OPEN ACCESS

2nd World Sustainability Forum
1-30 November 2012

www.wsforum.org

Article

Modelling Thermally Interacting Multiple Boreholes with Variable Heating Strength

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Abstract: Various heat transfer models are reported for vertical ground heat exchangers, and several basic analytical and numerical models of vertical heat exchangers are described and compared, and recent developments are discussed. To examine the effect of temperature rise in the soil surrounding a vertical ground heat exchanger on the performance of the ground heat pump, the heat transfer model that represents the temperature rise and heat flows outside the borehole is often coupled to the models inside the borehole via the borehole wall temperature. This temperature is an important factor that affects the heat delivery/removal strength of the system to/from the ground. In the current study, the results of a semi-analytical model that couples a model outside the borehole with one inside the borehole taking into account the transient borehole wall temperature is described. The results of this model for a constant borehole wall temperature are compared with those for a transient one with a numerical model. It is shown that transient borehole wall temperature results in more accurate temperatures for the circulating fluid flowing to the heat pump.

Keywords: geothermal energy; modeling vertical ground heat exchangers; numerical analysis; variable heat flux.

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1. Introduction

Measurements show that, below a certain depth in the ground, the temperature fluctuations observed near the surface of the ground diminish, and the temperature remains relatively constant (e.g. at about 6-42°C in various states in the US) throughout the year [1]. This is due to the high thermal inertia of soil and the time lag between the temperature fluctuations at the surface and their effect deeper in the ground.

Below a certain depth, therefore, the ground generally remains warmer than the outside air in winter and cooler in summer. The relatively cool ground may be used as a sink in summer to store the extracted heat from a conditioned space via a ground heat pump (GHP). In winter, the process may be reversed and the heat pump can extract heat from the relatively warm ground and transport it into the conditioned space. Compared to a conventional air source heat pump (ASHP), which circulates outdoor air to exchange heat, a ground heat pump exchanges heat by circulating a fluid in the ground which has a lower temperature than the outdoor air in the cooling mode and a higher temperature than the outdoor air in the heating mode. Consequently, the temperature lift across a GHP is lower than that of an air source heat pump for both heating and cooling. Thus, the efficiency of the heat pump, which depends directly on the temperature difference between the circulating fluid and the room, is enhanced for a GHP. Therefore, due to concern about greenhouse gas emissions and high energy prices, the placement of heat loops in the ground is an increasingly common practice for heating and cooling residential, commercial, institutional, recreational and industrial structures. Low temperature geothermal energy has the potential to contribute significantly to mitigating both of these problems.

1.1 Motivation and Objectives

While the use of geothermal systems is widespread, having had a revival in the 1980’s and recently, both the sustainability and impact of these systems on the environment are now being questioned. Due to their efficiency, the use of geothermal energy should be encouraged. However, little research is available to guide regulatory agencies and industry towards designs and installations that maximize their sustainability and minimize possible environmental impacts.

1.1.1 Environmental Impacts

Similar to most human activities, studies show the potential of geothermal heat exchangers for causing environmental impacts. While little research has been done regarding the impact of geothermal systems on the local environment, research on the movement of thermal plumes shows the potential for impact. Migration of thermal plumes away from these systems and changes in temperature from either closed or open loop systems or due to changes in ground water flow patterns from open-loop systems may cause undesirable temperature rises in nearby temperature-sensitive ecosystems where small temperature differences are important. For example, temperature disturbances in the ground caused by the operation of geothermal systems may result in disruption to sensitive life stages of aquatic organisms. Similar environmental effects are observed for heat loop and waterline projects (rivers and lakes) [2]. Markle and Schincariol [3] investigate the potential thermal impacts from below-water-table aggregate extraction on a cool-water stream in Southwestern Ontario, Canada which supports Brook trout and cool-water micro-invertebrates. They demonstrate the persistence of thermal plumes (persisting in an aquifer for 11 months and migration up to 250 m down gradient) and the sensitivity of the aquatic environment to very small temperature perturbations. Their results show that there is a surprisingly narrow range for spawning in cold water streams. They need to be cooled in the summer and warmed in the winter by the groundwater flow. Once the ground water temperature is affected due to the performance of ground heat exchangers, it can negatively affect the temperature of the cold water streams making these sites unsuitable for spawning. A study on the effects of thermal fluctuation on the microorganisms in the aquifers of the geothermal well field shows increases in total microbial number in aquifer samples, which correlated with the increase in temperature in the geothermal well field [4]. Moreover, counts of cultured bacteria suggested that even when no significant differences in total bacterial number were observed, there may have been changes in the types of microorganisms present in the aquifers of the geothermal well field.

What is unknown at this point is whether the environmental impacts of geothermal systems are acceptable considering the fact that they can reduce fossil fuel consumption and therefore, lower greenhouse gas emissions, and if geothermal systems can be developed in a manner that has reasonably small potential for impacting the environment.

1.1.2 Sustainability

There are also concerns that continued geothermal system development may result in undesirable effects on ground water resources. The sustainability of these systems at their design efficiency is now being questioned due to 'thermal polution' from the system itself, adjacent systems, or the urban environment. Studies from Manitoba, where the carbonate rock aquifer beneath Winnipeg has been exploited in thermal applications since 1965, indicate that in many cases these systems are not sustainable or not sustainable at the design efficiency [5-7]. In an area of the Carbonate Rock aquifer beneath Winnipeg in Manitoba, Canada, there are four systems that utilize groundwater for cooling purposes that are closely spaced. Temperatures at the production well have risen as a result of breakthrough of injected water. The results of numerical modeling also indicate that interference effects are present in three of the four systems examined in this study [6]. The influence of these systems on each other implies that these systems have a spacing that is smaller than the optimum for such systems, and indicates that there is a limit to the density of development that can occur in a given aquifer. Cases of thermal breakthrough in the aquifer have occurred in some geothermal systems.

In heating or cooling dominated climates, an annual energy imbalance is placed on the ground loop due to heating, cooling, and hot water production. For example, Manitoba has a heating dominated climate and there are concerns regarding the long term thermal performance of the ground loop. Long term thermal performance of such ground loop systems with imbalanced energy input and outputs in the ground may result in large temperature rises in the region that the loop is installed as well as the migration of thermal plumes away from these systems which might have stronger environmental impacts. Thermal imbalances could cause significant issues with a heat pump's long term sustainable performance if not properly considered at the design phase [8].

1.1.3 Thermal Interaction

Thermal disturbances in the soil associated with ground heat exchangers are likely to extend beyond property boundaries and affect adjacent properties. Therefore, with increasing interest in installing such systems in the ground and their potential dense population in coming years, procedures and regulations need to be implemented to prevent disputes between neighbours with potentially interacting systems and their possible negative effects on the performance of existing nearby systems. As stated by Ferguson [9], an analogy exists between ground water and heat flow in the ground which allows us to draw on experiences in ground water resource development and source water protection. In many ways, the problem of distributing subsurface energy rights is similar to water rights.

Careful management of geothermal developments to ensure fair access to the subsurface for thermal applications is likely needed. This will require a greater understanding of subsurface heat flow and input from the scientific and technical communities. These concerns have not been well addressed in all cases. Research is needed to allow the investigation of system performance and environmental impact in an integrated manner so that the best way of utilizing geothermal systems in an environmentally sensitive and sustainable manner can be determined.

1.1.4 Objectives

The overall objective of this project is to investigate the sustainability and potential environmental impact of low-temperature geothermal systems* and provide guidance in regulating the installation of these systems. In particular, we will focus on closed-loop systems as these represent the greatest area of future growth in Ontario. Numerical modelling and simulation of the heat exchange function in these systems will be used to evaluate the temperature rise in the soil surrounding these systems and the migration of thermal plumes away from them. This knowledge will guide proper site characterization, system design, construction and operation so that these systems are sustainable and impact the environment as well as other neighbouring systems as little as reasonably possible.

2 Background

System parameters, such as heat injection/removal rate and system spacing, affect the potential thermal interaction between geothermal energy systems, and can be prevented by restricting values of some of these parameters. Modeling the heat flows and temperature rise in the soil surrounding the GHEs is needed to determine their potential thermal interactions, sustainability and environmental impacts.

The heat transfer modelling in GHEs is complicated since their study involves transient effects in a time range of months or even years. Because of the complexities of this problem and its long time scale, the heat transfer in GHEs is usually analyzed in two separated regions (Fig. 2): the region inside the borehole containing the U-tubes and the grout and the soil region surrounding the borehole.

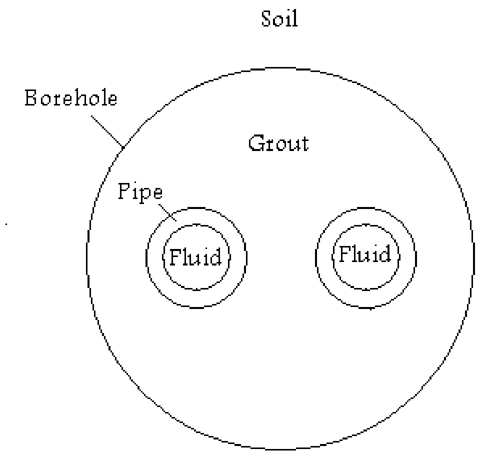
The transient borehole wall temperature is important for engineering applications and system simulation. It can be determined by modeling the region outside the borehole by various methods such as the line source theory. Based on the borehole wall temperature, the fluid inlet and outlet temperatures can be evaluated by a heat transfer analysis inside the borehole. In other words, the regions inside and outside borehole are coupled by the temperature of borehole wall. The heat pump model can utilize the fluid inlet and outlet temperatures for the GHE, and accordingly the dynamic simulation and optimization design for a ground coupled heat pump (GCHP) system can be

* Low-temperature geothermal systems also known as geoexchange systems interact closely with the shallow subsurface and have a near-environment temperature.

implemented. This is the basic idea behind the development of the two-region vertical ground heat exchanger model.

Changes in ground temperature and the circulating fluid often must be kept within acceptable limits over the life of the heat exchanger. Based on how heat transfer from the circulating fluid to the surrounding soil is simulated, these methods can be divided into analytical and numerical.

Figure 1. Cross-section of vertical ground heat exchanger. The fluid is ascending in one pipe and descending in the other.



2.1 Analytical Approach

In the analytical approaches, heat transfer inside the borehole wall, i.e. from the circulating fluid to the borehole wall, is usually modelled separately than the heat transfer outside the borehole wall, i.e. from the borehole wall to the surrounding soil.

2.1.1 Heat Transfer Inside the Borehole

The thermal analysis in the borehole seeks to define the inlet and outlet temperatures of the circulating fluid according to borehole wall temperature, its heat flow and the thermal resistance inside the borehole. The latter quantity is determined by thermal properties of the grouting material, the arrangement of flow channels and the convective heat transfer in the tubes. If the thermal resistance between the borehole wall and inner fluid is determined, the GHE fluid temperature can be calculated. Neglecting natural convection, moisture flow and freezing, the borehole thermal resistance can be calculated assuming steady-state heat conduction in the region between the circulating fluids and a cylinder around the borehole when the running time is greater than the critical time, that is $Fo > 5$, where Fo is the Fourier number, and the impact of thermal capacity of objects inside the borehole can be neglected [10]. Such simplification has been proved approximate and convenient for most engineering analyses dealing with responses of more than a few hours [11].

In all analytical models for inside of borehole, the axial heat flows in the grout and pipe walls are considered negligible as the borehole dimensional scale is small compared with the infinite extent of the ground beyond the borehole [12]. However, the fluid circulating through different legs of the U-tube exchangers heat with the surrounding ground and is of varying temperature along the tube. In particular, when the flow rate is low, there is a bigger temperature difference between the upward and downward channels which may result in thermal interference between the two channels and degrades efficiency of the ground heat exchanger. Due to the U-tube structure, the heat conduction in the cross section is clearly two-dimensional, and the variation of the fluid temperature along the borehole length is in the third dimension.

In some models such as Equivalent Diameter method [13-15] and Shape Factor method [16], the U-tube is conceived as a single pipe and heat transfer in the borehole is approximated as a steady-state one-dimensional process. This oversimplified one-dimensional model is not capable of evaluating thermal interference among borehole legs, analyzing dynamic responses within a few hours, or the axial temperature gradient along the borehole. In the two-dimensional model [17], the effect of U-tube placement is accounted for in the heat conduction problem. The temperature of the fluid in the U-tube is defined by superposing two separate temperature responses caused by the heat fluxes per unit length from the two pipes of the U-tube. A quasi-three-dimensional model was proposed by Zeng et al. [18-19] taking into account the fluid axial convective heat transfer and thermal "short-circuiting" among U-tube legs. At the instance of symmetric disposal of the U-tube inside the borehole, the temperature profiles in the two pipes are reduced as

$$\Theta_1(Z)=\cosh(\beta Z)-\frac{1}{\sqrt{1-P^2}}\left[1-P\frac{\cosh(\beta)-\sqrt{\frac{1-P}{1+P}}\sinh(\beta Z)}{\cosh(\beta)+\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}\right].\sinh(\beta Z)$$

$$\Theta_2(Z)=\frac{\cosh(\beta)-\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}{\cosh(\beta)+\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}\cosh(\beta Z)+\frac{1}{\sqrt{1-P^2}}\left[\frac{\cosh(\beta)-\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}{\cosh(\beta)+\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}-P\right].\sinh(\beta Z) \quad (1)$$

where the dimensionless parameters are defined as

$$\Theta=\frac{T_f(z)-T_b}{T'_f-T_b},\quad Z=\frac{z}{H},\quad P=\frac{R_{12}}{R_{11}}$$
$$\beta=\frac{H}{\dot{m}c_p\sqrt{(R_{11}+R_{12})(R_{11}-R_{12})}} \quad (2)$$

where z denotes the direction along the tube, H the borehole length, T_f the circulating fluid temperature, T_b the borehole wall temperature, and T_f' the temperature of the fluid entering the U-tube. Also, R_{11} and R_{22} are the thermal resistances between inlet and outlet legs of the U-tube and the borehole wall, respectively, and R_{12} is the thermal resistance between the inlet and outlet legs of the U-tube. It is seen in Eq. (3) that the Quasi-3-D model is able to reflect the variation of the temperature of the circulating fluid (T_f) along the tube (Z). Quasi-3-D models are preferred for design and analysis of ground heat exchangers, as they provide more accurate information on the heat flows inside the borehole.

2.1.2 Heat Transfer Outside the Borehole

Several simulation models for the heat transfer outside the borehole are available, most of which are based on analytical and/or numerical methods. The models vary in the way the problem of heat conduction in the soil is solved and the way the interference between boreholes is treated.

In the analysis of GHE heat transfer, some complicating factors, such as groundwater movement [20] usually prove to be of minor importance and are analyzed separately. Therefore, the problem of heat transfer outside the borehole becomes a heat conduction problem. The general heat conduction equation in cylindrical coordinates appears in the following form:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}_{gen}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (3)$$

where t denotes the time from the start of operation, α the thermal diffusivity of soil, and T the temperature of the ground. The first two terms on the left side of Eq. (3) are the heat flux components in the radial (r) direction, the third and the fourth terms are related to the circumferential (φ) and axial (z) directions, respectively, and the fifth term relates to the heat generated in the control volume. The right side of Eq. (3) represents the transient effects of heat conduction.

Unlike the area inside the borehole, heat conduction outside the borehole exhibits transient behavior. As a basic problem, the following assumptions are commonly made:

- The ground is homogeneous in its thermal properties and initial temperature.
- Moisture migration is negligible.
- Thermal contact resistance is negligible between the pipe and grout and between the grout and soil.
- The effect of ground surface is negligible for the initial 5-10 years (depending on the borehole depth).

Due to its minor order, heat transfer in the axial direction along the borehole, which accounts for the heat flux across the ground surface and down to the bottom of the borehole, is considered negligible. This assumption is valid for a length of the borehole distant enough from the borehole top and bottom. Also, heat transfer in the circumferential direction is negligible in this model assuming a single borehole. Therefore, the heat transfer is usually modeled with a one-dimensional analysis assuming that the axial and circumferential heat flows are negligible.

The earliest approach to calculating the heat transfer in the soil surrounding a ground heat exchanger is Kelvin’s line-source model, i.e. the infinite line-source which uses Fourier’s law of heat conduction. In the line-source theory, the borehole is assumed as an infinite line source of heat in the ground which is regarded as an infinite medium with an initial uniform temperature. This model derives an analytical relation for the temperature excess of the soil assuming a constant heat flow rate on the borehole wall (here, the line source). Another one-dimensional model based on Fourier’s law of heat conduction is the cylindrical source model [21]. In this model, the borehole is assumed to be a cylindrical pipe with infinite length buried in the ground. The governing equation for this model can be solved analytically for either a constant borehole surface temperature or a constant heat transfer rate from the borehole to the ground.

In both analytical models of Kelvin’s theory and the cylindrical source model, the borehole depth is considered infinite and the axial heat flow along the borehole depth is assumed negligible. Furthermore, when time tends to infinity, the temperature rise of the Kelvin’s theory for an infinite line source tends to infinity, making the infinite model weak for describing heat transfer mechanism in long time steps. Therefore, they can only be used for short time range of operations of GHP systems. To take into account axial temperature changes for boreholes with finite lengths and in long durations, Eskilson’s approach to the problem of determining the temperature distribution around a borehole is based on combination of analytical and numerical solution techniques. Eskilson [22] applies a numerical finite-difference method to the transient radial-axial heat conduction equation for a single borehole. Based on the Eskilson's model [22], Zeng et al. [18, 23] and Diao et al. [24] present an analytical solution to the transient finite line-source problem considering the effects of the finite borehole length and the ground surface as an isothermal boundary. They assume no temperature change on the ground surface (by superimposing an identical mirror borehole above the ground surface with negative strength). With these assumptions, the solution of the temperature excess for a heating rate per length of the source (q') constant is

$$T(r,z,t)-T_0=\frac{q'}{4k\pi}\int_0^H\left\{\frac{erfc\left(\frac{\sqrt{r^2+(z-h)^2}}{2\sqrt{\alpha t}}\right)}{\sqrt{r^2+(z-h)^2}}-\frac{erfc\left(\frac{\sqrt{r^2+(z+h)^2}}{2\sqrt{\alpha t}}\right)}{\sqrt{r^2+(z-h)^2}}\right\}dh \qquad (4)$$

where T is the temperature of the ground at radial distance r, axial distance z, and at time t, T_0 is the initial temperature of the ground, and q' is the heat flow rate per unit length of the borehole.

In the analytical models presented above, a number of assumptions are employed in order to simplify the complicated governing equations. In time varying heat transfer rates and the influence of surrounding boreholes on both long and short time scales, analytical methods are not as suitable as numerical methods. However, due to their much shorter computation times, they are still used widely in designing GHEs.

2.2 Numerical Models

System simulation models require the ability to operate at short time scales, often less than one minute. Therefore, the dynamic response of the grout material inside the borehole should be considered. This is only possible when the model is solved using numerical techniques. In addition to short time step solution, numerical techniques are advantages over the available analytical ones due to accounting for all the terms in the conduction equation (Eq. (3)) and the ability to apply transient boundary conditions on the model such as the surface, borehole wall and the inlet temperature boundaries. Model additions such as accounting for moisture migration in the soil and ground stratification are easier to be made in a numerical model than the analytical ones.

One of the disadvantages of numerical approaches is their computation time for long-term system performance. The diameters of the U-tubes in the borehole are fairly small, on the order of 10^{-1} m, while the size of the solution domain, which depends on the duration of system operation and its heating/cooling load, is approximately on an order of 10 m. A domain of a certain size can work well for one model, while it can be too small for another model requiring longer system performance durations or higher heating injection/removal rates. At the outer edge of the domain, a constant far-field temperature condition equal to the initial temperature is often applied. The sensitivity of the solution results to this boundary should always be examined and avoided by increasing the size of the domain.

The temperature gradient in the domain between the borehole wall and the far field changes gradually from large to small. Therefore, to reduce computer memory and computational time, the size of the mesh cells is chosen based on this gradual change. Furthermore, the symmetry about the ground heat exchanger can be used to save computation time. In such cases, the symmetric portion of the solution domain is replaced by an adiabatic wall boundary condition on the symmetry line. There are also several numerical techniques available in different numerical approaches which can be used to reduce the computation time.

2.3 Other Modeling Aspects

Performing energy and moisture balances at the ground surface involves very complex processes, taking into account solar radiation, cloud cover, surface albedo, ambient air temperature and relative humidity, rainfall, snow cover, wind speed, and evapotranspiration. Such details provide a proper account of the renewable energy resource. However, due to the complexity of adding all the above heat fluxes in a numerical model, some studies assume the ground surface temperature variation at the ground surface to take the form of a sine wave or Fourier series [25-28] while, in most analytical approaches, the ground surface boundary is assumed to have a constant temperature equal to the soil temperature deep in the ground (by superimposing an identical mirror borehole above the ground surface with negative strength). Moreover, some studies simplify the problem further and assume an adiabatic boundary condition at the ground surface.

Neglecting the existence of moisture in the soil, the heat flux is described via the conduction heat flow. The coupled heat and moisture flow in a soil system is described with a thermal energy balance coupled with a mass balance. This adds to the complication of the problem since the complete model contains a set of transient simultaneous partial differential equations with many soil parameters that are not readily available. Research shows that the effects of moisture migration are not significant to the operation of a vertical ground heat exchanger, it is expected that these effects are more pronounced with a horizontal ground heat exchanger (HGHE). This is because natural variations of temperature and moisture near the ground surface and operation of the HGHE may create a potentially greater moisture movement. During the cooling season, migration of soil moisture away from the GHE may lead to a drastic drop in soil thermal conductivity and consequently a significantly reduced heat transfer, which has a devastating effect on GHE performance. Therefore, although moisture migration effects can be neglected in early stages of design or conceptual development, not considering them in long-term operation of GCHP systems makes it impossible to assess the performance and potential failure of these systems [29].

A further complication in the design of ground-coupled heat pump systems is the presence of groundwater. Due to the difficulties encountered both in modeling and computing the convective heat transfer and in learning about the actual groundwater flow in engineering practice, each of the methods presented in the previous sections is based on Fourier’s law of heat conduction and neglect the effects of groundwater flow in carrying away heat. Where groundwater is present, flow will occur in response to hydraulic gradients, and the physical process affecting heat transfer in the ground is inherently a coupled one of heat diffusion (conduction) and heat advection by moving groundwater. Similar to the models discussed in the previous sections, here as well, the objective is to evaluate the temperature response in the soil surrounding ground heat exchangers.

2.4 Literature Review

In the analysis inside the borehole, quasi-3-D models reveal drawbacks of 1-D and 2-D models and are thus preferred for design and analysis of ground heat exchangers, as they provide more accurate information for performance simulation, analysis and design [18-19, 22, 24, 30]. To make the analytical results obtained by the line source theory for analysis outside of the borehole more accurate and comparable to numerical ones, several studies have focused on improvements [31-34]. Hellström [17], Kavanaugh [35], Bernier et al. [36], and Hikari et al. [37] focus on improvements on cylindrical source solution. Yang et al. [38] propose and develop an updated two-region vertical U-tube GHE analytical model coupling two solutions for inside and outside the borehole with the temperature of borehole wall.

Numerical methods have also been used extensively for evaluating the heat conduction inside the borehole and the soil surrounding it [11, 39-48].

Another aspect of ground source heat pump system is load variation and on-off cycling of the GHE governed by specified operational conditions [35-36, 47-48]. Some studies focus on the thermal interaction between the circulating fluid and soil taking into account heat flow with moisture transfer in the soil [29, 39, 42, 49]. The effect of ground water is analyzed by combining conduction heat transfer and advection in the soil surrounding vertical borehole heat exchangers using numerical [20, 50-52] and analytical approaches [53].

3 Current Model

In the current model, the temperature response in the soil surrounding multiple boreholes is evaluated using analytical and numerical approaches. The focus is specifically on thermal interaction among multiple boreholes, rather than estimating how heat flows in the region surrounding GHEs and causes temperature rise in the soil. The latter has been the focus of many studies of single boreholes.

To evaluate the long-term temperature response in the soil surrounding multiple borehole systems, a numerical finite volume method in a two-dimensional meshed domain is used [54]. The effect of installing ground heat exchangers in the ground and the temperature rise in the soil over the long term, for a period of 5 years, is considered. A transient periodic heat flux is assumed on the borehole wall reflecting the annual variation of heat storage/removal in the ground. When monthly bin weather information, building needs, and heat pump performance and efficiency data are available, this periodic heat flux can be calculated and used as a heat boundary condition in the numerical model. It is assumed that flow rate and the inlet temperature of the circulating fluid running in the U-tube inside the borehole will be adjusted according to the building heating needs. The 5-year simulation of the system shows that for a system that has a balanced heat injection and extraction into the soil, if the borehole spacing and the heat injection/extraction rate are designed within acceptable limits, there will not be any temperature increase or decrease in the soil surrounding the system. Any temperature rise or decrease in the soil surrounding the ground heat exchanger that is noticed after the first year operation needs to be compensated for during the second year operation so that the system can operate sustainably.

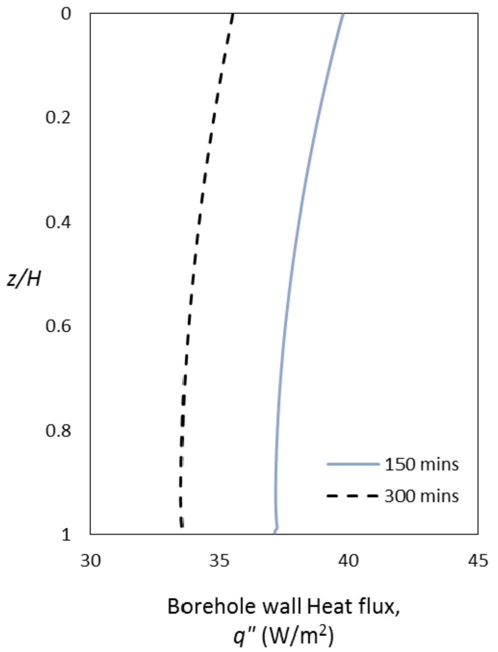
As mentioned previously, using a heat boundary condition can cause the temperature of the ground to rise infinitely without a stop in system operation. In reality, if the temperature of the soil surrounding a borehole becomes close to or higher than the inlet temperature of the circulating fluid exiting the heat pump, the system will not be able to deliver the desired heat to the ground and will automatically stop operating until the heat around it is dissipated away and the temperature drops to a lower value. In order to overcome such a limitation, the periodic heat boundary on the borehole wall can be replaced with a temperature boundary or the heat boundary can be updated at short time steps with respect to the soil temperature. This is possible if the heat transfer model for outside of the borehole is couples to the model inside the borehole.

Another limitation in most of the previous studies is the assumption of uniform heat input along the borehole length to the ground, either when the borehole is assumed as a cylinder or a line source of heat. In order to determine heat delivery/removal strength of the circulating fluid that runs in the borehole, the heat transfer model inside the borehole should be coupled to the one outside the borehole. In a recent study, Koohi-Fayegh and Rosen [55] use the analytical quasi-three-dimensional solution to the heat transfer problem of the U-tube configuration inside the borehole. This model evaluates the temperature of the circulating fluid along the borehole length and is be used in the model for outside the borehole to calculate the heat delivery/removal along the borehole caused by the temperature difference between the circulating fluid and the borehole wall temperature. The heat delivery/removal is implemented as the heat boundary condition in the analytical line source with finite length as well as in a three-dimensional finite volume model [56] and the results are compared [57]. The results show that due to the higher heating strength at the top end of the boreholes (about 3% total length), the possibility of thermal interaction at the top of the borehole is at its highest and it decreases along the borehole length as the heat flux from the borehole wall into the soil decreases. Therefore, with the objective of limiting boreholes' operations and sizes in order to prevent their thermal interaction, the top length of the boreholes is the critical area. It can be concluded that using a uniform heat flux along the borehole is only accurate for the middle length of the boreholes and moving any further to the top or bottom of the borehole, the temperature rise evaluations become inaccurate.

When calculating the heat input to the ground, it becomes clear that it varies with the borehole wall temperature. Although the soil temperature at the borehole wall rises as the system operates, it is often assumed that the soil temperature at the borehole wall is constant throughout the operation period. This assumption ignores the drop in heat injection strength when the borehole wall temperature increases and, therefore, underestimates the inlet temperature of the circulating fluid that is required to meet the heat injection needs of the system. In the fewer cases of multiple boreholes, superimposition of the temperature excesses resulted from individual boreholes seems to be the most popular solution in analytical approaches. In numerical approaches, the boundary condition that plays the role of heat delivery/removal is a heat flow rate per unit length boundary type that, regardless of being constant or variable based on the building needs, does not reflect the drop in the heat injection/removal strength when temperature of the soil around the borehole increases/decreases by its own performance or another nearby system's performance. This assumption forces the system to deliver a desired amount of heat to the ground regardless of the ground temperature. In reality, the amount of heat delivered to the ground is driven by the temperature difference between the circulating fluid and the ground temperature. In some cases, the assumption of constant borehole wall temperature is acceptable considering how the conduction problem is simplified. However, when determining how thermal interaction between two operating GHEs can affect their performance, the effect of the transient borehole wall temperature on their heat delivery strength and inlet fluid temperature becomes a very important factor. Therefore, this model is only able to illustrate the variation of the heat delivery/removal strength when the heat flow rate is low and the temperature changes at the borehole wall are small.

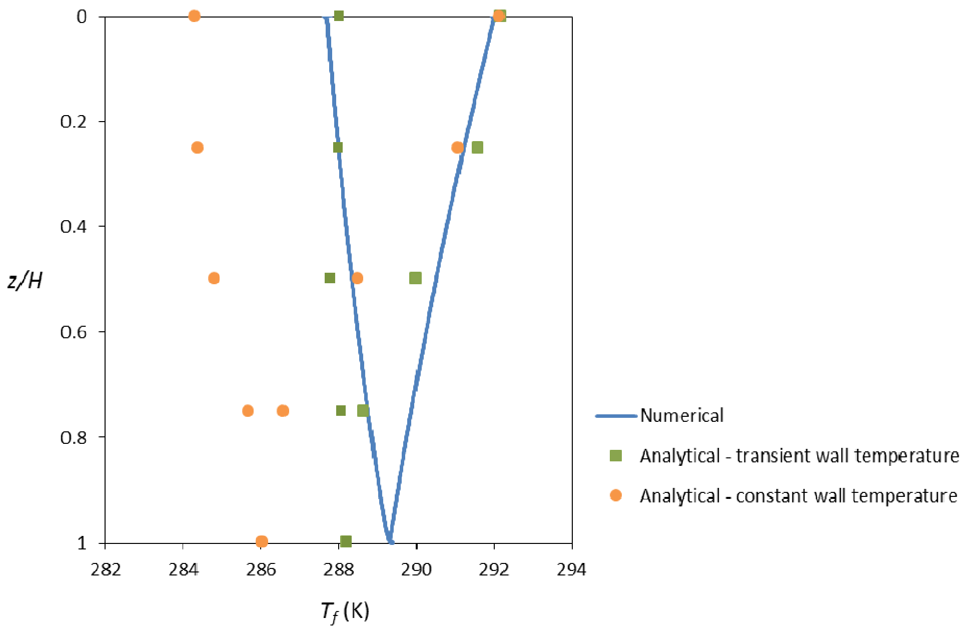
In order to account for higher heat flow rates or thermal interaction between multiple boreholes, the model should be modified to include the transient value of borehole wall temperature. Thus, the non-uniform heat flow rate along the borehole wall becomes transient as well. In this study, the results of a semi-analytical model that accounts for the transient borehole wall temperature are discussed. The model not only estimates how heat flows in the region surrounding GHEs, but also estimates how a temperature rise in the soil surrounding a borehole caused by the system itself or a neighboring geothermal system can interfere with its heat delivery strength. In an example of heat delivery to the ground (Fig. 2), the heat flow rate per unit length of the borehole drops after only a few hours of system operation due to the increase in the borehole wall temperature.

Figure 2. Distribution of borehole wall heat flux along the borehole length.



The drop in the heat flux on the borehole wall is due to the lower temperature difference between the circulating fluid and the increasing borehole wall temperature as the system operates. The circulating fluid temperature of the current model is compared with ones from numerical finite volume modeling of the system in Fig. 3 and show better accuracy compared with conventional analytical model assuming a constant wall temperature.

Figure 3. Distribution of circulating fluid temperature (T_f) along the borehole length



4 Conclusions

The assessment of the available analytical models show that they are not capable of estimating the heat delivery/removal strength when the soil surrounding them experiences a temperature rise. In the current study it is shown that the effect of the temperature rise in the soil surrounding boreholes is not negligible. The distance between two boreholes or two systems of boreholes, the heat flux from the borehole wall and the time of system operation all affect directly the amount of thermal interaction between the systems. However, the effect of these parameters on system operation and heat delivery/removal rate can only be studied in models that account for the change in the borehole wall temperature.

As mentioned in the previous section, the current model accounts for the drop in heat delivery strength when the borehole wall temperature increases during the operation time or by another nearby operating system. As a result, the inlet temperature of the circulating fluid needs to be adjusted to a higher/lower one to maintain the heat delivery/removal needs of the system. The next modification to current model is to adjust the inlet circulating temperature actively based on the system needs. This analysis is important since ground heat exchangers are coupled to a heat pump that can only work within a certain temperature lift and inlet and outlet circulating temperature ranges. If a system is able to deliver a certain amount of heat to the ground, the increase in the inlet circulating temperature due to temperature rise in the soil caused by a nearby system reflects how thermal interaction affects the sustainability of the system. The heating and cooling load profile throughout the year varies depending on the outside air temperature and several other factors such as the type of the building (residential, recreational and industrial structures), its size, the number of people in the building, etc. In order to study the potential for thermal interaction in the long term operation of neighbor systems, approximate yearly heat delivery/removal needs of the system in the long term must be defined based on available methods such as the Bin method. Then, the inlet temperature of the circulating fluid in the current model must be coupled to the yearly heat deliver/removal profile. This will probably require adjustments to the current numerical model.

After simulation of heat exchange processes within the system and surrounding environment through local scale assessment, simulation of migration of thermal plumes into the hydrogeological environment through intermediate and regional scale assessment will help gain an estimation of ecological impacts. Furthermore, the results presented in this report can be employed to model ground heat exchangers in order to examine the thermal interaction among multiple neighbouring systems. An overview of existing government regulations for horizontal and vertical systems will help gain an estimation of system performance under such temperature limitations. Once these conditions are identified, a comparison with the simulation results of heat exchange processes within the system and surrounding environment through local scale assessment will help examine the sustainability of these systems. http://energy.nstl.gov.cn/MirrorResources/902/index.html

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