Effects of Ground Heat Flux on Performance of Vertical Borehole Heat Exchangers

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Keywords: borehole heat exchanger; ground heat flux; urbanization; line-source model; geothermal potential

ABSTRACT

There are various analytical and semi-analytical modelling techniques used for prediction of the impacts of borehole heat exchangers (BHEs) on the thermal conditions in the subsurface. They are attractive because they are easy to use, compact and computationally efficient. However, (semi-)analytical formulations also cut down the complexity of the conditions in the field by limited resolution of variations in space and time, and by often simplified specifications of boundary conditions. In this presentation, we focus on the definition of the land surface boundary condition in line source solutions. As BHEs are thin elongated forms that can be approximated by a linear shape function, the main attention is commonly given to radial heat transfer, but less so on the axial effects. Given the long operation time, however, the sharp physical boundary at the top may exert a substantial influence on the temperature evolution in the shallow ground and thus influence the performance of the ground source heat pump. We examine formulations with Dirichlet type boundaries included in the line source equation. Homogeneous as well as inhomogeneous implementations are feasible, which offer new flexibilities for simulation of nonuniform land surface impacts such as those associated with varying land use types. The presented approach also facilitates an account for the accelerated ground heat flux due to global warming and to urbanization which can be observed in so-called subsurface urban heat islands in many cities. As a consequence, it is revealed by the results for synthetic scenarios that the neglect of such effects may underestimate the regeneration capacity of BHEs operated in an unbalanced mode.

1. INTRODUCTION

Vertical borehole heat exchangers (BHEs) represent standard applications of shallow geothermal energy utilization for heating and cooling purposes. They consist of tubes in vertical boreholes, which are used to circulate a heat carrier fluid to exchange energy with the ground. This heat exchange is commonly dominated by conductive fluxes around the borehole, which are slow, and this is why boreholes of a depth of tens to hundreds of meters are required to reliably fulfill the energy demand of buildings. Being operated for over many decades, the thermal performance of BHEs strongly depends on the ambient ground thermal properties within the installed depth. These include the temperature regime (Rybach and Eugster 2010, Casasso and Sethi 2014, Hein et al. 2016), governing physical ground properties (Molina-Giraldo et al. 2011, Chung and Choi 2012, Li et al. 2019), as well as any heat contribution or loss around the borehole such as basal, lateral, and ground surface heat flux (Kurevija et al. 2011, Wagner et al. 2012, Rivera et al. 2015b, Radioti et al. 2017) or groundwater-controlled advective heat flux (Wang et al. 2009, Raymond et al. 2011, Zanchini et al. 2012, Hecht-Méndez et al. 2013, Angelotti et al. 2014, Dehkordi and Schincariol 2014).

There has been a growing interest recently in the role of the ground heat flux (Bandos et al. 2009, Bayer et al. 2016, Rivera et al. 2016a, b, Radioti et al. 2017, Choi et al. 2018, Jensen-Page et al. 2018, Zhou et al. 2019). This is because assuming constant land surface conditions and steady heat flux through the land surface may not be appropriate when planning BHEs for many decades. There will be accelerated ground heat flux due to global warming and due to urbanization such as observed in so-called subsurface urban heat islands in many cities (Taniguchi et al. 2008, Menberg et al. 2013, Zhan et al. 2014, Zhu et al. 2015, Bayer et al. 2019). Changes in land use are likely one of the most notorious anthropogenic perturbations in urban environments. They significantly change the coupled thermal regime at the ground surface leading in most cases to increased ground surface temperatures (GST). The associated stored heat is regarded as a potential source of low-enthalpy geothermal energy to supply the heating energy demands in urban areas (Zhu et al. 2010, Focaccia et al. 2018). As a consequence, it is revealed that neglect of such effects may underestimate the regeneration capacity of BHEs operated in an unbalanced mode. Vice versa, potential savings of borehole meters can be computed as a consequence of additional heat supply from the land surface (Rivera et al. 2016b, 2017, Choi et al. 2018).

There are various modelling techniques used for prediction of the interaction between borehole heat exchangers (BHEs) and the ground. Analytical or semi-analytical models are attractive because they are easy to use, compact and computationally efficient (Zarrella et al. 2013, Erol et al. 2015, Cimmino 2016). However, analytical formulations also cut down on the complexity of the conditions in the field by limited resolution of variations in space and time, and often by simplified specifications of boundary conditions. In this presentation, we focus on the definition of the land surface boundary condition in line source solutions in order to focus on the impact of different ground heat flux assumptions (Rivera et al. 2015a, 2017). As BHEs are thin elongated forms that can be approximated by a linear shape function, the main attention is given to radial heat transfer, but less on the axial effects. Given the long operation time, however, the sharp physical boundary at the top may exert a substantial influence on the temperature evolution in the shallow ground and thus influence the performance of the ground source heat pump. Our objective here is to inspect the effect of increased ground surface temperatures on BHE performance and extractable energy, considering long-term heat extraction from the ground. This is examined by hypothetical scenarios that are simulated by superpositioned line source formulations.

2. METHODOLOGY

2.1 Model for estimating the heat extraction rates in BHEs

The unitary response factor approach based on g-functions is implemented (Eskilson 1987). The g-functions offer a relationship between the mean borehole wall temperature and the heat extraction rate. The mean borehole wall temperature $\overline{T_{BW}(t)}$ can be calculated by superpositioning different effects as follows (Rivera et al. 2015a, 2016b, 2017):

$$\overline{T_{BW}(t)} = \overline{T_{BHE}(t)} + \overline{T_{TBC}(t)} + \overline{T_{IC}} \tag{1}$$

where $\overline{T_{BHE}(t)}$ is the contribution from the BHE itself estimated with the finite line source model, $\overline{T_{TBC}(t)}$ is the contribution from (increased) urban GST and $\overline{T_{IC}}$ is the contribution from the initial conditions defined by the geothermal gradient k and the unaffected GST T_k (Fig. 1).
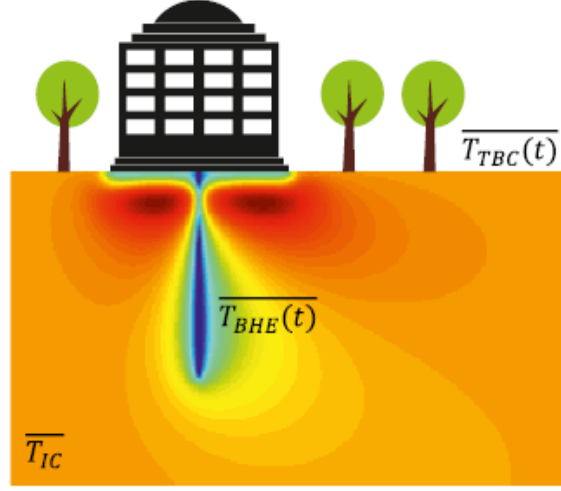

Figure 1: Illustration of superpositioning functions for calculating the mean borehole wall temperature.

The functional forms are the following (Rivera et al. 2017):

$$\overline{T_{BHE}(t)} = \overline{T_{FLS}(t)} =$$

$$= \frac{q}{8\lambda\pi} \int_{\frac{r_b^2}{4at}}^{\infty} \frac{1}{\varphi} exp(-\varphi) \left\{ 4erf\left(\frac{H\sqrt{\varphi}}{r_b}\right) - 2erf\left(\frac{2H\sqrt{\varphi}}{r_b}\right) + \frac{r_b}{H\sqrt{\pi\varphi}}\left[4exp\left(-\frac{H^2\varphi}{r_b^2}\right) - exp\left(-\frac{4H^2\varphi}{r_b^2}\right) - 3\right] \right\} d\varphi \tag{2}$$

Eq. **Error! Reference source not found.** can be formulated in dimensionless form in terms of the g-function to obtain a unitless borehole wall temperature ($\overline{\theta_{BW}}$) as follows

$$\left[T_{BW}\left(\frac{t}{t_s}\right) - \overline{T_{IC}}\right]\frac{\lambda}{q} = \overline{\theta_{BW}\left(\frac{t}{t_s}\right)} = \frac{1}{2\pi}g\left(\frac{t}{t_s},\frac{r_b}{H}\right) + \frac{\lambda\Delta T_{GST}}{q}f\left(F_o = \frac{t_{urb}+t}{9t_s}\right) = \frac{1}{2\pi}g\left(\frac{t}{t_s},\frac{r_b}{H}\right) + Q_T f\left(\frac{t_{urb}+t}{t_s}\right) \tag{3}$$

Where λ is the thermal conductivity of the porous medium, q is the heat extraction rate, t is the time of BHE operation, t_s is a time scale factor, g is the g-function estimated with the finite line source solution, r_b is the borehole radius, H is the borehole length, ΔT_{GST} is the net increased temperature at the ground surface, t_{urb} is the time of preexisting urban warming before BHE operation.

Finally, the mean temperature of the circulating temperature within the BHE can be estimated by:

$$\overline{T_{fluid}} = \overline{T_{TBC}(t_{urb} + t)} + \overline{T_{IC}} + qR(t) = \overline{T_{BW}(t)} + qR_b \tag{4}$$

where R_b is the effective thermal resistance of the borehole.

2.2 Synthetic case study

For this study, we examine the role of enhanced ground heat flux by simulating a single BHE in a synthetic case study. The specific parameter assumptions for this example are listed in Table 1 and oriented at common conditions in central Europe. As shown here 100 years before installation of the BHE, urbanization had started. In the model, we compare associated instantaneous GST increase by up to 4 K. Only two modes of operation for heating are distinguished: The first one represents the conventional scenario. Here, according to Swiss guidelines, the BHE is designed to ensure a fluid temperature above -1.5 °C for a planning horizon of 50 years. In the second sustainable scenario, the BHE is expected to never reach a fluid temperature beneath this threshold. These two scenarios thus are intended to compare full exploitation of the available energy within a given time horizon vs. continuous operation that relies

on reservoir replenishment. Obviously, the latter may benefit from enhanced heat input from the ground surface due to urbanization. These two scenarios are also contrasted with the base case, which does not account for any increase in GST.

Table 1. Physical ground characteristics and system operation parameters applied in this study correspond to the values given in Rivera et al. (2017).

Variable	Magnitude	Units
Thermal diffusivity, a	8.9×10^{-7}	$m^2 s^{-1}$
Geothermal gradient, k	0.03	$K m^{-1}$
Thermal conductivity, λ	2.4	$W m^{-1} K^{-1}$
Operational hours (full load), t	2000	hours
Borehole radius, r_b	0.14	m
Borehole resistance, R_b	0.15	$m K W^{-1}$
Initiation of urbanisation before BHE installation, t_{urb}	100	years

3. RESULTS

3.1 Conventional scenario

In a first step, the results for the conventional scenario are shown in Fig. 1. It illustrates the derived annual mean specific heat extraction rate (qL_{ayl}), as well as the specific heat extraction rate as if it were applied during full load hours per year only (qL_{flh}). These values are obviously influenced by the assumed ground surface temperature increase due to urbanization, GST. For instance, assuming a GST increase of 4°C, the resulting maximum annual heat extraction rates qL_{ayl} range between 29 W m^{-1} for BHE length 150 m and 31.5 W m^{-1} for BHE length 50 m. Interestingly, especially short BHEs are favourable with the highest feasible specific heat extraction rates, because enhanced ground heat flux mitigates subsurface heat depletion. Depending on the assumed value of GST, however, the compensating effect of ground heat flux declines with increasing borehole length, and there is a minimum specific heat extraction rate at around 150 m for a GST increase by 4 °C, at around 110 m for 2 °C, and at around 90 m for 1 °C. For greater installation depths, the specific heat extraction rates rise again.
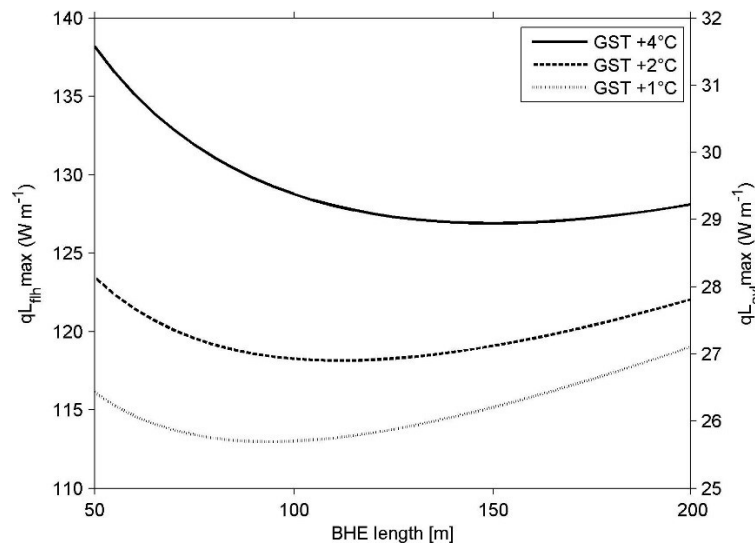

Figure 2: Feasible specific heat extraction rates for the conventional scenario: annual mean specific heat extraction rate (qL_{ayl}), and specific heat extraction rate if applied during full load hours per year only (qL_{flh})

The effect of enhanced ground heat flux from urbanization can also be illustrated with the resulting maximum extractable energy (Fig. 3). Clearly, this energy rises with BHE length, but there are differences depending on the assumed GST increase. Obviously, these differences are barely affected by the installation depth, reflected by the nearly parallel curves shown in Fig. 3.
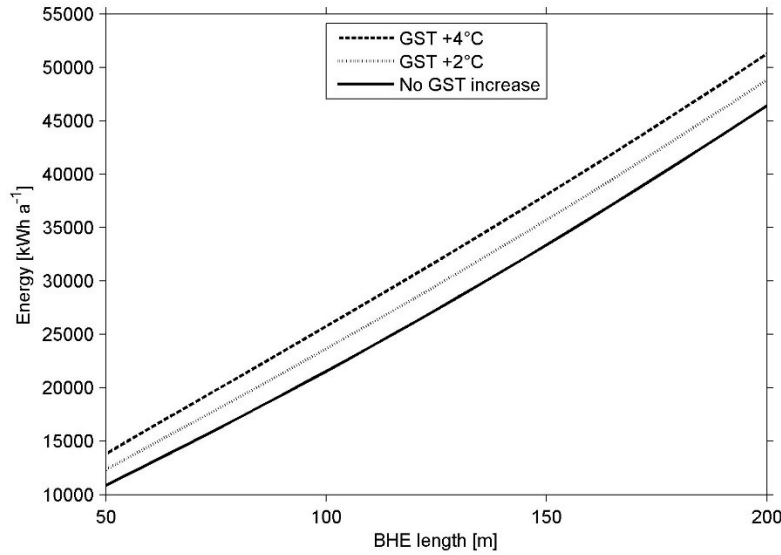
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Figure 3: Extractable energy computed for different increase of ground surface temperature (GST) for the conventional scenario.

In Fig. 4, we show the relative effect of ground surface heating. This figure depicts the energy potential compared to neglecting any changes in GST. The contour map provides values between 1 and 1.26 for GST increase by up to 4 °C and borehole lengths between 50 m and 200 m. As expected, the highest differences are found for short boreholes and for high GST increase. If we consider the common case of a 100 m borehole installed in a urbanized area with pronounced ground heating of 4°C, the energy extraction rate is by 19 % higher than when ground surface heating is ignored.
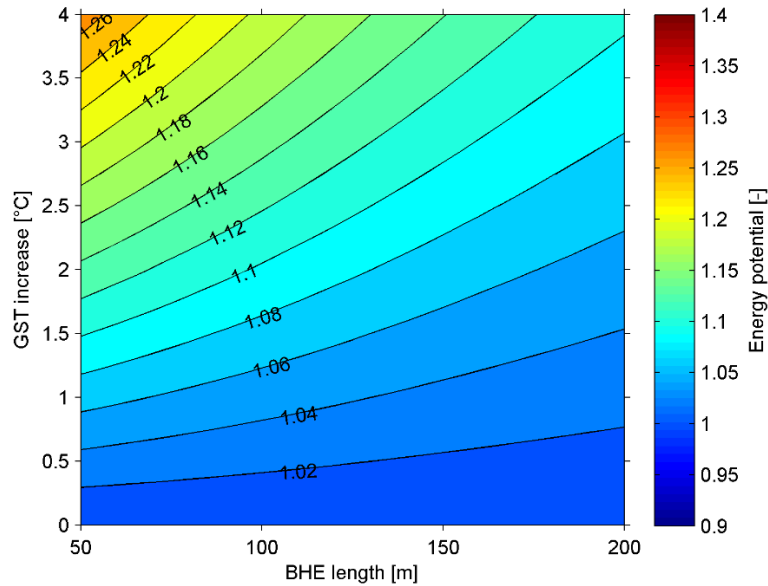

Figure 4: Ratio between conditions with ground heating (GST increase > 0°C) and those without for the conventional scenario.

3.2 Sustainable scenario

The crucial difference between the previous conventional scenario and the sustainable scenario here is that it is assumed that the ground is able to replenish the heat deficit from BHE operation in the long run. For both scenarios, according to Swiss guidelines, the temperature at the BHE is not allowed to fall below a limit value within a long-term operation horizon of 50 years. However, in this sustainable scenario, after 50 years, continued operation is foreseen. Infinite operation within the given temperature limits is only possible by applying a lower heat extraction during the first 50 years and by including axial energy replenishment of the BHE in the modelling approach. This is also revealed when comparing the specific heat extraction rates between the conventional (Fig. 2) and the sustainable scenario (Fig. 5). The obtained results show slightly lower maximally feasible values, but even so, the overall trends are similar.
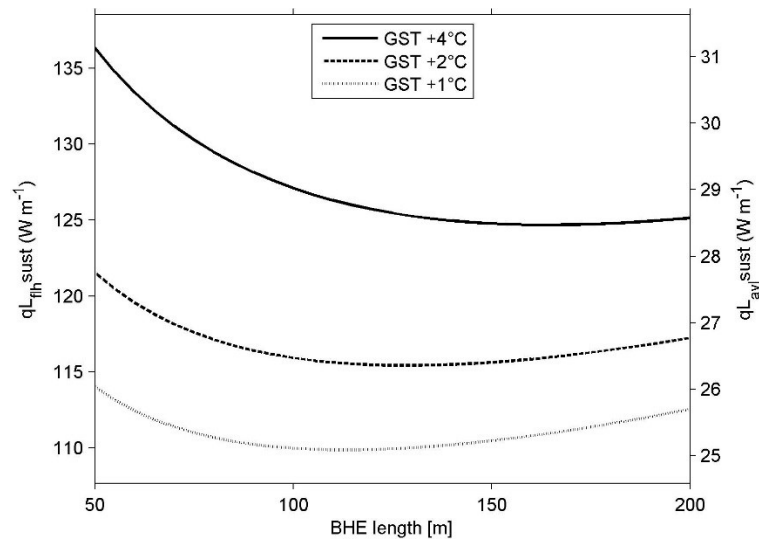
Figure 5: Feasible specific heat extraction rates for the sustainable scenario: annual mean specific heat extraction rate (qL$_{ayl}$), and specific heat extraction rate if applied during full load hours per year only (qL$_{flh}$)

Equivalent to Fig. 3, Fig. 6 illustrates the associated energy for the case without GST increase, as well as for conditions with an increase of 2 °C and 4 °C. In comparison to the conventional scenario in Fig. 3, only minor differences are observed, and the energy extracted per year (or power) is slightly smaller for the sustainable scenario.
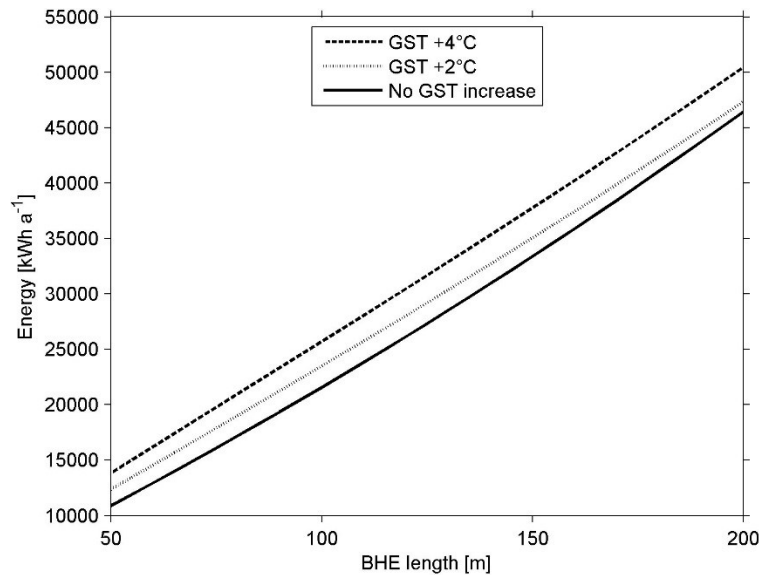

Figure 6: Extractable energy computed for a different increase of ground surface temperature (GST) for the sustainable scenario.

Finally, we also compare the relative energy potential between the results for the sustainable scenario with GST increase to that without. The reference taken is the conventional case as in Fig. 4. This means, we compare the extractable energy assuming GST increase and sustainable use to the generally considered standard case: a lifetime of the system limited to 50 years without considering any ground heating. For the sustainable scenario inspected here, the beneficial effect of increased GST is visible in Fig. 7 similar to Fig. 4. However, especially for long BHEs and small ground surface heating, the relative energy potential becomes smaller than 1. This means, sustainable operation in such case is only possible by reduced heat extraction rates. This is particularly the case for longer BHEs, where the relative contribution of the heat coming from the ground surface is smaller. Depending on the assumed GST increase, extractable energy for a BHE length of 50 m is still increased by up to 27%. However, for a BHE length of 200 m, the change in extractable energy ranges from -6.8% to +8.6%.
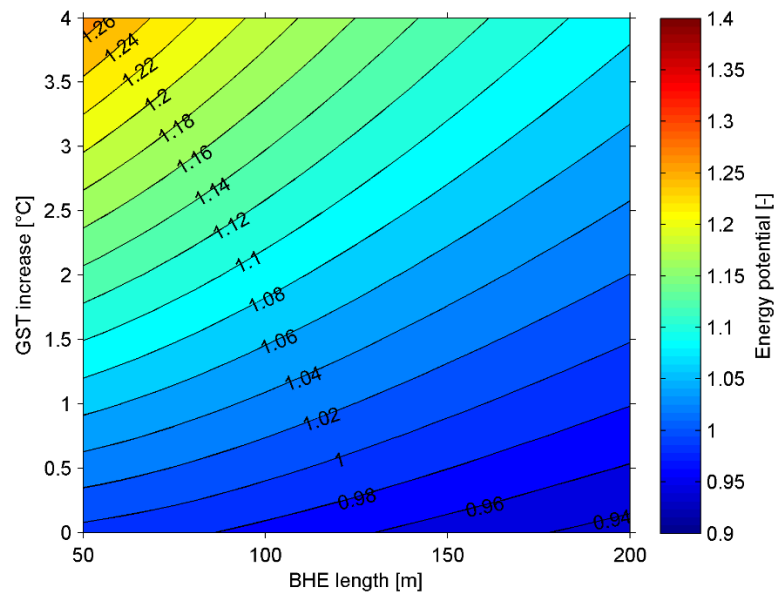
Figure 7: Ratio of extractable energy between conditions with ground heating (GST increase > 0°C) and those without for the sustainable scenario. For the reference without GST increase, the same assumptions as for the conventional scenario are applied: the system is planned for a time horizon of 50 years but without considering any longer term operation such as for the sustainable scenario.

4. CONCLUSIONS

The presented semi-analytical simulation approach was revealed to be efficient and useful for the accounting of enhanced ground heat flux as observed in urbanized areas. It is demonstrated by comparing different theoretical scenarios to the derived specific heat extraction rates, and the total energy sourced from the ground depends on the assumed value of the ground surface temperature (GST). Obviously, especially short BHEs are strongly influenced by the axial replenishment of the energy deficits from the ground surface. We also inspected the role of a crucial BHE design criterion, which is represented by the definition of a conventional and a sustainable scenario. While in the conventional variant, a standard approach is taken that ensures operation within a given planning horizon. In the sustainable scenario, operation beyond also needs to be ensured. This means, after the horizon of 50 years in this study, any deficits created by imbalanced BHE operation need to be naturally replenished. The results demonstrate that this is feasible especially if axial effects are properly represented in the model.

ACKNOWLEDGEMENTS

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