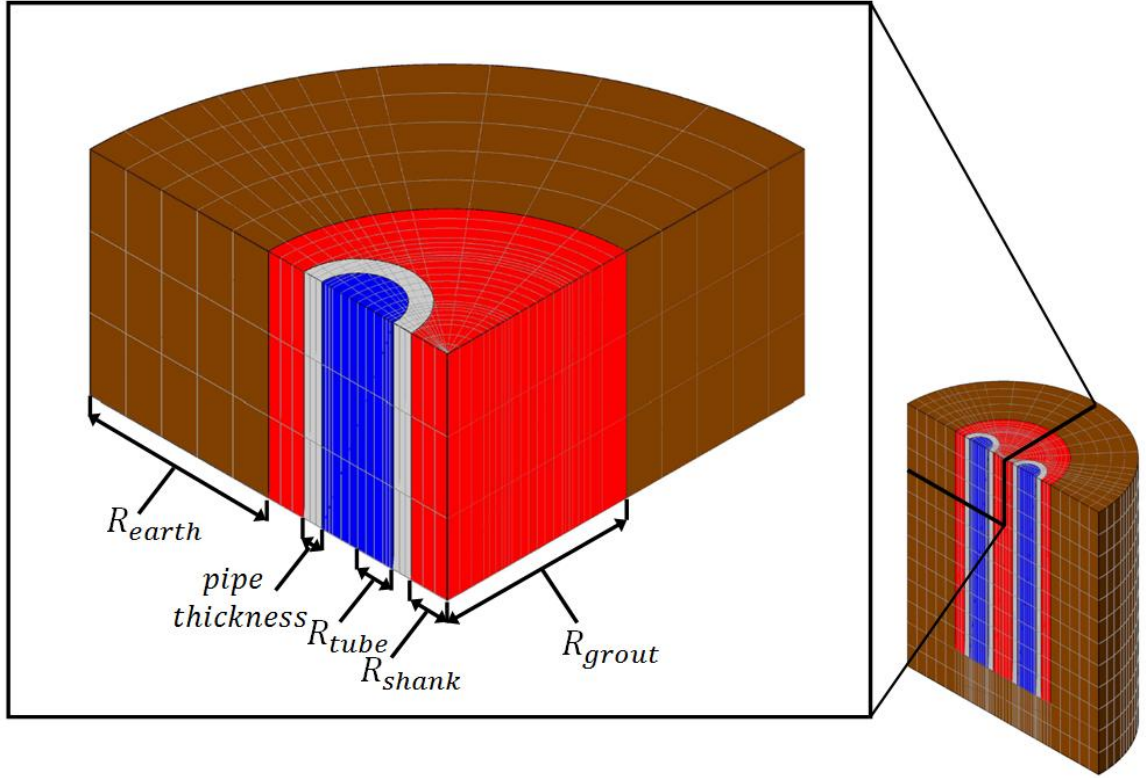
The 3 dimensional matrices allocated for the thermal properties and velocities are called in a later 'SET\_FIELD\_QUANTITIES\_HORIZONTAL' subroutine. The thermal properties and velocities entered by the user are stored in their respective 3 dimensional matrix at their appropriate location. For a horizontal GLHE, the subroutine is broken into several "DO" loops for each thermal property and velocity. Figure 5.1 shows a quarter section of a horizontal GLHE. The fluid thermal conductivity is placed in the 3 dimensional thermal conductivity matrix at nodes  $i = 1 \text{ to } n_z, j = 1 \text{ to } n_{f,fluid} - 1$  and  $k = 1 \text{ to } n_\theta$ . Similarly, the thermal conductivity in the  $y^+$  region of the fluid is stored at nodes  $i = 1 \text{ to } n_z, j = n_{f,fluid} \text{ to } n_{f,y^+} - 1$  and  $k = 1 \text{ to } n_\theta$ . The pipe thermal conductivity at nodes  $i = 1 \text{ to } n_z, j = n_{f,y^+} \text{ to } n_{f,wall} - 1$  and  $k = 1 \text{ to } n_\theta$ . Finally, the earth thermal conductivity is stored at nodes  $i = 1 \text{ to } n_z, j = n_{f,wall} \text{ to } n_r$  and  $k = 1 \text{ to } n_\theta$ . An additional "IF ELSE" command is executed to locate the nodes above the surface of the GLHE. Since convection is the only heat transfer taking place at the surface, the thermal conductivity at or above the surface is set to  $10^6 \left( \frac{W}{m \cdot K} \right)$ . The same "DO" loops are mimicked for density, specific heat, and velocities in the axial, radial and azimuthal direction, with exception to the "IF" statement to account for surface temperature.



**Figure 5.1:** Quarter section of the horizontal GLHE used in GEO3D.

### 5.1.2 Vertical GLHE Properties

Developing a grid system with the properties intended by the modeler proves more difficult for a vertical GLHE than a horizontal GLHE. Since the origin of the grid is taken at the center of the borehole, the grids volumes continuously grow as the radius increases, causing modeling problems in the fluid, pipe and grout, which are circular cross sectional regions off the centerline of the computational domain (see Figure 5.2). This causes these regions to have a jagged cross sectional shape as opposed to a smooth circular shape. The black lines in Figure 4.5 show the actual shape of the fluid, tube, and grout but the computational shape of these objects has to follow the closest grid lines. The computational shape of these objects is dictated by the material properties applied to each control volume.



**Figure 5.2:** Section of a vertical GLHE and some inputs used to develop the model.

Like the horizontal GLHE, a “SET\_FIELD\_QUANTITIES\_VERTICAL” subroutine uses “DO” loops to store thermal properties and velocities in their appropriate location. “IF ELSE” commands are used to find the locations of the nodes in the fluid, pipe and grout. Three “DO” loops are used to store thermal properties at nodes  $i = 1$  to  $n_z$ ,  $j = 1$  to  $n_{f,grout} - 1$  and  $k = 1$  to  $n_\theta$ , similar to section 5.1.1. Inside the loops, values for  $x$ ,  $y$  and  $r_{tube}$  are calculated using

$$x = \text{abs}(r(j) \cdot \cos(\theta(k))) \quad (5.1)$$

$$y = r(j) \cdot \sin(\theta(k)) \quad (5.2)$$

$$r_{tube} = \text{sqrt}((r_{center} - x)^2 + y^2) \quad (5.3)$$

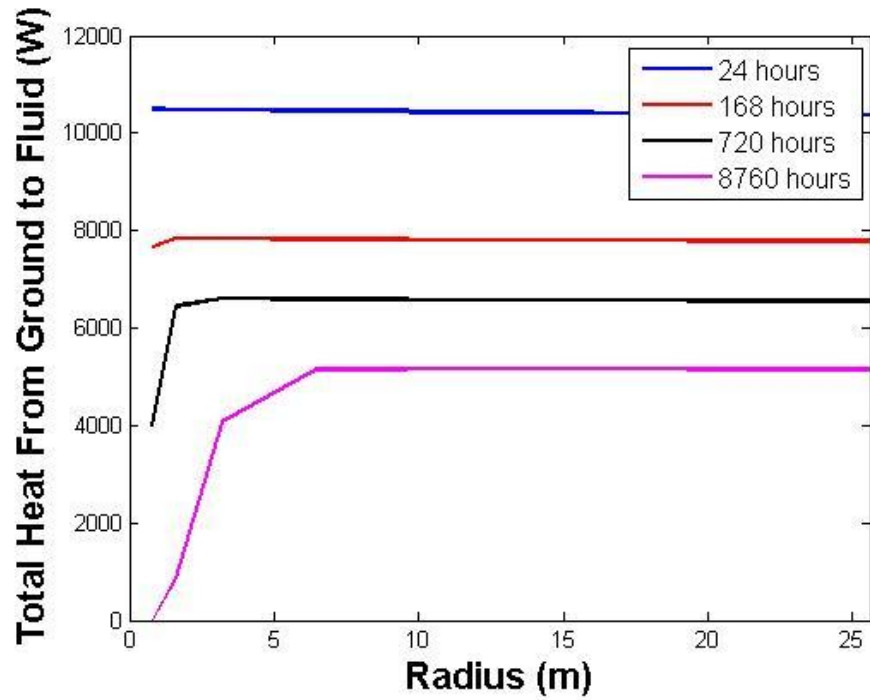
From there, if  $r_{tube}$  is less than or equal to  $R_{tube}$ , the thermal properties and velocities are equal to the specified fluid values. If  $r_{tube}$  is greater than or equal to  $R_{tube}$  and  $r_{tube}$

is less than or equal to  $(R_{tube} + pipe\ thickness)$ , the nodes are set to the pipe properties and velocities. All other nodes are stored as grout thermal properties and velocities. Finally, the earth thermal properties and velocities are stored at nodes  $i = 1\ to\ n_z, j = n_{f,grout}\ to\ n_r$  and  $k = 1\ to\ n_\theta$ .

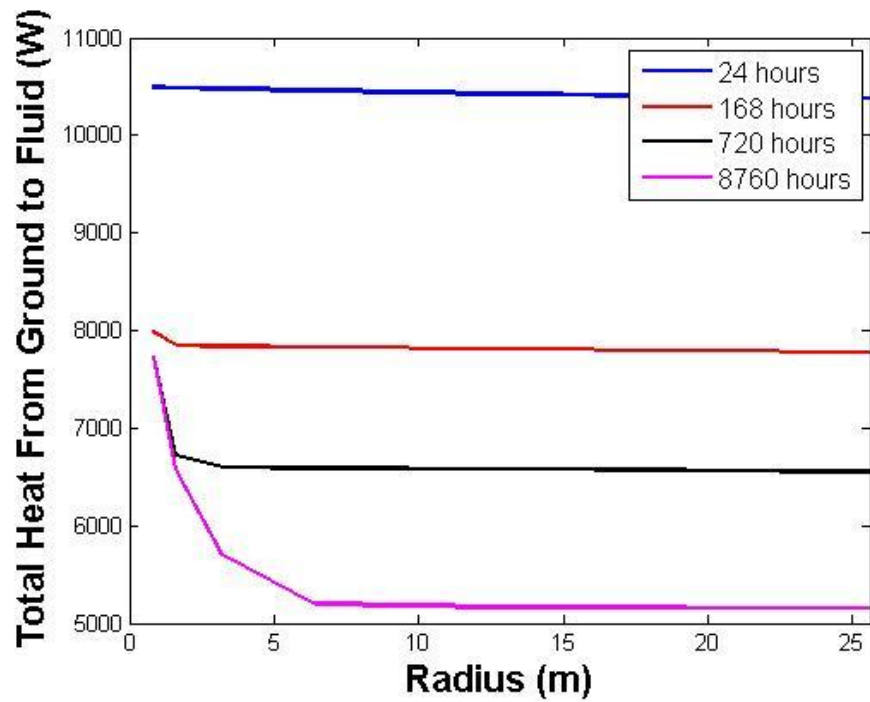
## 5.2 Boundary Conditions

Two boundary conditions can be used for a GLHE: an adiabatic boundary condition or a constant temperature boundary condition. A study using both boundary conditions was implemented to find the most accurate solution while using the smallest far field soil radius. The heat extracted from the pipe is strongly influenced by both boundary conditions. However, at some soil radius the boundary condition no longer affects the heat being extracted or rejected. It is this radius that needs to be minimized so that the computation time can be minimum.

The study was performed using GEO2D and used a constant entering water temperature of 5 (°C) over a 1 year period. The thermal properties, velocities, grid variability, number of control volumes and geometry of the GLHE were the same for the adiabatic and constant temperature boundary condition. The only factor changing in each case was the earth thickness. GEO2D was ran for both boundary conditions with soil radiuses of 0.8, 1.6, 3.2, 6.4, 12.8 and 25.6 (m). The total heat extracted from the pipe at the end of a day, week, month and year was then found. The results from the adiabatic boundary condition and the constant temperature boundary condition can be seen in Figure 5.3 and Figure 5.4, respectively.



**Figure 5.3:** The total heat extracted from the pipe at various radiuses using an adiabatic boundary condition.



**Figure 5.4:** The total heat extracted from the pipe at various radiuses using a constant temperature boundary condition.

For each study, the portion of the line that levels off demonstrates a soil radius that is acceptable to use on the model. At the end of the first day while using a radius of 0.8 (m), both boundary conditions have little influence on the heat being extracted. For both boundary conditions, a soil radius greater than 1.6 (m) is necessary for an analysis exceeding a month. Similarly, a full years analysis requires a soil radius of at least 6.4 (m). The results show that both the adiabatic and the constant temperature boundary conditions are acceptable to use for analysis. However, using a constant temperature boundary condition can show unrealistic results at the soil far field radius since the temperature along this boundary is constant. Thus, an adiabatic boundary condition was used for GEO3D.

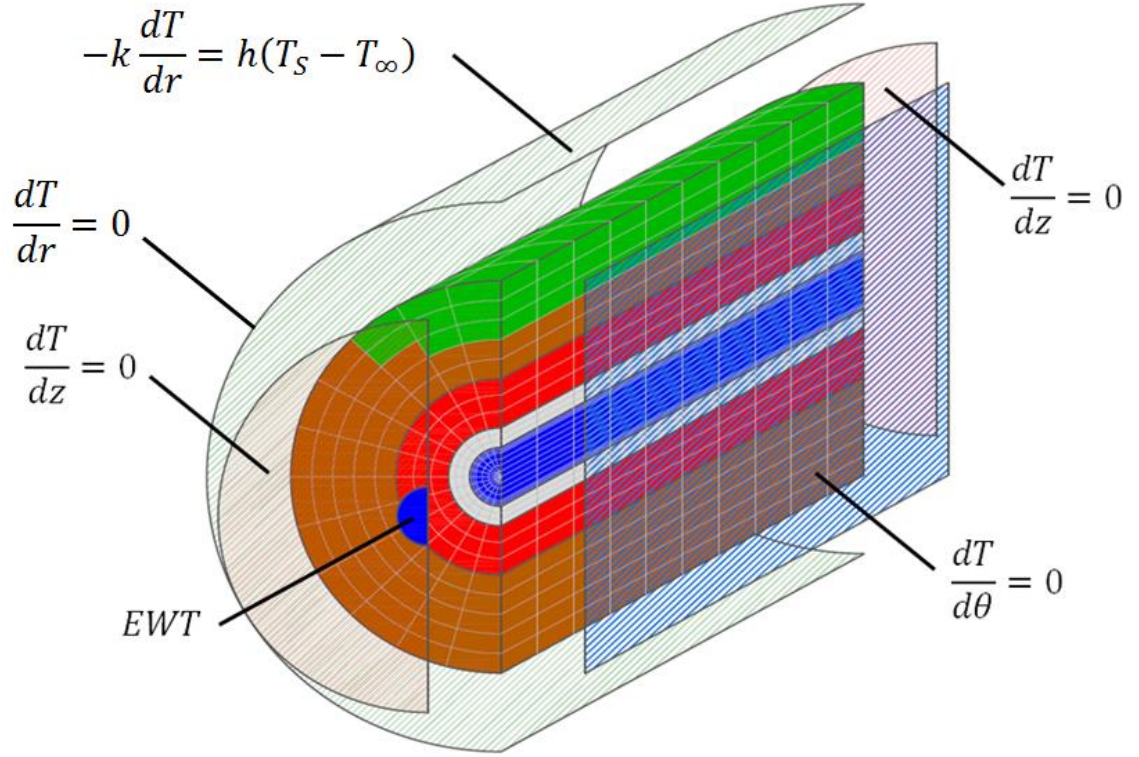
Several boundary conditions are implemented into the grid system when modeling a horizontal or vertical GLHE. Most boundaries in the model are taken as being adiabatic, but some important ones are not. An adiabatic process eliminates all heat transfer entering the nodes; or in other words, it is a perfect insulator. So that adiabatic boundary conditions do not affect the solution, they must be taken far enough away from the GLHE tube so that they have no influence on the computed results. This means that the outer soil radius must be far enough to not interfere with the heat flow occurring in the tube and ground, yet minimized to reduce the computation time, as discussed by Gross (Gross, 2011). A unique aspect of GEO3D is the inclusion of ground surface heat transfer. It is believed that this is going to prove important in horizontal GLHE design. The program includes ground surface heat transfer for both the horizontal and vertical loops, but the entire tube is so much closer to the surface in horizontal designs than vertical designs. To determine the ground surface heat transfer a surface heat transfer coefficient is calculated that includes the effects of the outdoor temperature and wind speed.

### 5.2.1 Horizontal GLHE Boundaries

For a horizontal GLHE, the boundary condition along the outer radius is made so that  $\frac{dT}{dr} = 0$  (see Figure 5.5). This is done for the entire outer radius surface that is under the ground surface. For the portion of the outer radial surface that resides above ground a convective boundary condition is used,

$$-k \frac{\partial T}{\partial r} = h(T_s - T_\infty) \quad (5.4)$$

The technique used to determine the heat transfer coefficient, in this equation is described section 5.2.3. At the inner radius a symmetry boundary condition is used,  $\frac{dT}{dr} = 0$ , which is the same as an adiabatic boundary condition. Similarly, the half circle ends at  $z = 0$  and  $z = L$  are set to  $\frac{dT}{dz} = 0$ , with the exception of the fluid inlet, which is set to the exiting fluid temperature from the program's heat pump model. For the first time step the inlet fluid temperature is set equal to the ground temperature. The boundary conditions for the areas that divide the model for symmetry in the azimuthal direction at  $\theta = 0$  and  $\theta = \pi$  are  $\frac{dT}{d\theta} = 0$ . Thus it can be seen that most boundary conditions are taken as being adiabatic with the exception of the ground surface and the inlet fluid. The temperature of the inlet fluid is the primary driver of this transient heat transfer problem.



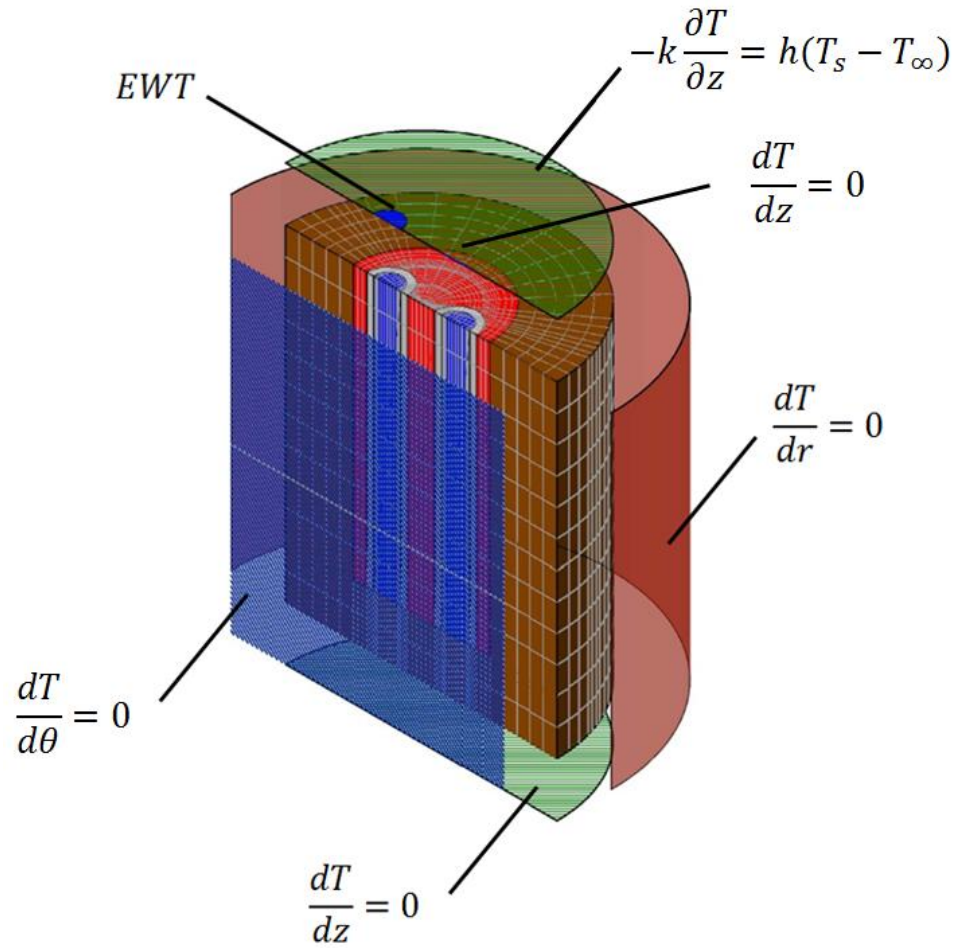
**Figure 5.5:** The boundary conditions used for a horizontal GLHE in GEO3D.

## 5.2.2 Vertical GLHE Boundaries

Like the horizontal GLHE, the boundary condition along the outer radius for a vertical GLHE is set to  $\frac{dT}{dr} = 0$  (see Figure 5.6), except this time the outer radial boundary does not intersect with the ground surface; an axial surface does this. Thus the entire outer radial surface is taken as adiabatic. Note that the vertical GLHE computational domain is rotated 90° relative to the ground when compared to the horizontal loop GLHE. At the inner radius a symmetry boundary condition is used,  $\frac{dT}{dr} = 0$ , is used. The axial surfaces for the vertical computational domain are located at  $z = 0$  and  $z = L$ . The surface at  $z = L$  uses the adiabatic boundary condition,  $\frac{dT}{dz} = 0$ . The surface at  $z = 0$  is the ground surface and uses the convective boundary condition

$$-k \frac{\partial T}{\partial z} = h(T_s - T_\infty) \quad (5.5)$$

for all non-fluid areas. The area where the working fluid enters the GLHE is given the temperature of fluid exiting the heat pump. For the first time step this temperature is set equal to the ground temperature. The area where the fluid leaves the GLHE the boundary condition  $\frac{dT}{dz} = 0$  is used. The boundary conditions for the areas that divide the model for symmetry in the azimuthal direction at  $\theta=0$  and  $\theta = \pi$ , are  $\frac{dT}{d\theta} = 0$ .



**Figure 5.6:** The boundary condition for a vertical GLHE in GEO3D.

### 5.2.3 Surface Heat Transfer Coefficient Determination

A subroutine in FORTRAN is used to calculate the heat transfer coefficient for each time step for a year's time. First, calculation of a Richardson number is executed and can be expressed as

$$Ri = \frac{g(T_{amb}-T_s)}{T_K \cdot u^2} \frac{(z_0 \cdot z)^{1/2}}{\ln\left(\frac{z}{z_0}\right)} \quad (5.6)$$

where  $T_{amb}$  is the outside dry bulb temperature in (°C) or (°F),  $T_s$  is the yearly average surface temperature in (°C) or (°F),  $T_K$  is the mean temperature between  $z$  and  $z_0$  in (°C) or (°F),  $z_0$  is the roughness height of the ground surface in ( $m$ ) or ( $ft$ ), and  $z$  is the height of the wind speed measurement in ( $m$ ) or ( $ft$ ) (Stathers, Black, & Novak, 1985). From there, a neutral stability momentum transfer coefficient is calculated by

$$D_m = \frac{\kappa^2 \cdot u_w}{\left(\ln\left(\frac{z}{z_0}\right)\right)^2} \quad (5.7)$$

where  $\kappa$  is the von Karman constant and  $u_w$  is the local wind speed in  $\left(\frac{m}{s}\right)$  or  $\left(\frac{ft}{s}\right)$  (Deru, 2003). The stability correction relationship from Jensen (1973) is calculated and can be expressed as

$$D_h = D_m(1 - 16R_i)^{0.75}, \text{ for } R_i \leq 0 \quad (5.8)$$

or

$$D_h = D_m(1 + 10R_i)^{-1}, \text{ for } R_i > 0 \quad (5.9)$$

Utilizing these quantities, the forced heat transfer coefficient is calculated using

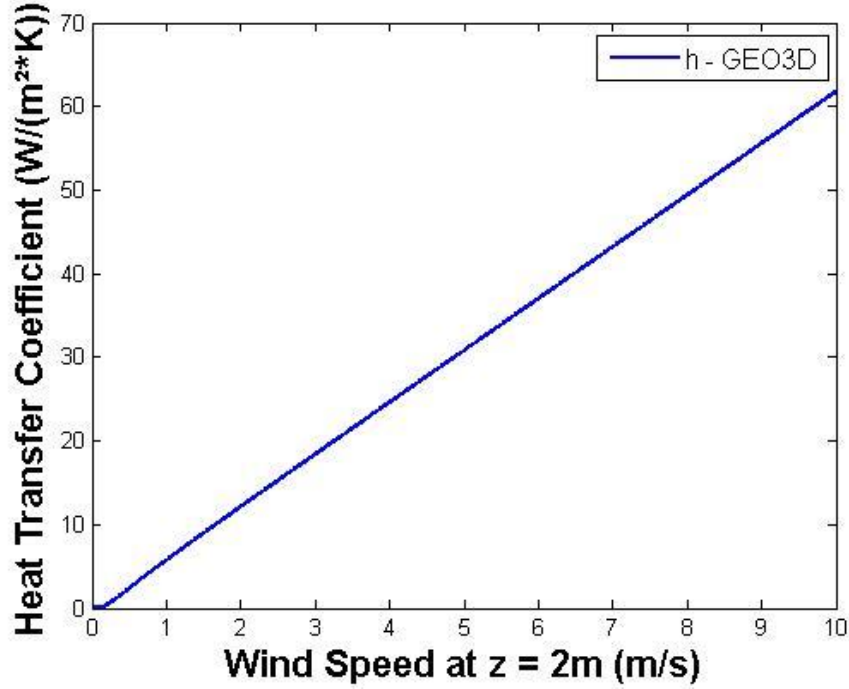
$$h_f = \rho_{air} \cdot C_{p_{air}} \cdot D_h \quad (5.10)$$

and the natural heat transfer coefficient is calculated as

$$h_n = 0.15 \cdot k_{air} \left( \frac{g(T_s - T_{amb})}{T_K \cdot \nu \cdot \alpha} \right)^{1/3} \quad (5.11)$$

Finally, the surface heat transfer coefficient is calculated by

$$h = (h_f^4 + h_n^4)^{1/4} \quad (5.12)$$



**Figure 5.7:** The heat transfer coefficient produced by GEO3D with changing wind speeds,  $(T_{amb} - T_s) = 10$  (°C) and  $z_0 = 0.0075$  (m).

The heat transfer coefficient produced by GEO3D with wind speeds increasing from  $0 \left( \frac{m}{s} \right)$  to  $10 \left( \frac{m}{s} \right)$  is shown in Figure 5.7. The results are comparable to those produced by Jensen (Deru, 2003). The heat transfer coefficients calculated are stored in a matrix and are called in later subroutines to accurately simulate the effects of ground surface heat transfer in GEO3D.

# Chapter 6

## Summary

Since 2010, Wright State University has been developing a GLHE sizing program called, GEO2D. GEO2D gives the modeler a user friendly GUI to easily model the GLHE desired. Additionally, heating and cooling loads are calculated from EnergyPlus for a building designed by the modeler. The heat transfer analysis, performed by FORTRAN, uses a transient, two-dimensional, finite volume technique to accurately predict the ground temperature and heat transfer rates at any time. GEO2D has been developed and Wright State is currently in the process of developing GEO3D. GEO3D extends GEO2D to three dimensions and gives the Wright State geothermal program the ability to handle both horizontal and vertical GLHE. In addition, GEO3D allows the program to handle heat transfer between the ground surface and the air.

The objective of this work has been the support of the development of GEO2D and GEO3D. This work has done this in a number of ways. First, this work performed a detailed literature search of the work that has been done in GLHE modeling. Second, this work has done a detailed description of the commercial codes currently available for analyze and design GLHEs. In particular, this work has checked the g-function method against GEO2D. Essentially any commercial code of significance has been discussed in this thesis. Next, this work has developed the subroutines for producing three-dimensional grid systems for both a horizontal and vertical GLHE for use in GEO3D. Lastly, this work has developed computer code for the boundary conditions and material property allocation used in GEO3D.

The commercial programs available today lack useful outputs such as heat pump COP's or temperature fields surrounding the heat exchanger; this is due to the heat transfer method used by these programs. Most GLHE sizing programs use a short time-step g-function to simulate the heat transfer. Although quick at generating results, this method has been proven to produce errors. Chapter 2 discusses Eskilson's long time-step g-function (Eskilson, 1987) in detail and current modifications to it. To check the accuracy of the g-function technique, this work wrote a program to analyze a GLHE using Eskilson's g-function technique. Results from the g-function technique were directly compared to results from GEO2D. For a constant heat extraction rate from the ground the g-function produces results that differ from those of GEO2D by more than 0.5 ( $^{\circ}\text{C}$ ). For a realistic heating and cooling load for a Dayton, Ohio area home, results show that the long time-step g-function does not account for peak heating and cooling loads, which can lead to under sizing of a GLHE system.

This work discusses six commercial GLHE programs available today. These are: GS2000, RETScreen, Earth Energy Designer, GLHEPRO, GLD2000, and TRNSYS. All of the programs, except RETScreen, use or have an option to use Eskilson's g-function method. RETScreen concentrates on the economics portion of all renewable energies and neglects the heat transfer accuracy needed for a GLHE. Earth Energy Designer and GLHEPRO solely use Eskilson's g-function. GS2000 uses the line source method for a horizontal GLHE and the g-function for a vertical GLHE. GLD2000 offers the most complete geothermal analysis package. A built in heat load calculator predicts the heating and cooling load and uses the cylindrical source method and g-function calculation to simulate the heat transfer in the ground. TRNSYS proposes the most detailed renewable energy analysis program. The geothermal portion of the program can use a numerical heat transfer calculation or a g-function calculation for the ground loop heat exchanger. A number of additions can be added to the system including solar panels and supplemental heat and cooling towers. When these programs are compared to GEO2D, they all lack in at least one area of: heat transfer analysis, user friendliness and/or useful outputs. The present 2-dimensional, transient, finite difference, heat

transfer technique used in GEO2D offers a quick and accurate solution. The prestigious heat load calculator, EnergyPlus, forecasts the hourly loads for any building designed by the user. Furthermore, the easy to use graphical user interface in Matlab provides a number of useful outputs including: heating and cooling loads, COP's, temperature profiles, EWT, and energy loads.

A limitation of GEO2D is that it cannot accurately represent the near field of a vertical GLHE due to the U-tube arrangement for the fluid flow. The U-tube arrangement causes the round tubes to be off the centerline of the computational domain. This creates an azimuthal component in the heat transfer and temperature field. To handle this Wright State is developing a three-dimensional GLHE program called GEO3D. Going from two-dimensions to three-dimensions causes a great increase in the gridding routine used in the program. A proper grid that handles the different material regions was developed as part of this thesis work. This gridding scheme allows non-uniform grid spacing in each of the different material regions. The amount of non-uniformity is controlled by the user. Because three-dimensional cylindrical gridding system is used, the round cross sections of the U-tube are modeled with a stepping routine. Thus, the circular tubes are replaced with jagged edge circular control volumes. This is not a perfect way to perform this modeling, but is very satisfactory. This problem does not exist with the horizontal GLHE because the heat exchanger tube centerline lies on the centerline of the computational domain.

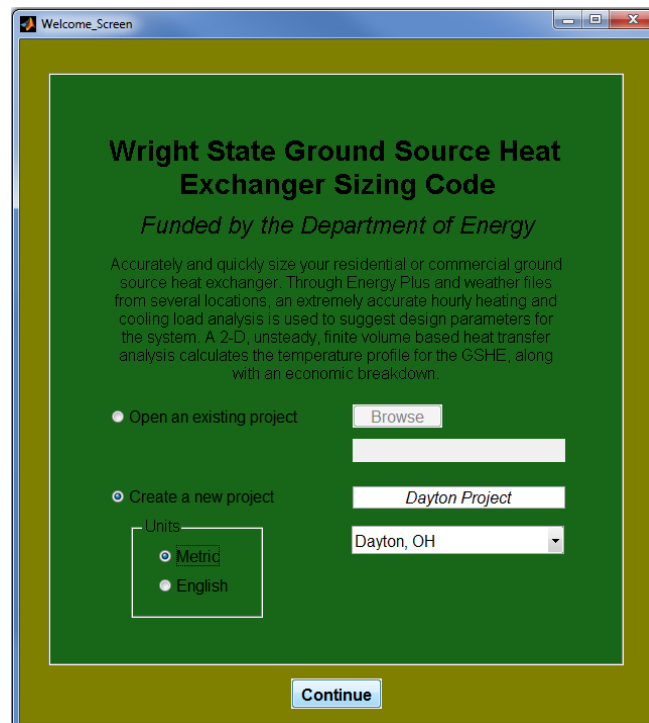
Going to this three-dimensional grid arrangement provides another advantage in GEO3D compared to GEO2D. GEO3D is able to model ground surface heat transfer. One of the objectives of this work was to implement the three-dimensional boundary conditions in GEO3D. While most of the boundary conditions in GEO3D are adiabatic boundary conditions the ground boundary condition required switching to a convective boundary condition and determining an air to ground heat transfer coefficient. The air to ground heat transfer coefficient used in this work includes both forced and natural convection between the ground surface and the air. For the horizontal GLHE model the

implementation of the ground convective boundary condition meant that any portion of the computational domain above the ground surface had to take on a thermal conductivity of  $10^6$  (W/m-K). This large thermal conductivity naturally brings the ground thermal conductivity from the outer radius of the computational domain to the correct location of the ground. It should be mentioned that because of the cylindrical gridding system used the ground does have a jagged shape to it. Lastly it was the mandate of this thesis work to apply proper material properties to all material regions in GEO3D. This was done.

Overall this thesis work was an important step in the development of GEO2D and in the development of GEO3D. It is believed that these are two of the better GLHE computer program available today. Of course there is still some work to finish GEO3D, but GEO2D is done and has produced a number of useful results at this time.

# Appendix A

## GUI Description



**Figure A.1:** The welcome screen used by GEO2D.

The 'Welcome\_Screen' GUI provides a welcome screen for the user that gives an overview of the program. The welcome screen also prompts the user to open an existing project or to create a new project. Also, if the user selects a new project, they must select a project name, the units to be used throughout the project and the city to simulate.

The screenshot shows a software window titled "Building\_Specifics" with a green background. It contains several panels for inputting building details:

- Floor Area = 120 m²**: A dropdown menu set to "Rectangle" and a diagram of a rectangle labeled "Area 1" with "Length" and "Width" dimensions.
- Air Infiltration**: Four radio button options:
  - ☒ Tightly Sealed (0.35 ACH)
  - ☐ Moderately Sealed (0.65 ACH)
  - ☐ Somewhat Drafty (0.95 ACH)
  - ☐ Very Drafty (1.25 ACH)
- Windows, Doors, and Ceiling Height**: A table-like structure with two columns for input.
 

| Parameter       | Value | Area | Unit |
|-----------------|-------|------|------|
| # of Window 1   | 4     | 2.8  | m²   |
| # of Window 2   | 2     | 2    | m²   |
| # of Window 3   | 5     | 1.6  | m²   |
| # of Ext. Doors | 2     | 2.44 | m    |
- Construction**: Two dropdown menus. The first is set to "1/2\" wood siding, 1/2\" plywood, 2x6 w...". The second is set to "R-13, 2x6 wood studs, gypsum board".
- Area 1**: Two input fields: "Length" with value "10" and "Width" with value "12", both in meters.
- Ground Condition**: Four radio button options:
  - ☐ Conditioned Basement
  - ☐ Unconditioned Basement
  - ☒ Concrete Slab
  - ☐ Crawl Space
- Thermostat Settings**: Two columns for "Winter Setting" and "Summer Setting".
 

| Setting | Winter Setting | Summer Setting |
|---------|----------------|----------------|
| Day     | 21 °C          | 25 °C          |
| Night   | 21 °C          | 25 °C          |
- Second Floor**: A radio button option that is currently unselected.
- Continue**: A button at the bottom center of the window.

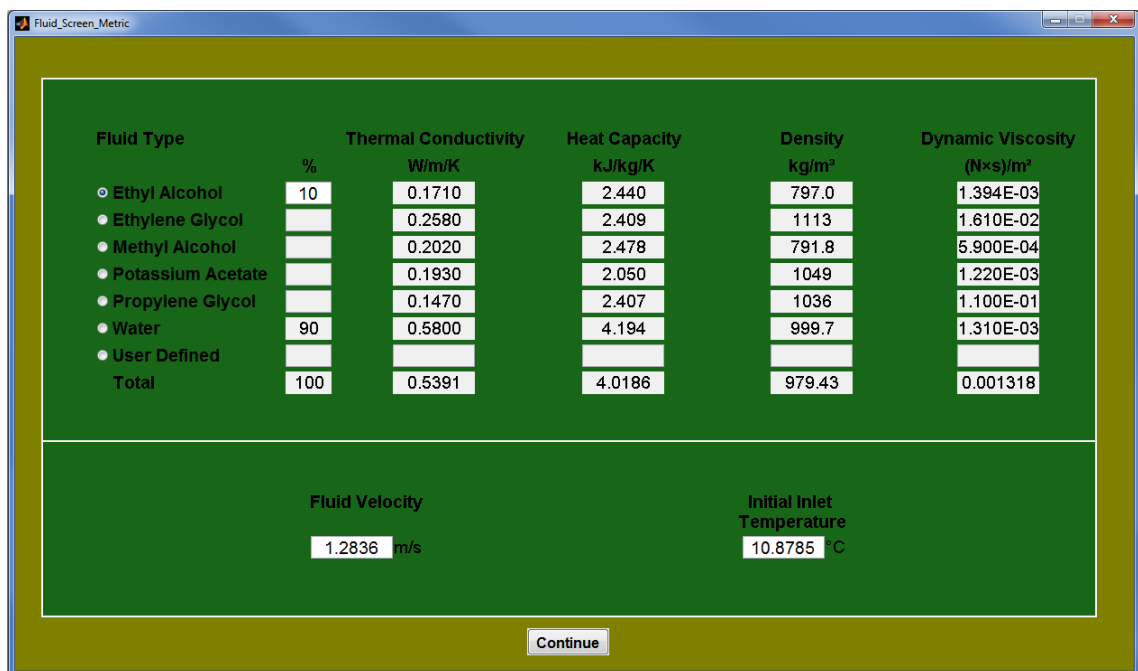
**Figure A.2:** The novice user GUI used to design the building.

The GUI executes a simple heating and cooling load calculation for the designed building in the previously specified location. The program prompts the user for building geometry and dimensions, inside thermostat temperature, total area of doors and windows, insulation type and building construction properties, and air infiltration. After completion, the user must select 'Continue', causing execution of EnergyPlus.



**Figure A.3:** The heat pump selection menu following EnergyPlus simulation.

The GUI displays the recommended heat pump size based on the max heating and cooling load provided by EnergyPlus. The max heating and cooling loads are displayed for the user to view. A drop down menu with all the heat pump capable of modeling is provided for the user to select from.



**Figure A.4:** The fluid selection screen in GEO2D.

The 'Fluid\_Screen\_Metric' GUI displays various fluids for a GLHE. Upon selection, the user must specify the percent of antifreeze/water mixture. Also, a suggested fluid velocity and initial fluid inlet temperature is given, but can be adjusted by the user. The suggested fluid velocity is determined by the recommence flow rate for the heat pump previously selected by the user. The recommended initial inlet temperature comes from the average outdoor temperature of the selected location.

The screenshot shows a window titled 'Pipe\_Screen\_Metric' with a green background. It contains two tables for selection. The first table lists pipe materials with their thermal conductivity, heat capacity, and density. The second table lists nominal pipe sizes with their outer diameter, wall thickness, and inner diameter. A 'Continue' button is at the bottom.

| Pipe Material                                 | Thermal Conductivity<br>W/m/K | Heat Capacity<br>kJ/kg/K | Density<br>kg/m³ |
|-----------------------------------------------|-------------------------------|--------------------------|------------------|
| <input checked="" type="radio"/> Polyethylene | 0.2833                        | 0.3200                   | 58.74            |
| <input type="radio"/> Polybutylene            | 0.0734                        | 0.4681                   | 81.77            |
| <input type="radio"/> Copper                  | 231.8                         | 0.0920                   | 559.3            |
| <input type="radio"/> User Defined            |                               |                          |                  |

| Nominal Size                        | Outer Diameter<br>mm | Wall Thickness<br>mm | Inner Diameter<br>mm |
|-------------------------------------|----------------------|----------------------|----------------------|
| <input type="radio"/> 15            | 21.340               | 2.769                | 15.799               |
| <input checked="" type="radio"/> 20 | 26.670               | 2.870                | 20.930               |
| <input type="radio"/> 25            | 33.401               | 3.378                | 26.645               |
| <input type="radio"/> 32            | 42.164               | 3.556                | 35.052               |
| <input type="radio"/> 40            | 48.260               | 3.683                | 40.894               |
| <input type="radio"/> 50            | 60.325               | 3.912                | 52.502               |
| <input type="radio"/> 80            | 88.900               | 5.486                | 77.927               |
| <input type="radio"/> 100           | 114.300              | 6.020                | 102.260              |
| <input type="radio"/> 125           | 141.300              | 6.553                | 128.194              |
| <input type="radio"/> 150           | 168.275              | 7.112                | 154.051              |
| <input type="radio"/> User Defined  | 26.670               | 2.870                | 20.930               |

Continue

**Figure A.5:** GEO2D's pipe material and dimensions selection.

The 'Pipe\_Screen\_Metric' GUI provides various pipe materials and dimensions for a GLHE. The user must first select a material or input the thermal properties for a user defined pipe material. From there, pipe dimensions for the corresponding pipe are displayed for the user to select, or the user can again input user defined dimensions. Also, recommended dimensions are displayed for the user. These dimensioned are determined from the heat pump sized previously selected by the user.

| Soil Type                                           | Thermal Conductivity<br>W/m/K | Heat Capacity<br>kJ/kg/K | Density<br>kg/m³ |
|-----------------------------------------------------|-------------------------------|--------------------------|------------------|
| <input type="radio"/> Sandy Soil (Dry)              | 1.3                           | 3.385                    | 800.0            |
| <input type="radio"/> Sandy Soil (Moist)            | 2.5                           | 2.480                    | 1200             |
| <input type="radio"/> Sandy Soil (Wet)              | 2.8                           | 1.720                    | 1480             |
| <input type="radio"/> Silty Loam (Dry)              | 0.6                           | 2.322                    | 680              |
| <input checked="" type="radio"/> Silty Loam (Moist) | 1.3                           | 1.814                    | 1280             |
| <input type="radio"/> Silty Loam (Wet)              | 2.3                           | 2.285                    | 1480             |
| <input type="radio"/> Silty Clay (Dry)              | 0.4                           | 1.082                    | 1120             |
| <input type="radio"/> Silty Clay (Moist)            | 0.8                           | 0.7440                   | 2240             |
| <input type="radio"/> Silty Clay (Wet)              | 1.1                           | 0.8247                   | 2340             |
| <input type="radio"/> User Defined                  |                               |                          |                  |
| <input type="checkbox"/> Grout                      |                               |                          |                  |

Continue

**Figure A.6:** The soil type and thermal properties.

The 'Soil\_Type\_Metric' GUI displays various soil and their corresponding thermal properties. The user must simply select their desired soil and continue. A grout option is also available.

| Loop Type                                               | Length of Pipe (m) | Depth of Borehole (m) | Diameter of Borehole (m) | Number of Boreholes |
|---------------------------------------------------------|--------------------|-----------------------|--------------------------|---------------------|
| <input checked="" type="radio"/> Horizontal Closed Loop | 305                | 2                     | 0.18669                  | 4                   |
| <input type="radio"/> Vertical Closed Loop              |                    | 50                    |                          |                     |
| <input type="radio"/> Pond Closed Loop                  |                    |                       |                          |                     |
| <input type="radio"/> Vertical Open Loop                |                    |                       |                          |                     |

Continue

**Figure A.7:** The loop type selection screen in GEO2D.

The 'Loop\_Configuration\_Metric' GUI provided the user with 4 ground heat exchanger options. Currently, only an horizontal and vertical loop can be modeled. After selection of the GLHE type, the user must enter geometries dimensions. Suggested dimensions are provided for the user.

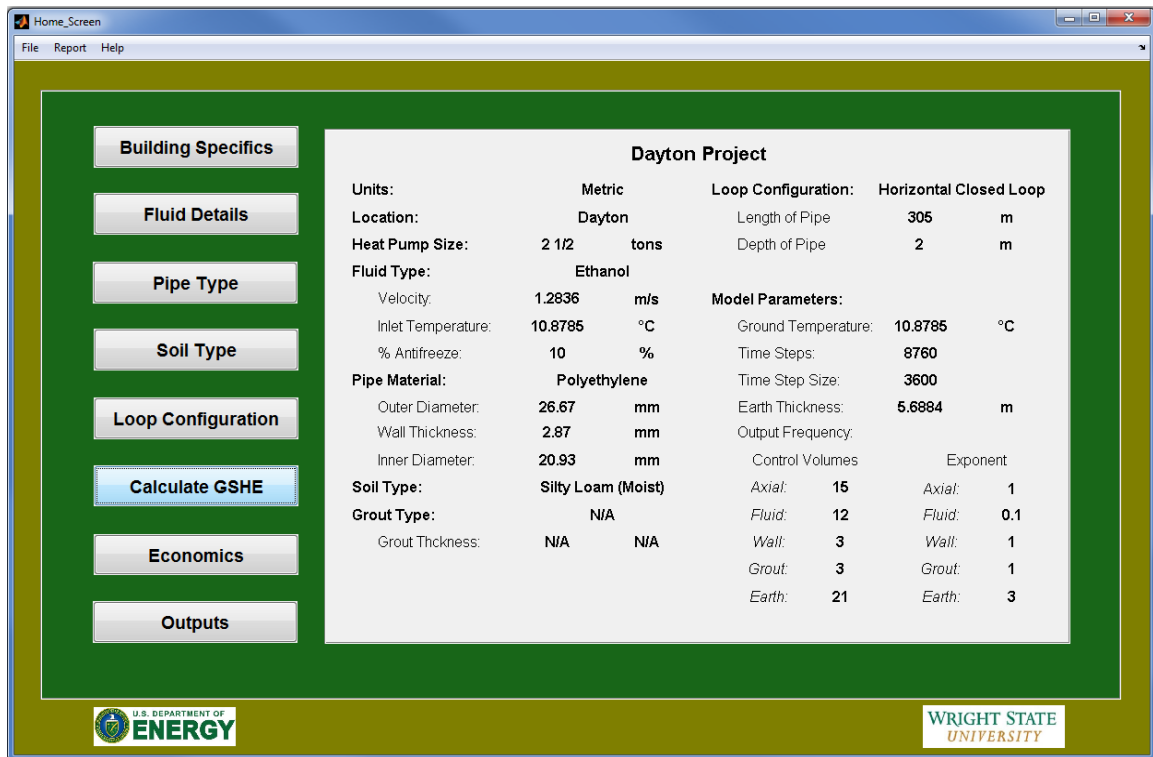
The screenshot shows a window titled 'Soil\_Properties\_New\_2' with a green background. It contains three columns of input fields:

| Other Simulation Details               |            | Number of Control Volumes |    | Grid Exponent |     |
|----------------------------------------|------------|---------------------------|----|---------------|-----|
| Ground Temperature                     | 10.8785 °F | Fluid                     | 12 | Fluid         | 0.1 |
| No. of Time Steps                      | 8760       | Pipe Wall                 | 3  | Pipe Wall     | 1   |
| Time Step Size                         | Hourly     | Grout                     | 3  | Grout         | 1   |
| Output Frequency                       | Daily      | Soil                      | 21 | Soil          | 3   |
| Soil Thickness<br>(Boundary Condition) | 5.6884 m   | Axial                     | 15 | Axial         | 1   |

At the bottom center of the window is a 'Continue' button.

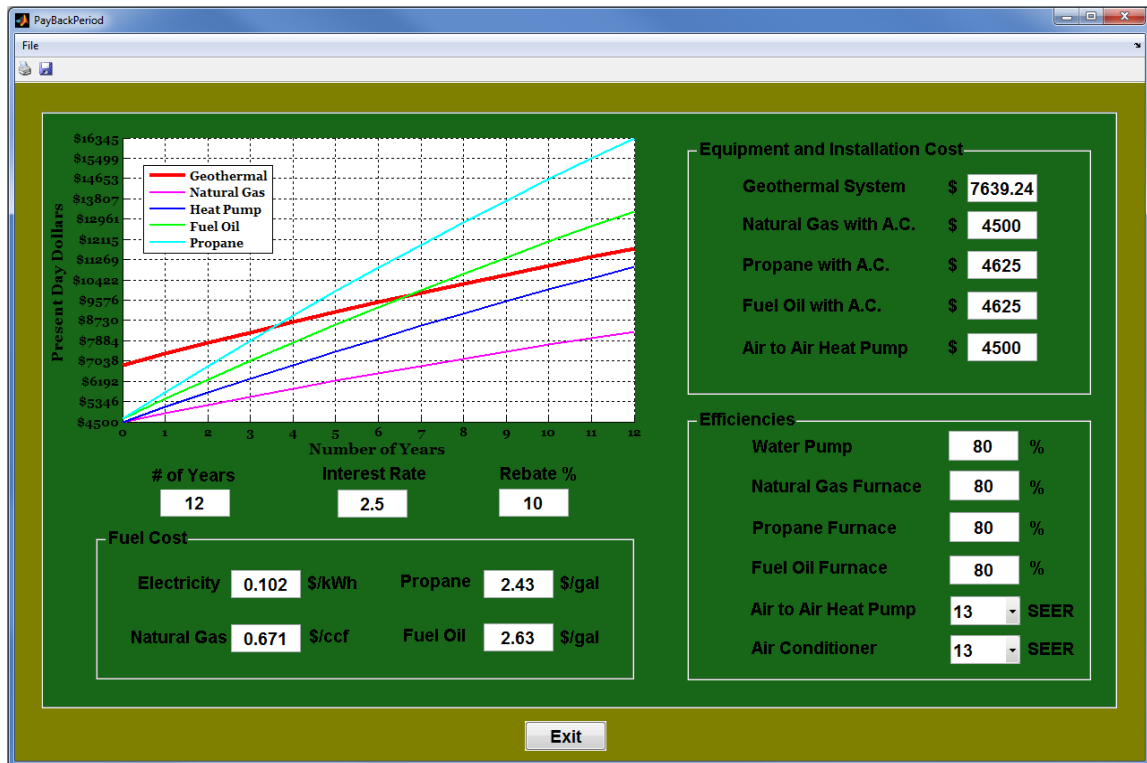
**Figure A.8:** Inputs for ground temperature, time steps, number of grids and grid exponents.

The 'Soil\_Properties\_New\_2' GUI is the final step before sending the text file to FORTRAN. The GUI prompts the user for the initial ground temperature, the number of time steps to simulate, the size of each time step, the output frequency and the far field radius of the soil. A function for the far field radius, and number of control volumes and their grid exponent was determined to reduce computation time while maintaining accuracy of the simulation. The user can change these recommended values.



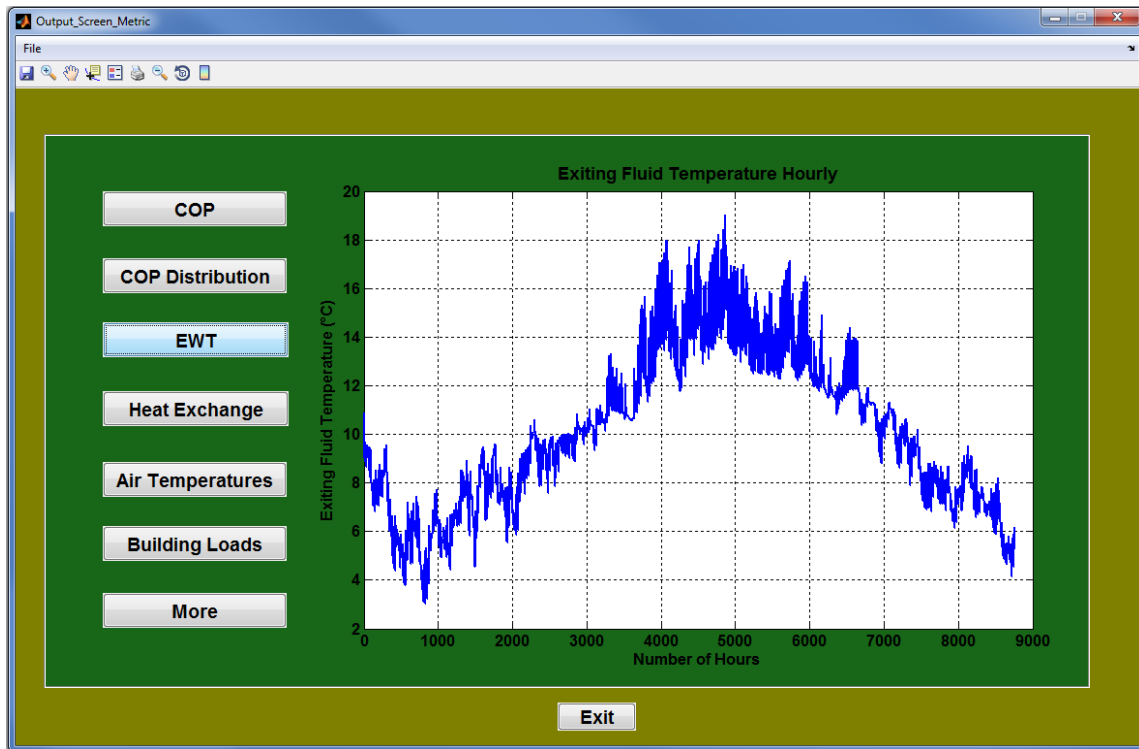
**Figure A.9:** GEO2D's home screen GUI, which displays current GLHE selections.

The 'Home\_Screen' GUI allows the user to easily select other GUI programs that design the overall GLHE. These programs are executed upon selection of their corresponding push button. The push buttons included in the GUI include: Building Specifics, Fluid Details, Pipe Type, Soil Properties, Loop Configuration, Calculate GSHE, Economics and Outputs. The push buttons are enabled or disabled, depending on the priority of the GLHE modeling. Also, 'Home\_Screen' displays the properties selected by the user. Additionally, the GUI provides a 'File' menu to open a project, create a new project or close the GUI. A report menu is also available to view the details of the project in a text file.



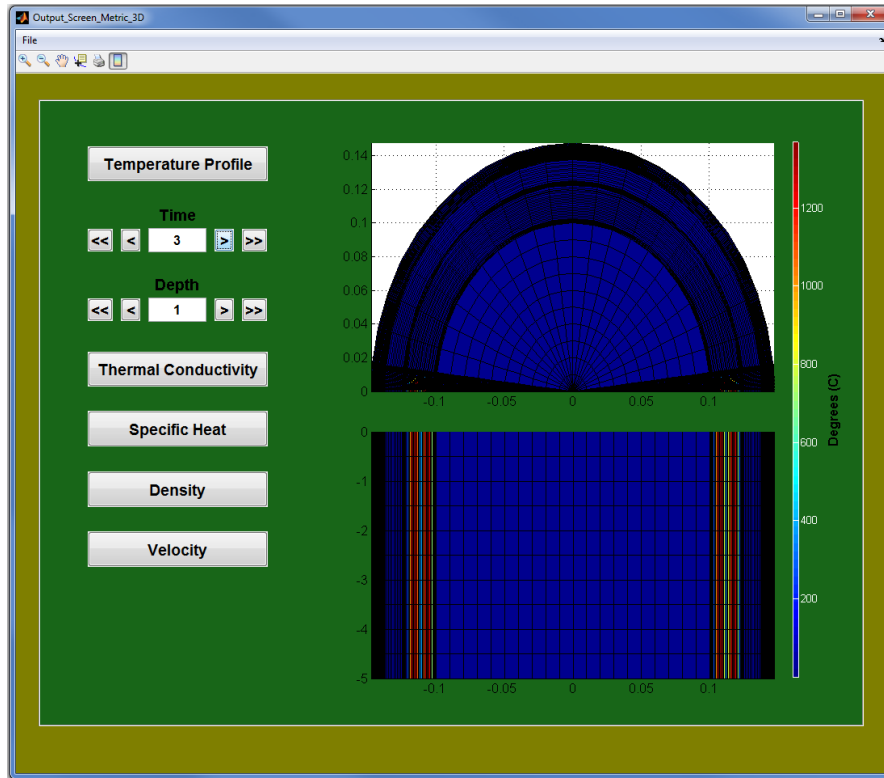
**Figure A.10:** The economics screen used by GEO2D.

The 'PayBackPeriod' GUI provides an economic illustration of 5 heating and air conditioning methods. Values for the installation cost, efficiencies of the systems, fuel costs, interest rate, rebate rate and the time period to evaluate are given. The user can change these values to get a more accurate simulation.



**Figure A.11:** The six different outputs capable of displaying in GEO2D.

The GUI displays COP's, COP distribution, entering water temperatures, heat exchange, air temperatures, building loads and an option to view the 3D temperature fields and thermal property fields. A graph representing the user's selection is shown.



**Figure A.12:** The temperature profile and thermal property GUI used by GEO3D.

The GUI displays temperature fields and thermal property fields. The temperature fields can be viewed at different times and depths. Thermal conductivity, specific heat, density and velocity profiles can be viewed also.

# Appendix B

## GUI Project Report

```

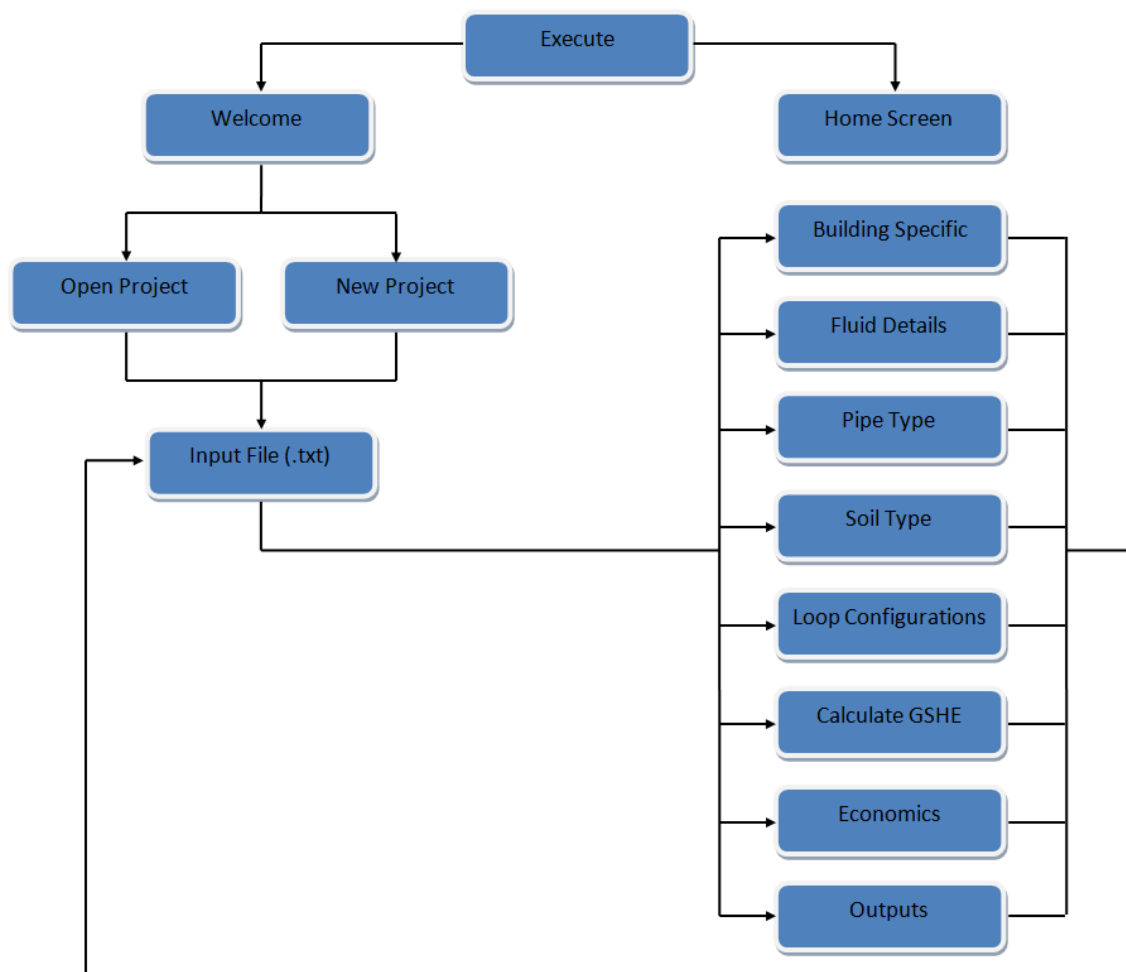
report.txt - Notepad
File Edit Format View Help
***** Project Report *****
*****
Units:
Location: Dayton, OH
Heat Pump Size: 3 (tons)
*****
***** Fluid Properties *****
*****
Fluid Type: Ethylene Glycol
Fluid Velocity: 1.2438 (m/s)
Fluid Inlet Temperature: 10.879 (°C)
Antifreeze: 20 (%)
Fluid Dynamic Viscosity: 0.004268 ((Nxs)/m²)
Fluid Thermal Conductivity: 0.5156 (w/m/K)
Fluid Heat Capacity: 3.837 (kJ/kg/K)
Fluid Density: 1022.4 (kg/m³)
*****
***** Pipe Properties *****
*****
Pipe Material: User Defined
Pipe Outer Diameter: 26.67 (mm)
Pipe Thickness: 2.87 (mm)
Pipe Inner Diameter: 20.93 (mm)
Pipe Thermal Conductivity: 0.5 (w/m/K)
Pipe Heat Capacity: 2.1 (kJ/kg/K)
Pipe Density: 900 (kg/m³)
*****
***** Soil Properties *****
*****
Soil Material: Silty Loam (Moist)
Soil Thermal Conductivity: 1.3 (w/m/K)
Soil Heat Capacity: 1.814 (kJ/kg/K)
Soil Density: 1280 (kg/m³)
*****
***** Grout Properties *****
*****
Grout Material: N/A
Grout Thickness: N/A N/A
Grout Thermal Conductivity: N/A N/A
Grout Heat Capacity: N/A N/A
Grout Density: N/A N/A
*****
***** Loop Details *****
*****
Loop Configuration: Horizontal Closed Loop
Length of Pipe: 183.7 (m)
Depth of Pipe: 3 (m)
*****
***** Loop Model *****
*****
Initial Ground Temperature: 10.879 (°C)
Number of Time Steps: 8
Time Step Size: 86400
Earth Thickness: 1280 (m)
Control Volumes in Axial: 15
Control Volumes in Fluid: 9
Control Volumes in Wall: 3
Control Volumes in Grout: 3
Control Volumes in Earth: 11
Exponent in Axial: 1
Exponent in Fluid: 0.1
Exponent in Wall: 1
Exponent in Grout: 1
Exponent in Earth: 3

```

**Figure B.1:** The project report generated by GEO2D.

# Appendix C

## GUI Flow Chart



**Figure C.1:** A flow chart representation of GEO2D.

# Appendix D

## FORTRAN Input File

```

Input_gshte.txt - Notepad
File Edit Format View Help
3.600000e+003 !Time step size in seconds
8760 !Number of time steps
3.050000e+002 !Length of tube in axial direction in m
1.046500e-002 !Thickness of fluid or inner tube radius in m
2.870000e-003 !Tube wall thickness in m
5.688400e+000 !Earth Thickness in meters
15 !Number of control volumes in axial direction
12 !Number of control volumes in fluid in radial direction
3 !Number of control volumes in wall in radial direction
21 !Number of control volumes in earth in radial direction
1.000000e+000 !Grid variability in the axial direction
1.000000e-001 !Grid variability in the fluid in the radial direction
1.000000e+000 !Grid variability in the tube wall in the radial direction
3.000000e+000 !Grid variability in the earth in the radial direction
5.391000e-001 !Thermal conductivity of the fluid in w/m-c
4.018600e+003 !Specific heat of the fluid in J/kg-c
9.794300e+002 !Density of the fluid in kg/m^3
1.318400e-003 !Dynamic viscosity of the fluid in N-s/m^2
2.833000e-001 !Thermal conductivity of the tube wall in w/m-c
3.200000e+002 !Specific heat of the tube wall in J/kg-c
5.874000e+001 !Density of the tube wall in kg/m^3
1.300000e+000 !Thermal conductivity of the earth in w/m-c
1.814000e+003 !Specific heat of the earth in J/kg-c
1.280000e+003 !Density of the earth in kg/m^3
1.283600e+000 !Mean fluid velocity in m/s
1.087850e+001 !Fluid inlet temperature in C
1.087850e+001 !Earth temperature in C
-5.987200e+003 !Coeff (1,1) for cooling capacity
4.279900e+005 !Coeff (1,2) for cooling capacity
-1.242500e+007 !Coeff (1,3) for cooling capacity
5.675900e+000 !Coeff (2,1) for cooling capacity
-4.245600e+002 !Coeff (2,2) for cooling capacity
1.397500e+004 !Coeff (2,3) for cooling capacity
-2.768500e-003 !Coeff (3,1) for cooling capacity
-5.109000e-002 !Coeff (3,2) for cooling capacity
3.109300e+001 !Coeff (3,3) for cooling capacity
-2.195400e+002 !Coeff (1,1) for cooling power
1.609300e+004 !Coeff (1,2) for cooling power
1.008800e+006 !Coeff (1,3) for cooling power
-5.502700e-002 !Coeff (2,1) for cooling power
4.770800e+000 !Coeff (2,2) for cooling power
-1.402100e+003 !Coeff (2,3) for cooling power
3.769100e-004 !Coeff (3,1) for cooling power
2.422000e-002 !Coeff (3,2) for cooling power
1.652600e+000 !Coeff (3,3) for cooling power
6.061300e+003 !Coeff (1,1) for heating capacity
-6.846800e+005 !Coeff (1,2) for heating capacity
-1.025400e+007 !Coeff (1,3) for heating capacity
3.256200e+000 !Coeff (2,1) for heating capacity
6.652200e+002 !Coeff (2,2) for heating capacity
1.323200e+004 !Coeff (2,3) for heating capacity
1.791500e-003 !Coeff (3,1) for heating capacity
4.723500e-001 !Coeff (3,2) for heating capacity
2.052400e+001 !Coeff (3,3) for heating capacity
-5.904200e+002 !Coeff (1,1) for heating power
-1.556000e+004 !Coeff (1,2) for heating power
7.606600e+004 !Coeff (1,3) for heating power
6.800200e-001 !Coeff (2,1) for heating power
1.259400e+001 !Coeff (2,2) for heating power
3.481000e+001 !Coeff (2,3) for heating power
5.532900e-006 !Coeff (3,1) for heating power
8.786100e-003 !Coeff (3,2) for heating power
2.175700e+000 !Coeff (3,3) for heating power
-7.367500e-001 !Coeff 1 for fan cooling capacity correction factor
1.066000e+000 !Coeff 2 for fan cooling capacity correction factor
6.799900e-001 !Coeff 3 for fan cooling capacity correction factor
-2.624500e-002 !Coeff 1 for fan heating capacity correction factor
2.298000e-001 !Coeff 2 for fan heating capacity correction factor
9.091400e-001 !Coeff 3 for fan heating capacity correction factor
-3.020300e-003 !Coeff 1 for fan cooling power correction factor
-7.624300e-003 !Coeff 2 for fan cooling power correction factor
1.004000e+000 !Coeff 3 for fan cooling power correction factor
2.566500e+000 !Coeff 1 for fan heating power correction factor

```

**Figure D.1:** The text file generated by Matlab that is sent to FORTRAN for heat transfer analysis.

# Appendix E

## FORTRAN Example Subroutine

```

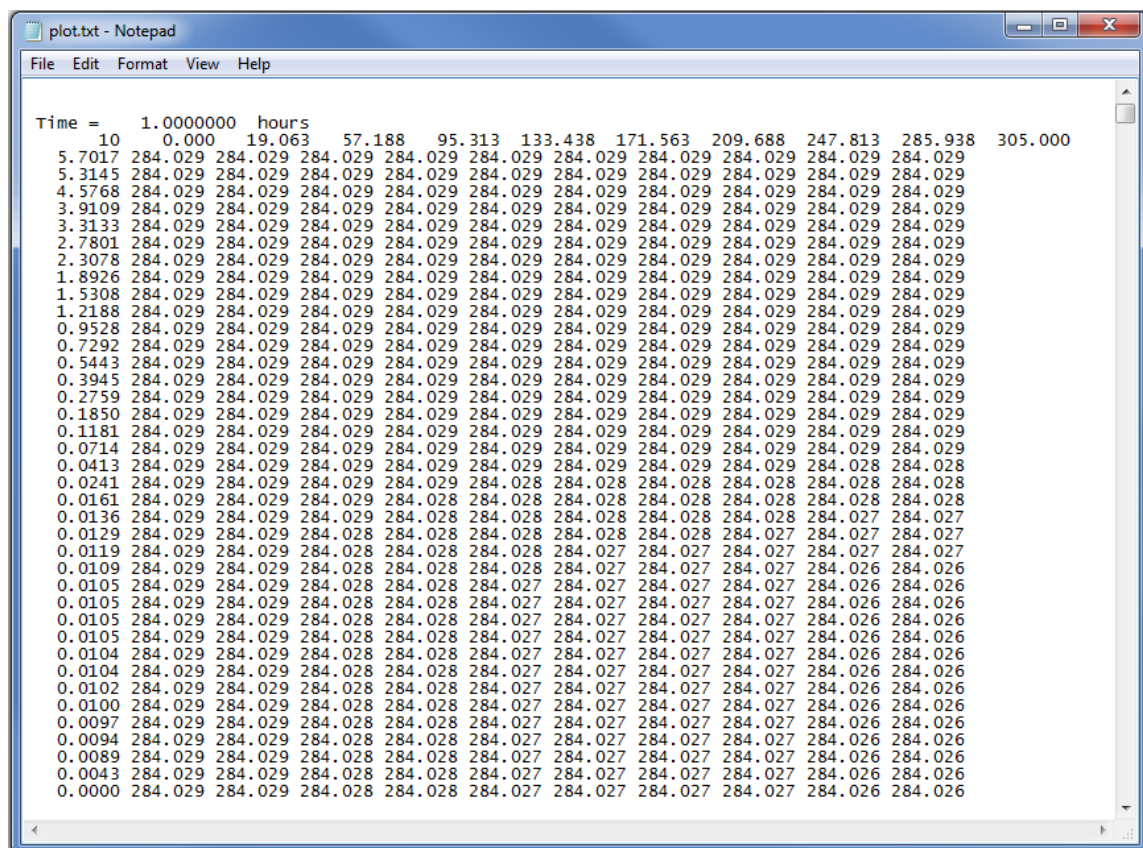
! Thermal Conductivity.
!   Fluid.
      Do i = 1,n_z,1
        Do j = 1,nf_r_shank-1,1
          Do k = 1,n_az,1
            kcond(i,j,k)=kcond_fluid+kcond_turb(j)
          End Do
        End Do
      End Do
!   Y-plus.
      Do i = 1,n_z,1
        Do j = nf_r_shank,nf_r_wall_l-1,1
          Do k = 1,n_az,1
            kcond(i,j,k)=kcond_fluid+kcond_turb(j)
          End Do
        End Do
      End Do
!   Tube wall.
      Do i = 1,n_z,1
        Do j = nf_r_wall_l,nf_r_yplus_l-1,1
          Do k = 1,n_az,1
            kcond(i,j,k)=kcond_tube
          End Do
        End Do
      End Do
!   Earth.
      Do i = 1,n_z,1
        Do j = nf_r_yplus_l,n_r,1
          Do k = 1,n_az,1
            if(r(j)*sin(az(k))<depth_tube)then
              kcond(i,j,k)=kcond_earth
            else
              kcond(i,j,k)=10**6
            endif
          End Do
        End Do
      End Do

```

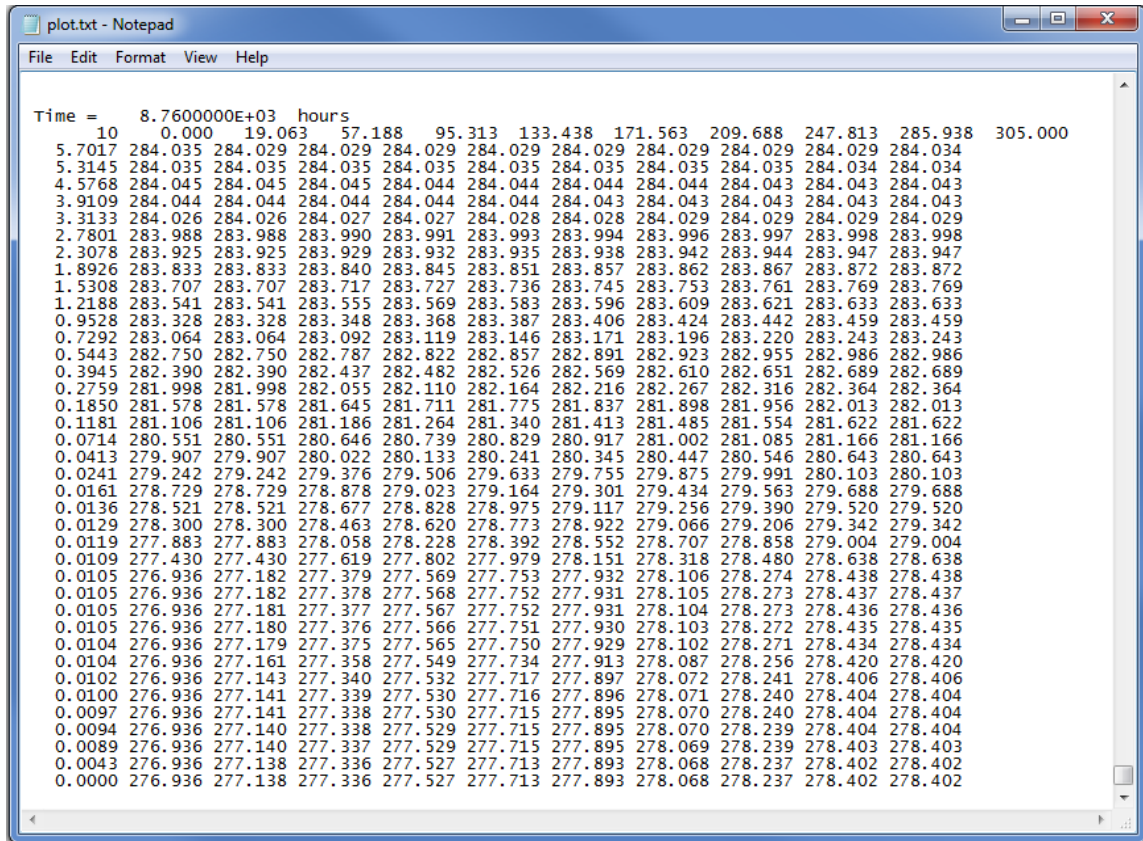
**Figure E.1:** A sample subroutine from the “SET\_FIELD\_QUANTITIES\_HORIZONTAL”.

# Appendix F

## FORTTRAN Output File



**Figure F.1:** The temperature profile produced by GEO2D, for the first hour.



**Figure F.2:** The temperature profile produced by GEO2D, at hour 8760.

# Appendix G

## g-function Program

```
% Kyle Hughes
% g-function
% 2011-10-27

clear all
close all
clc
hold on

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%*****Calculating and Plotting the g-factor*****%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
H = 600; %Borehole Depth (m)
rb = .015; %Borehole Radius (m)
a = .3; %Thermal Diffusivity (m^2/hr)
ts = H^2/(9*a); %Time Scale
t = (5*rb^2)/a:1:ts; %Array for first series of Time (hr)
g = log(H./(2.*rb))+(1/2).*log(t./ts); %First approximation for G-factor
T=log(t./ts); %Log scale for time
plot(T,g,'linewidth',2); %Plot log scale of time vs. g-factor
xlabel('ln(t/ts)','FontSize',16,'Fontweight','Bold')
ylabel('g-factor','FontSize',16,'Fontweight','Bold')
legend('\fontsize{12}g-function',2)
box on
t2 = ts:1:8760; %Array for second series of Time (hr)
g2 = log(H/(2*rb)); %Second approximation for g-factor
T2 = log(t2./ts); %Log scale for time
%%

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%***** Finding the Equation for the g-factor line *****%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
m = (g(length(g))-g(1))/(T(length(T))-T(1)); %Slope
G = m.*T+g(length(g)); %y=mx+b
%%
```

```

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%*****Inputs*****
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Q_data = dlmread('total_pipe_energyThesis_g-function.txt'); %Hourly loads
T_ground = 11.667; %Undisturbed ground temperature
k_ground = 1.5; %Thermal Conductivity of ground
Q=-Q_data/(H); %Q per length
%%

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%***** Calculating the Summation *****
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Stot = (Q(1)-0)/(2*pi*k_ground)*(m*log(1/ts)+g(length(g)));
T_borehole(1) = T_ground + Stot;
T_fluid(1) = T_ground + 2.8931*10^-6*(Q(1)*1000);
for i=2:1:8760
    j=i;
    p=2;
    while j>1
        Stot(1) = (Q(1)-0)/(2*pi*k_ground)*(m*log((i)/ts)+g(length(g)));
        Stot(p) = (Q(p)-Q(p-1))/(2*pi*k_ground)*(m*log((j-
1)/ts)+g(length(g)));
        p=p+1;
        j=j-1;
    end
    T_borehole(i) = T_ground + sum(Stot);
    T_fluid(i) = T_borehole(i)+2.8931*10^-6*(Q(i)*1000);
end
%%

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%***** Results *****
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
display(T_borehole);
figure(3)
t=1:8760;
plot(t,T_borehole,'linewidth',2);
xlabel('Time (hours)','FontSize',16,'Fontweight','Bold')
ylabel('Temperature (°C)','FontSize',16,'Fontweight','Bold')
legend('\fontsize{12}Borehole Temperature')
box on

figure(4)
Entering_Temp = dlmread('entering_fluid_temp.txt');
Exiting_Temp = dlmread('exiting_fluid_tempThesis_g-function.txt');
Average_Temp = (Entering_Temp + Exiting_Temp)/2;
hold on
hold all
plot(t,T_fluid,'linewidth',2)
plot(t,Average_Temp,'Color',[.152,.402,.164],'linewidth',2)
xlabel('Time (hours)','FontSize',16,'Fontweight','Bold')
ylabel('Temperature (°C)','FontSize',16,'Fontweight','Bold')

```

```

legend('\fontsize{12}Long time-step g-function', '\fontsize{12}GEO2D')
box on
ylim([min(Average_Temp)-2 max(Average_Temp)+2])
difference = 100*(T_fluid-Average_Temp)./Average_Temp;
figure(5)
plot(t,difference,'linewidth',2,'color','r')
ylim([0 max(difference)])
xlabel('Time (hours)', 'FontSize',16, 'Fontweight', 'Bold')
ylabel('Percent (%)', 'FontSize',16, 'Fontweight', 'Bold')
legend('\fontsize{12}Percent Difference')
box on

figure(6)
delta_T = abs(T_fluid-Average_Temp);
plot(t,delta_T,'color','r','linewidth',2)
xlabel('Time (hours)', 'FontSize',16, 'Fontweight', 'Bold')
ylabel('Temperature (°C)', 'FontSize',16, 'Fontweight', 'Bold')
legend('\fontsize{12}Temperature Difference')
box on

figure(2)
plot(t,Q_data,'color','r','linewidth',2)
xlabel('Time (hours)', 'FontSize',16, 'Fontweight', 'Bold')
ylabel('Heat Pulse (W)', 'FontSize',16, 'Fontweight', 'Bold')
legend('\fontsize{12}Heat Extraction/Rejection')
box on
ylim([0 2000])

```

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