A novel model for the estimation of thermal influence of neighbouring borehole heat exchangers

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ABSTRACT

Ground source heat pumps (GSHPs) connected to vertical boreholes are popular systems to provide heat and/or refrigeration in residential and commercial buildings. The diffusion of these systems poses the question on how to effectively and sustainably handle the underground thermal resource without overexploiting it. In particular, problems can rise in densely populated areas where either heat extraction or heat rejection is dominant.

Although several models are available and used to estimate the thermal influence between individual boreholes or group of hydraulically connected boreholes, the development of models that can quantify the thermal influence of neighbouring boreholes having different boundary conditions (it is the case for individual GSHP installations in neighbourhood) is still at its early stages. The availability of such tools is essential both to enable the legislators to set appropriate rules for the allocation of the underground thermal resource and to enable the designers to properly size these systems.

In this paper, we develop a model based on the stacked finite line source method that is tailored to estimate the thermal interaction of neighbouring GSHPs. The model takes as input the heat load of each GSHP and imposes uniform temperature on every borehole. The model is applied to a fictitious densely populated area to calculate the temperature changes on the boreholes walls of the systems. The results are compared with the results obtained with another model previously proposed by the authors.

1. INTRODUCTION

Ground source heat pumps (GSHPs) connected to borehole heat exchangers (BHEs) are one of the most efficient ways to provide heating and cooling. The performance of these systems is strongly affected by the temperature of the ground in proximity of the BHE(s); in particular, higher temperatures in the underground lead to better performance of GSHPs used to provide heating.

When a single, isolated borehole is used only for extracting heat, the temperature of the ground in proximity of the BHE decreases, leading to a decrease in the performance of the GSHP system. After some years of operation, the temperature in the ground reaches an equilibrium, and so does the performance of the system.

Several neighbouring BHEs extracting heat result in longer time for the temperature of the ground surrounding the BHEs to reach the equilibrium, and in a higher temperature drop in the ground compared to a single, isolated BHE extracting heat. This means that the performance of GSHP systems in dense ground source heat pump areas (DGSHPAs), here referred to as areas where several neighbouring, independent GSHPs operate, is worse than the performance of isolated systems, if the systems are prevalently used for heating.

Since the temperature of the ground is of paramount importance to design and forecast the performance of GSHPs, several models have been developed to estimate the temperature trend in the ground surrounding BHEs (Eskilson, 1986; Hellström and Sanner, 1984; Spitler, 2000; Lamarche, 2011; Cimmino and Bernier 2014; Monzó et al., 2015; Lazzarotto and Björk, 2016). Most of the models developed so far focus on borehole fields, where neighbouring BHEs belong to the same installation and are hydraulically connected, and therefore subject to the same boundary conditions (same inlet fluid temperature).

When neighbouring BHEs belong to different installations, they are instead subject to different boundary conditions; it is the case for DGSHPAs. Being able to model such scenarios is becoming more and more important because of the increasing popularity of GSHP systems.

Differently from the tools developed for forecasting the temperature evolution around BHEs in borehole fields, the tools available for DGSHPAs are still at their early stages. A software was developed by Hellström (Stockholms stad, 2005); only a technical description was found; a detailed explanation of the underlying methodology was not found, making it impossible to reproduce the results; moreover, the software can only consider a limited number of neighbouring boreholes. Another model was developed by Witte (Witte, 2018); it is based on the infinite line source (ILS) model (Ingersoll at al., 1954), that in case of long times and distances overestimates the temperature drop in the ground. We have also proposed a model in a previous article (Fascì et al., 2018); it is based on the finite line source (FLS) model (Claesson and Eskilson, 1987; Zeng et al., 2002); this model represents the reality better than the ILS model, but still tends to overestimate the temperature drop in the ground.

We propose here a new method tailored to DGSHPAs, based on the stacked finite line source (SFLS) model (Cimmino and Bernier, 2014). The advantage of the new method lies in imposing uniform temperature as a boundary condition on each borehole wall, while our previous method, based on the simple FLS model, imposes uniform heat flux on each borehole wall. The uniform temperature boundary condition was shown to lead to a better approximation of the reality than the uniform heat flux boundary condition in most cases (Eskilso, 1986; Cimmino, 2015). A methodology based on the SFLS was prevously proposed by Cimmino and Bernier (2014) to model borehole fields, but cannot be used for DGSHPAs because it assumes same fluid inlet temperature for all the boreholes, condition that is not valid for DGSHPAs. Our methodology is therefore a generalisation of the methodology proposed by Cimmino and Bernier to DGSHPAs.

In this paper, we give a detailed explanation of the new methodology we propose, apply it to a fictitious scenario and calculate how neighbouring boreholes influence each other in our scenario. The results are compared to the results obtained using the method we had previously proposed.

2. MODEL DESCRIPTION

In this article, we propose a new methodology to evaluate the temperature trend on the borehole walls of neighbouring ground source heat pumps in DGSHPAs. The methodology is based on the SFLS model.

Each borehole in the DGSHPA is modelled as several finite segments stacked on top of each other (figure 1); the number of segments is the same for all the boreholes.

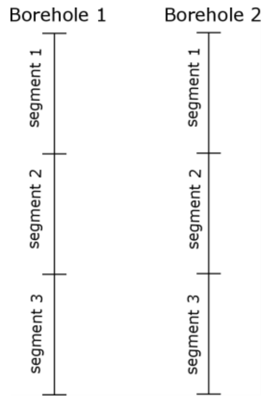

Figure 1: Boreholes modelled as finite segments stacked on top of each other.

The higher the number of segments per borehole, the more accurately the model simulates the uniform temperature boundary condition; in particular, using 1 segment per borehole corresponds to the uniform heat flux boundary condition, using 12 segments per borehole was shown to be an accurate approximation of the uniform temperature boundary condition for several scenarios (Cimmino, 2015). Each segment is modelled as a FLS. According to the FLS model (Cimmino and Bernier, 2014), the average temperature change, at time t, on the wall of a borehole segment buried at depth D_2 and long H_2, due to the constant thermal extraction of another borehole segment buried at depth D_1, long H_1, and at axial distance r, is:

$$\Delta T_2 = q_1 \cdot\ h_{1\to 2} = q_1 \cdot \frac{\left(\theta(\alpha, r, t, H_1, H_2, D_1 - D_2) - \theta(\alpha, r, t, H_1, H_2, H_1 + D_1 + D_2)\right)}{2\pi k} \qquad [1]$$

With:

$$\theta(\alpha, r, t, H_1, H_2, \Delta z) = \frac{1}{2H_2}\int_{\frac{1}{\sqrt{4\alpha t}}}^{\infty} \frac{1}{s^2} exp(-r^2 s^2) \begin{bmatrix} ierf\left((\Delta z + H_2)s\right) -\ ierf\left((\Delta z - H_1)s\right) + \\ -\ ierf(s\Delta z) -\ ierf\left((\Delta z + H2 - H_1)s\right) \end{bmatrix} ds \qquad [2]$$

$$ierf(X) = Xerf(X) - \frac{1}{\sqrt{\pi}}(1 - e^{-x^2}) \qquad [3]$$

q_1 is the constant linear heat extraction of the extracting segment; k the ground conductivity; α the ground diffusivity; and erf the error function, defined as:

$$erf(X) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}\ dz \qquad [4]$$

When several segments extract heat, superposition in space applies; therefore the average temperature change on the wall of a borehole segment can be calculated as the sum of the temperature changes due to each neighbouring borehole segment extracting heat. In an area of n boreholes, each one divided into m segments, the temperature change on the yth segment of the xth boreholes, at time t, due to a constant heat extraction of all the boreholes, is:

$$\Delta \mathrm{T}_{x,y}^{t} = \sum_{i=1}^{n}\sum_{j=1}^{m} q_{i,j}^{t} \cdot h_{i,j\to x,y}^{t} \qquad [5]$$

If the heat extraction is not constant in time, temporal superposition can be used (Lazzarotto, 2015).

The temperature change on the y_{th} segment of the x_{th} borehole, at time t_e, can then be calculated as:

$$\Delta T_{x,y}^{t_e} = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{e-1}\left[q_{i,j}^{tk}\left(h_{i,j\to x,y}^{t_e-t_k+t_1} - h_{i,j\to x,y}^{t_e-t_k}\right)\right] + q_{i,j}^{t_e} \cdot h_{i,j\to x,y}^{t_1} \qquad [6]$$

Equation 6 can be written for each borehole segment, leading to *n* x *m* equations for each time step, while the number of total unknowns per time step is *2 x n x m* (heat load and temperature of each borehole segment). The additional equations needed to solve the problem are found by imposing the boundary conditions on the heat load and temperature. Regarding the load, in a DGSHPA, the heat load of each borehole segment is unknown, but the sum of the heat loads of all the borehole segments is known for every borehole. Therefore, for each of the *n* boreholes in the DGSHPA, it can be written:

$$q_i = \sum_{j=1}^{m} l_{1,1} \cdot q_{i,j} \qquad [7]$$

This provides *n* additional equations.

Finally, if uniform temperature along each borehole is assumed as a boundary condition, for each borehole it can be written:

$$\Delta T_{i,1} = \Delta T_{i,2} = \Delta T_{i,3} = \cdots = \Delta T_{i,m} \qquad [8]$$

This reduces the number of unknown temperatures from *n* x *m* to *n*.

Therefore, the number of unknowns for such problems is *n* + *n* x *m* (*n* temperatures and *n* x *m* heat loads). For each time step, a system of *n* x *m* equations 6 and *n* equations 7 can then be used.

As an example, we show how the system looks like for two boreholes (n =2) divided into three segments (m =3):

$$\begin{bmatrix} 0 & 0 & l_{1,1} & l_{1,2} & l_{1,2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & l_{2,1} & l_{2,2} & l_{2,3} \\ -1 & 0 & h_{1,1\to1,1}^{t_1} & h_{1,2\to1,1}^{t_1} & h_{1,3\to1,1}^{t_1} & h_{2,1\to1,1}^{t_1} & h_{2,2\to1,1}^{t_1} & h_{2,3\to1,1}^{t_1} \\ -1 & 0 & h_{1,1\to1,2}^{t_1} & \cdots & \cdots & \cdots & \cdots & h_{2,3\to1,2}^{t_1} \\ -1 & 0 & h_{1,1\to1,3}^{t_1} & \cdots & \cdots & \cdots & \cdots & h_{2,3\to1,3}^{t_1} \\ 0 & -1 & h_{1,1\to2,1}^{t_1} & \cdots & \cdots & \cdots & \cdots & h_{2,3\to2,1}^{t_1} \\ 0 & -1 & h_{1,1\to2,2}^{t_1} & \cdots & \cdots & \cdots & \cdots & h_{2,3\to2,2}^{t_1} \\ 0 & -1 & h_{1,1\to2,3}^{t_1} & \cdots & \cdots & \cdots & \cdots & h_{2,3\to2,3}^{t_1} \end{bmatrix} \cdot \begin{bmatrix} \Delta T_1{}^{t_k} \\ \Delta T_2{}^{t_k} \\ q_{1,1}{}^{t_k} \\ q_{1,2}{}^{t_k} \\ q_{1,3}{}^{t_k} \\ q_{2,1}{}^{t_k} \\ q_{2,2}{}^{t_k} \\ q_{2,3}{}^{t_k} \end{bmatrix} = \begin{bmatrix} q_1{}^{t_k} \\ q_2{}^{t_k} \\ b_{1,1}^{t_k} \\ b_{1,2}^{t_k} \\ b_{1,3}^{t_k} \\ b_{2,1}^{t_k} \\ b_{2,2}^{t_k} \\ b_{2,3}^{t_k} \end{bmatrix} \qquad [9]$$

In system 9, $l_{x,y}$ represents the length of the y_{th} segment of the x_{th} borehole; $b_{x,y}^{t_k}$ is 0 at the first iteration, and otherwise calculated as:

$$b_{x,y}^{t_k} = \sum_{k=1}^{e-1}\left[q_{i,j}^{t_k}\left(h_{i,j\to x,y}^{t_e-t_k} - h_{i,j\to x,y}^{t_e-t_k+t_1}\right)\right] \qquad [10]$$

In system 9, the matrix of the coefficients is the same for all the time steps. The column vector of constant terms changes at every time step; the first *n* terms take into account the current heat extraction of each borehole, the other *n x m* terms take into account the heat extraction of each borehole segment at the previous time steps, that is why they are set to 0 at the first iteration.

By solving system 9, the temperatures along the walls of each borehole in a DGSHPA and the load profile along the borehole walls can be calculated at every time step.

In this article, we implemented the described methodology using the Julia language, and applied it to a fictitious DGSHPA chosen as a case study. We calculated the temperature evolution on the central borehole (CB) of the DGSHPA, that is the BHE most affected by the operation of the surrounding BHEs. We also calculated how all the BHEs are affected by the operation of the other BHEs at a certain time step. We compared the results obtained with the new methodology with the results obtained using our previous methodology.

3. CASE STUDY

The fictitious DGSHPA considered is characterized by boreholes arranged in a square grid; the radius of the area considered for the study is 200 m. An example of the configuration descripted is visible in figure 2 (notice that the radius considered in this paper is not the radius indicated in the picture; a smaller radius is shown in the picture for visual clarity).

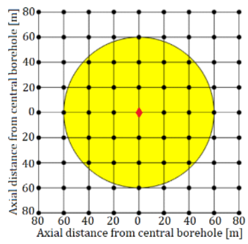

Figure 2: Configuration of the boreholes. The yellow area is the DGSHPA. The black dots within this area represent boreholes extracting heat,

arranged in a square grid. The red diamond represents the central borehole.

For simplicity, it is assumed that all the boreholes have the same annual heat extraction and geometry. The properties of the boreholes and the ground are shown in table 1.

Table 1. Borehole and ground characteristics for the case study

Borehole properties				Ground properties			
Total annual borehole heat load ($HL_{b,a}$) [kWh/year]	Length [m]	Buried depth [m]	Diameter [cm]	Conductivity [W/m/K]	Density [kg/m^3]	Specific heat [J/kg/K]	Undisturbed Temperature [°C]
10 000	100	0	15	3,1	2300	870	8

The model was run several times changing the number of segments per borehole from 1, 2, ... , 12.

3. RESULTS AND DISCUSSION

Figure 3 shows the thermal influence of the neighbouring boreholes on the CB, as a function of the years of operation of the systems and number of borehole segments used for the simulation. The results show only the influence of the neighbouring boreholes on the CB, and not the effect of the CB on itself. The results obtained using 1 segment per borehole correspond to the boundary condition "uniform heat flux", therefore to the results obtained with our previous model. The results obtained using 12 segments per borehole are assumed to correspond to the boundary condition "uniform temperature".

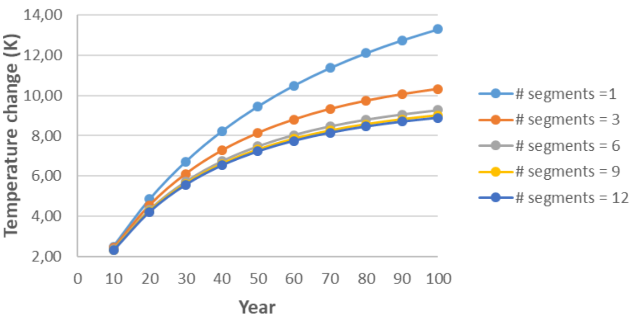

Figure 3: temperature change on the BHE wall of the CB due to the neighbouring systems.

Figure 3 shows that the results of the model vary with the number of segments per borehole used for the simulation, and that the difference in the results can be considered negligible (< 1.5%) for a number of segments higher than 9. Therefore, we can conclude that using 12 segments per borehole leads to a good approximation of the uniform temperature boundary condition also for our scenario. Imposing uniform flux boundary condition (1 segment per borehole) or uniform temperature boundary condition (12 segments per borehole) leads to significantly different results; moreover, the difference between the two results increases as the number of years increases. This is the same result observed for borehole field (Cimmino and Bernier, 2014). In particular, for the case studied, the temperature calculated at 10 years of simulation using the uniform heat flux boundary condition is around 8% higher than the temperature calculated using the uniform temperature boundary condition; the temperature calculated at 100 years of simulation using the uniform heat flux boundary condition is around 50% higher than the temperature calculated using the uniform temperature boundary condition.

Figure 4 shows the thermal influence of the neighbouring boreholes on every borehole of the DGSHPA as a function of its position from the centre of the area. The results exclude the effect of the operation of each borehole on itself. The results are shown for the 100th year of operation and several number of segments considered.

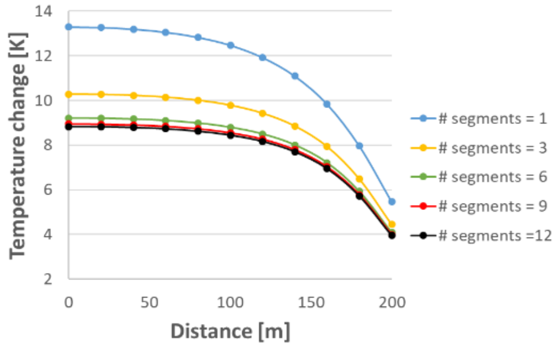

Figure 4: temperature change on the BHE walls of all the BHEs in the DGSHPA due to the neighbouring systems, after 100 years of operation.

Figure 4 shows that the results of the model vary with the number of segments per borehole also for boreholes farther from the centre, but the relative difference between the results obtained with the two different models vary with the position of the borehole. In particular, for the case studied, after 100 years of operation, the temperature of the wall of a borehole at the periphery of the area (200 m from the centre of the area) calculated using the uniform heat flux boundary condition is around 38% higher than the temperature calculated using the uniform temperature boundary condition; the temperature of the wall of a borehole at centre of the area (within 60 m from the centre of the area) calculated using the uniform heat flux boundary condition is around 50% higher than the temperature calculated using the uniform temperature boundary condition. It can be deduced that the central BHEs are more sensitive than the external BHEs to the boundary condition used.

The results obtained suggest that using the new model rather than the old one is especially important in case of long time simulation and interest in the central boreholes. Since the new model is more complicated to implement and requires more computational time, it might be useful to know under which conditions the old model is still acceptable. Another idea might be to find some rules of thumbs to adopt in order to use the old model and then scale the results as if obtained from the new model. More study is obviously needed for this.

3. CONCLUSIONS

In this paper, we described a novel methodology to evaluate the thermal interference among neighbouring BHEs in DGSHPAs. We applied it to a specific case study and showed that the results obtained with our new methodology differ significantly from the results obtained with the methodology we had previously proposed. More study might suggest that for certain scenarios the old model is also accurate enough, or that by the use of some rules of thumbs the old model can be used and then the results can be scaled as if obtained from the new model. In absence of such a study, since the new methodology gives a closer representation of the reality than the old methodology, we suggest to use the methodology proposed in this paper to study DGSHPAs.

NOMENCLATURE

BHE = borehole heat exchanger

CB = central borehole

D = buried depth [m]

DGSHPA = dense ground source heat pumps area

erf = error function

FLS = finite line source

GSHP = ground source heat pump

H = length [m]

ILS = infinite line source

k = ground conductivity [W/mK]

$l_{x,y}$ = length of the y_{th} borehole segment of the x_{th} borehole [m]

q_x = total heat extraction of the x_{th} borehole [W]

$q_{x,y}$ = linear heat extraction of the y_{th} segment of the x_{th} borehole [W/m]

r = radial distance between two borehole segments [m]

SFLS = stacked finite line source

t = time [s]

α = ground diffusivity [m^2/s]

ΔT = temperature change [K]

Δz = axial distance between two borehole segments

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