Regulating Underground Boundaries for Geothermal Energy Systems: An Analytical Approach to Evaluating the Effect of Thermal Interaction of Geothermal Heat Exchangers on their Sustainability

CCTC 2013 Paper Number 1569695577

S. Koohi-Fayegh[1] and M.A. Rosen[1]
[1] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada.

Abstract

A semi-analytical model that couples a model outside the borehole with one inside the borehole is proposed. To examine the effect of temperature rise in the soil surrounding a vertical ground heat exchanger on the performance of an associated ground heat pump, the model inside the borehole needs to reflect the transient temperature difference between the running fluid and the borehole wall temperature. In this model, the borehole wall temperature is assumed to be transient and the results of this model are compared with those for a constant borehole wall temperature. It is shown that transient borehole wall temperature assumption results in more accurate temperatures for the circulating fluid flowing to the heat pump.

Keywords: geothermal energy; borehole; vertical ground heat exchanger; variable heat flux.

Résumé

Unmodèle semi-analytique combinant un modèle représentant les paramètres (température et flux) à l'extérieur du trou de forage à un modèle adapté aux variables à l'intérieur du trou est proposé. Pour étudier l'effet de l'élévation de température du sol entourant un échangeur de chaleur souterrain sur la performance d'une thermopompe associée utilisant le sol comme source de chaleur, le modèle adapté à l'intérieur du trou de forage doit rendre compte de la différence transitoire entre les températures du fluide en circulation et de la paroi du trou de forage. Dans ce modèle, on suppose que la température de la paroi du trou de forage est variable, et les résultats sont comparés à ceux obtenus dans le cas d'une température de paroi constante. Il est démontré qu'en prenant comme hypothèse une température de paroi du trou de forage variable, on obtient des résultats plus précis sur la température du fluide circulant vers la pompe à chaleur.

Mots clés : énergie géothermique; trou de forage; échangeur de chaleur vertical souterrain; flux thermique variable.

1. Introduction

Below a certain depth, 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. Thus, the efficiency of the heat pump, which depends directly on the temperature lift across a GHP, is enhanced for a GHP.

While the use of geothermal systems is widespread, having had a revival in the 1980's and recently, the sustainability of these systems at their design efficiency is being questioned due to unexpected temperature rises caused by the system itself or adjacent systems. Studies indicate that in many cases these systems are not sustainable or not sustainable at the design efficiency [1-2]. The influence of these systems on each other indicates that there is a limit to the density of development of these systems that can occur in a given region. 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 ground heat exchangers (GHEs) is needed to determine their potential thermal interactions and sustainability.

The heat transfer in GHEs is usually analyzed in two separate regions (Figure 2): the region inside the borehole containing the U-tubes and the grout and the soil region surrounding the borehole. The analysis of the two regions can be coupled by the temperature of borehole wall. This temperature can be determined by modeling the region outside the borehole by various available methods. Based on the borehole wall temperature, the fluid inlet and outlet temperatures can be evaluated by a heat transfer analysis inside the borehole. 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 implemented. This is the basic idea behind the development of the two-region vertical ground heat exchanger model. Several analytical models for the heat transfer inside and/or outside the borehole are available [3-7]. 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 a recent study, Koohi-Fayegh and Rosen [8] 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 coupled to 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 calculated from the model inside the borehole 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 [14] and the results are compared [9].

Using a heat boundary condition can cause the temperature of the ground to rise infinitely without a stop in system operation [10]. 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 soil temperature drops to a lower value. In order to overcome such a limitation when modeling the system, 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 outside of the borehole is coupled to the model inside the borehole. In the fewer cases of multiple boreholes, 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 an important factor.

The overall objective of this paper is to investigate the sustainability of geothermal systems due to temperature rise in the soil surrounding boreholes. "Thermal pollution" occurs in the form of increased temperatures in the vicinity of ground heat exchangers and is caused by the system itself, adjacent systems, or the urban environment. An analytical model is presented which is capable of examining the effect of temperature rise on system operation despite its simplifying assumptions. This knowledge will guide proper system design and operation so that these systems are sustainable and impact other neighbouring systems as little as reasonably possible.

2. Mathematical model

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

2.1. 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 between the borehole wall and inner fluid. 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. 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.

The fluid circulating through different legs of the U-tube exchanges heat with the surrounding ground and is of varying temperature along the tube. Due to the U-tube structure, the heat conduction in the cross section is two-dimensional, and the variation of the fluid temperature along the borehole length is in the third dimension. 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. [3] taking into account the fluid axial convective heat transfer and heat exchange between U-tube legs. For symmetric placement of the U-tube inside the borehole, the temperature profiles in the two pipes are derived as

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

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

where the dimensionless parameters are defined as

$$\Theta = \frac{T_f(Z) - T_b}{T_f' - T_b}, \quad Z = \frac{z}{H}, \quad P = \frac{R_{12}}{R_{11}}$$
$$\beta = \frac{H}{\dot{m}c_p\sqrt{(R_{11}+R_{12})(R_{11}-R_{12})}} \tag{2}$$

and 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).

Using the dimensionless parameters introduced in Eqs. (1) and (2), the heat transferred to the soil from each of the pipes in the borehole can be obtained from

$$q'(Z) = (T_f' - T_b)\left[\frac{\Theta_1(Z)}{R_1^\Delta} + \frac{\Theta_2(Z)}{R_2^\Delta}\right] \tag{3}$$

where

$$R_1^\Delta = R_2^\Delta = R_{11} + R_{12} \tag{4}$$

if the configuration of the U-tube in the borehole is symmetric. Equation (3) evaluates the spatial distribution of the heating strength along the rod. Note that the current variable heat source (VHS) model has made certain simplifying assumptions, such as constant borehole wall temperature (T_b).

2.2. Heat transfer outside the borehole

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 grout and soil.
- The effect of ground surface is negligible for the initial 5-10 years (depending on the borehole depth).
- The ground surface is assumed to have an isothermal boundary condition.
- Heat transfer in the axial and circumferential directions is negligible.

Modifying Kelvin's line-source model, Zeng et al. [4] present an analytical solution to the transient finite line-source problem considering the effects of the finite borehole length. 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). Modifying the model slightly to account for the variation of heat flow rate along the line source [8,9], the temperature profile in the soil around the boreholes is calculated as

$$\theta(\bar{R},Z,Fo)=\frac{1}{4k\pi}\int_0^1 q'(\bar{H})\left[\frac{erfc\left(\frac{\sqrt{\bar{R}^2+(Z-\bar{H})^2}}{2\sqrt{Fo}}\right)}{\sqrt{\bar{R}^2+(Z-\bar{H})^2}}-\frac{erfc\left(\frac{\sqrt{\bar{R}^2+(Z+\bar{H})^2}}{2\sqrt{Fo}}\right)}{\sqrt{\bar{R}^2+(Z+\bar{H})^2}}\right]d\bar{H} \qquad (5)$$

where $\theta = T - T_0$, $Z=\frac{z}{H}$, $\bar{H}=\frac{h_z}{H}$, $\bar{R}=\frac{r}{H}$ and $Fo=\frac{\alpha t}{H^2}$. Also, $q'(\bar{H}')$ denotes the heating strength per unit length, *t* the time from the start of operation, *α* the thermal diffusivity of soil, and *T* the temperature of the ground.

2.3. Model coupling

In order to determine heat delivery/removal strength of the circulating fluid inside the borehole, the borehole wall temperature must be defined by coupling the heat transfer model inside the borehole to the one outside the borehole. Similar to a previous study by Koohi-Fayegh and Rosen [8], the model for the temperature rise outside the borehole (Eq. (5)) is coupled to the one for inside the borehole via the heat flow rate per unit length of the borehole (Eq. (3)). How the two models are coupled and what parameters are kept constant vary depending on the objective of the study.

In order to compare the results of steady borehole wall temperature with results of transient borehole wall temperature, the operation of the system is studied for a constant running fluid temperature. The case of steady borehole wall temperature delivers a steady amount of heat per unit length to the surrounding soil and, therefore, $q'(\bar{H})$ remains steady in Eq. (5). However, for the transient borehole wall temperature, $q'(\bar{H})$ varies with time. Therefore, in this case, the borehole wall temperature (T_b in Eq. (3)) is updated at every time step to a new value calculated from the model outside the borehole for $\bar{R}_b = r_b/H$. Since this model relates to time varying heat transfer rates, the problem of heat conduction from the borehole wall to the soil becomes subject to a time-dependant boundary condition $q'(\bar{H},\tau)$. The variations of heat injection/removal on the borehole can vary due to the transient temperature of the soil at borehole wall. These variations can be approximated by a sequence of constant heat fluxes $q_i'(\bar{H})$ where the *i*th heat flux is applied at $t=\tau_i$ and lasts for a time span Δt_i. Assuming that the governing equations and boundary conditions for the problem are linear, we can obtain the temperature distribution in the body by applying the principle of superposition and obtain the temperature distribution in the body corresponding to the arbitrary continuous boundary condition which we can express as a sequence of, say, *n* small steps. Therefore, if the temperature rise distribution in the soil corresponding to a constant boundary condition $q'(\overline{H})$ is

$$\theta(R,Z,Fo) = \int_0^1 q'(\overline{H})\, I(R,Z,Fo)\, d\overline{H} \tag{6}$$

where

$$I(R,Z,Fo) = \frac{1}{4k\pi}\left[\frac{erfc\left(\frac{\sqrt{\overline{R}^2+(Z-\overline{H})^2}}{2\sqrt{Fo}}\right)}{\sqrt{\overline{R}^2+(Z-\overline{H})^2}} - \frac{erfc\left(\frac{\sqrt{\overline{R}^2+(Z+\overline{H})^2}}{2\sqrt{Fo}}\right)}{\sqrt{\overline{R}^2+(Z+\overline{H})^2}}\right] \tag{7}$$

the temperature distribution in the soil corresponding to the varied $q_i'(\overline{H}) = q'(\overline{H},\tau_i)$ at time *t* is

$$\begin{aligned}\theta(R,Z,Fo) = & \int_0^1 q_1'(\overline{H})\, I(R,Z,Fo_{t-\tau_1})\, d\overline{H} \\ & + \int_0^1 \left[q_2'(\overline{H}) - q_1'(\overline{H})\right] I(R,Z,Fo_{t-\tau_2})\, d\overline{H} \\ & + \int_0^1 \left[q_3'(\overline{H}) - q_2'(\overline{H})\right] I(R,Z,Fo_{t-\tau_3})\, d\overline{H} \\ & + \ldots + \\ & + \int_0^1 \left[q_n'(\overline{H}) - q_{n-1}'(\overline{H})\right] I(R,Z,Fo_{t-\tau_n})\, d\overline{H}\end{aligned} \tag{8}$$

where

$$Fo_{t-\tau_i} = \frac{\alpha(t-\tau_i)}{H^2} \tag{9}$$

and q_i' is the heat flow rate on the line source (here, the borehole) at time τ_i to τ_{i+1}. The accuracy of the solution can be improved by increasing the number of the time steps. In this problem, the variations in the heat input profile due to the variation in the soil temperature at the borehole wall $(q'(\overline{H},\tau))$ are not known when modeling the system. However, the solution to the temperature of the running fluid inside the borehole can be used at every time step in order to estimate the heat input variations. When the temperature response in the soil (Eq. (8)) is coupled with the heat input model inside the borehole (Eq. (3)), the temperature response will be evaluated based on a transient borehole temperature and heat input profile.

To study the effect of the temperature increase in the soil surrounding the borehole on the operation of the heat pump when an average constant heat flow rate is maintained, the outlet temperature of the running fluid is the most important parameter and it can be calculated by coupling the two models for inside and outside the borehole. In this case, in order to maintain the required heat flow rate, it is assumed that the temperature of the borehole wall increases over time (Eq. (5)) while the inlet and outlet temperature of the fluid are modified accordingly from Eq. (1) and

$$q'_{ave} H = \dot{m} c_p \left(T'_f - T_{f,out} \right) \tag{10}$$

Note that q'_{ave} on the left hand side of Eq. (10) is maintained at a constant rate.

In the next section, some of the results are based on the case of constant inlet fluid temperature and varying average heat flow rate and some are based on varying inlet and outlet fluid temperatures by maintaining a constant average heat flow rate.

3. Results and discussion

In Figure 1, the results of the heat flux on the borehole wall calculated from the semi-analytical model that accounts for the transient borehole wall temperature (TBT) are shown over the borehole length. This model not only estimates how heat flows in the region surrounding GHEs, but also can estimate 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. It is seen in Figure 2 that 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. This is due to the lower temperature difference between the circulating fluid and the increasing borehole wall temperature as the system operates. This effect is ignored with the assumption of constant borehole wall temperature (CBT) when modeling these systems.

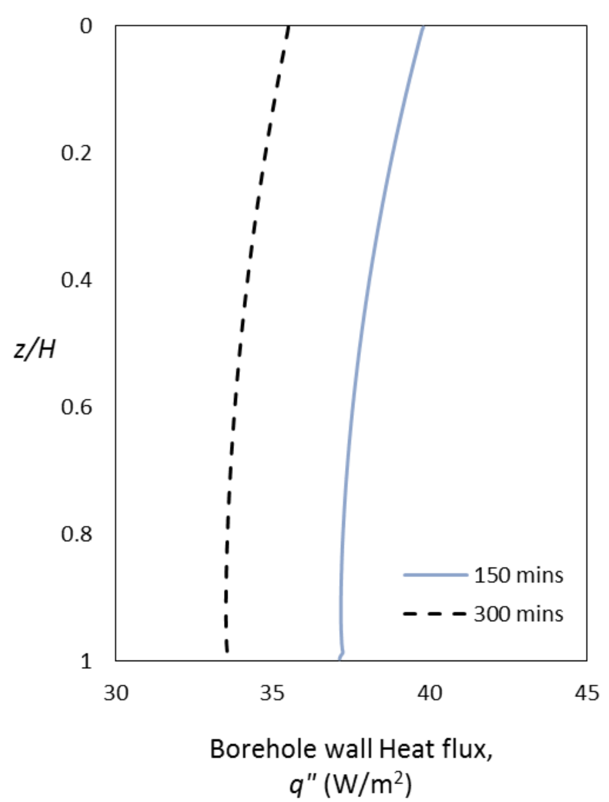

Figure 1. Distribution of borehole wall heat flux along the borehole length.

The circulating fluid temperature of the two models with constant and transient borehole wall temperature are compared in Figure 2. It is seen that for similar inlet fluid temperatures, the outlet fluid temperature of the TBT model is higher than that of the CBT model in the heat delivery mode. From these results, it is also expected that the outlet fluid temperature of the TBT model is lower than that of the CBT model in the heat removal mode. This is due to lower temperature difference between the running fluid and the increasing borehole wall temperature in heat delivery mode and the decreasing borehole wall temperature in heat removal mode. As a result, the running fluid loses/gains less heat to/from the soil in the heat delivery/removal mode. Ignoring this effect will result in overestimating the heat delivery/removal amounts. More importantly, when discussing the efficiency of the heat pump, which depends directly on the outlet temperature of the running fluid, the underestimated outlet fluid temperature in the CBT model results in overestimated values of the ground heat pump efficiency.

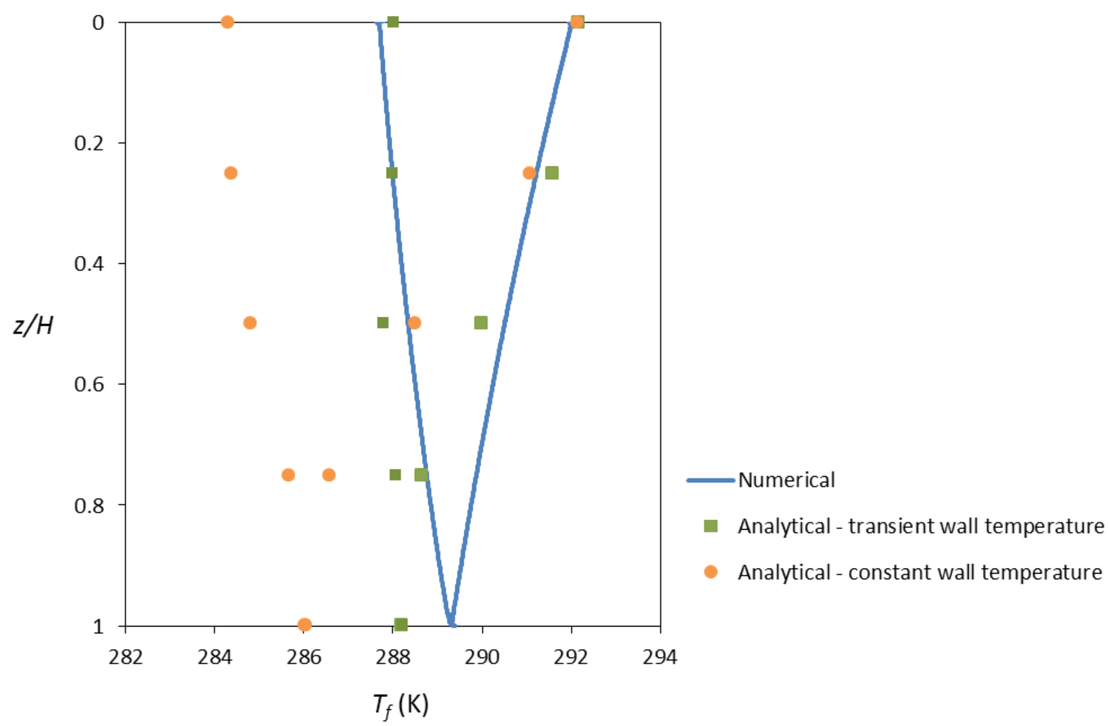

Figure 2. Distribution of circulating fluid temperature (T_f) along the borehole length for a constant inlet fluid temperature $T_f' = 292\,\mathrm{K}$.

In order to prevent the gradual drop in borehole heat flux, illustrated in Figure 2, the inlet temperature of the circulating fluid is one of the parameters that can be varied during system operation. In Figure 3, the circulating fluid temperature of the two models with constant and transient borehole wall temperature are compared for the case where the average borehole heat flux along its length is maintained at a steady rate of 30 W/m. It is seen in Figure 3 that the temperature difference between the inlet and outlet stays constant throughout system operation, which is a result of maintaining a constant heat flow rate. However, when delivering heat to the soil, the inlet and outlet temperature rise over time as a result of soil temperature increase in the vicinity of the borehole. Monitoring the outlet temperature of the running fluid is advantageous since this temperature is often the key parameter in the system to examine if the heat pump will operate under the soil temperature conditions. Therefore, this temperature can be the coupling parameter between the model inside the borehole and the heat pump. It is seen that the assumption of constant borehole wall temperature ignores the drop in heat injection strength when the borehole wall temperature increases and, therefore, underestimates the outlet temperature of the circulating fluid that is required to meet the heat injection needs of the system.

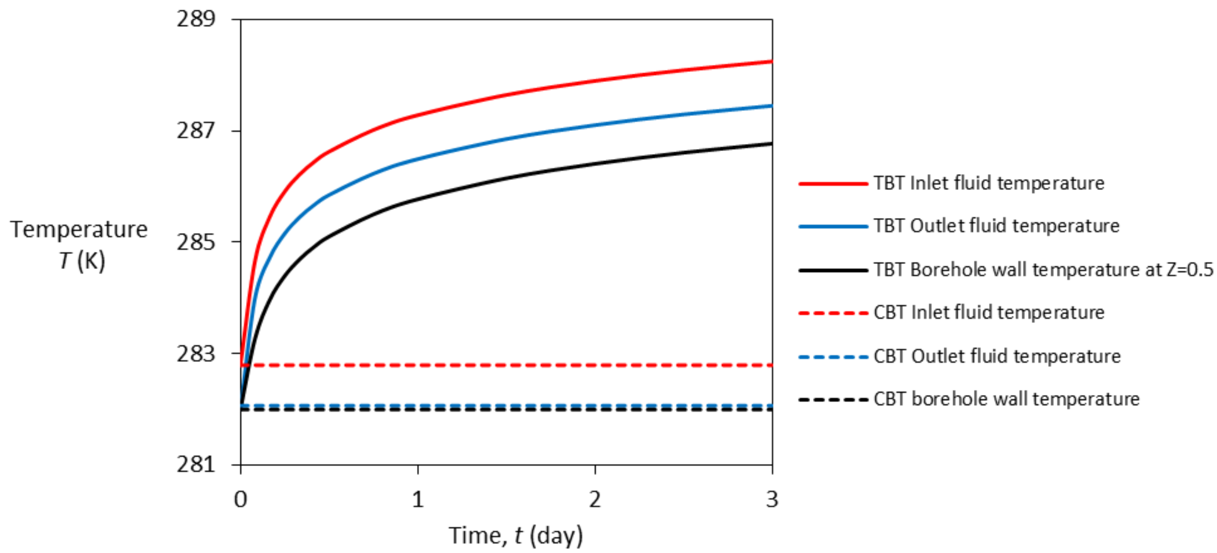

Figure 3. Inlet and outlet temperature history of the circulating fluid for the two models with constant (CBT) and transient (TBT) borehole wall temperature where the average borehole heat flux along its length is maintained at a steady rate of 30 W/m.

In cases of multiple boreholes, superposition of the temperature excesses resulting from individual boreholes seems to be the most popular solution in analytical approaches. In reality, the system is not linear and the amount of heat delivered to the ground is driven by the temperature difference between the circulating fluid and the ground temperature. When the ground temperature experiences a temperature rise from a neighbor system, the inlet temperature of the borehole needs to be increased to deliver the required amount of heat to the ground. It is seen in Figure (4) that when the temperature of the soil surrounding the borehole increases, the outlet temperature of the circulating fluid is increased. Once there is a temperature rise in the soil surrounding a borehole, the inlet fluid needs to be increased in order to maintain the required heat flow rate. Therefore, this results in an increased outlet fluid temperature which can lower the efficiency of the ground heat pump. The correlation is shown to be linear, since according to Eq. (1), we have

$$\frac{T_{f,out}-T_{b@Z=0}}{T_f'-T_{b@Z=0}}=\frac{\cosh(\beta)-\sqrt{\frac{1-P}{1+P}}\sinh(\beta)}{\cosh(\beta)+\sqrt{\frac{1-P}{1+P}}\sinh(\beta)} \qquad (11)$$

The right hand side of Eq. (11) depends only on the U-tube placement, system geometry and U-tube mass flow rate. Therefore, the outlet fluid temperature becomes a linear function of borehole wall temperature. Here, the assumption of steady borehole wall temperature is not acceptable when determining how thermal interaction between two operating GHEs can affect their performance since it underestimates the borehole wall temperature.

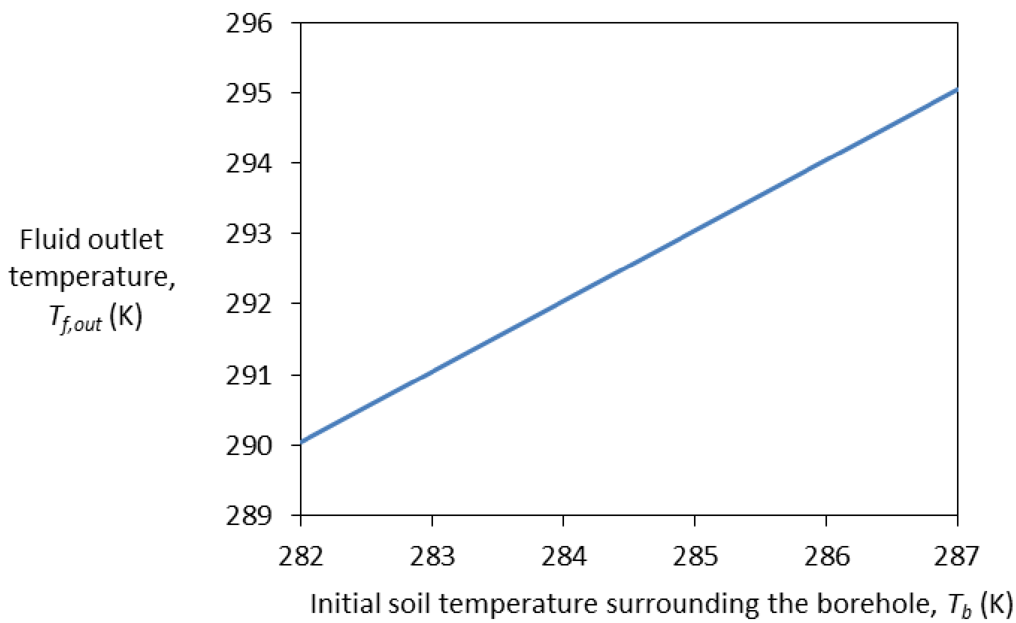

Figure 4. Fluid outlet temperature variation with respect to initial soil temperature after 5 months of heat delivery to the ground with borehole average heat flow rate per unit length 30 W/m.

4. Conclusions

The proposed model allows the temperature response in the soil surrounding multiple boreholes to be evaluated accurately using an analytical approach. The focus is specifically on a model that can examine thermal interaction among multiple boreholes, rather than estimating how heat flows in the region surrounding GHEs cause temperature rise in the soil. The latter has been the focus of many studies of single boreholes. In the current study it is shown that the effect of the temperature rise in the soil surrounding boreholes is not negligible. The effect of parameters such as borehole distance on system operation and heat delivery/removal strength can only be studied in models that account properly for the change in the borehole wall temperature.

5. References

[1] Ferguson, G., Woodbury, A.D., "Observed thermal pollution and post-development simulations of low-temperature geothermal systems in Winnipeg, Canada". *Hydrogeology*, Vol. 14, Iss. 7, 2006, pp. 1206-1215.

[2] Younger, P.L., "Ground-coupled heating-cooling systems in urban areas: How sustainable are they?", *Bulletin of Science, Technology & Society*, Vol. 28, Iss. 2, 2008, pp. 174-182.

[3] Zeng, H.Y., Diao, N.R., Fang, Z., "Heat transfer analysis of boreholes in vertical ground heat exchangers", *International Journal of Heat and Mass Transfer*, Vol. 46, Iss. 23, 2003, pp. 4467–4481.

[4] Zeng, H.Y., Diao, N.R., Fang, Z., "A finite line-source model for boreholes in geothermal heat exchangers", *Heat Transfer Asian Research*, Vol. 31, Iss. 7, 2002, pp. 558–567.

[5] Lamarche, L., Beauchamp, B., "A new contribution to the finite line source model for geothermal boreholes", *Energy and Building,* Vol. 39, Iss. 2, 2007, pp. 188–198.

[6] Yang, W., Shi, M., Liu, G., Chen, Z., "A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification", *Applied Energy*, Vol. 86, 2009, pp. 2005–2012.

[7] Fang, Z.H., Diao, N.R., Cui, P., "Discontinuous operation of geothermal heat exchangers", *Tsinghua Science and Technology*, Vol. 7, Iss. 2, 2002, pp. 194–197.

[8] Koohi-Fayegh, S., Rosen M.A., "Thermally interacting multiple boreholes with variable heating strength", *Proc. eSim Conference*, 2-3 May 2012, Halifax, Nova Scotia.

[9] Koohi-Fayegh, S., Rosen M.A., "On thermally interacting multiple boreholes with variable heating strength: Comparison between analytical and numerical approaches", *Sustainability* 2012, 4, pp. 1848-1866.

[10] Koohi-Fayegh, S., Rosen M.A., "Modelling thermally interacting multiple boreholes with variable heating strength", *Proc. 2nd World Sustainability Forum*, 1-30 Nov 2012.

6. Acknowledgements

Support provided by the Ontario Ministry of Environment through its Best in Science program and by the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

7. Biography

Seama Koohi-Fayegh is a PhD student at the University of Ontario Institute of Technology. In her PhD thesis, she studies on the thermal sustainability of geothermal energy systems from the aspect of system interactions and environmental impacts. She obtained her Masters degree in 2008 at Ferdowsi University of Mashhad, Iran.

Dr. Marc A. Rosen is a Professor of Engineering at the University of Ontario Institute of Technology, where he served as founding Dean of the Faculty of Engineering and Applied Science. He is a Director of Oshawa Power and Utilities Corporation, and has been President of the Engineering Institute of Canada and the Canadian Society for Mechanical Engineering. He is Editor-in-Chief of the journal Sustainability and Editor of Energy Conversion and Management.