Modelling for Optimization of Brine Temperature in Ground Source Heat Pump Systems

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ABSTRACT: The potential for high energy efficiency of ground source heat pump systems has resulted in rapidly growing numbers and sizes of such installations. The energy efficiency potential of a ground source heat pump system can be further enhanced by optimized design of the ground collector and storage system. A key parameter is the brine temperature and this paper evaluates some methods for its calculation. We also introduce three key numbers to characterize ground storage systems and their load situation. Finally, the effects of different building load patterns and borehole system designs and configurations on brine temperature are analyzed.

Keywords: ground source heat pumps (GSHP), brine temperature, simulation, ground-coupled, ground heat exchanger (GHE)

1. INTRODUCTION

Requirements for heating and cooling in buildings have changed considerably in recent years. Improved building envelopes have resulted in significantly reduced heating demands in newly built and renovated buildings. In addition, the improved envelopes, together with increased internal loads, have also introduced unprecedented cooling requirements in many of these buildings. As a result, many commercial and office buildings today have cooling demands during the day, even in cold climates, and heating demands at night. Other commercial buildings, like shopping-centres and supermarkets, have simultaneous heating and cooling demands. These changes in building load profiles, coupled with the ever-increasing operating cost of the traditional heating and cooling systems, have prompted researchers and practitioners to develop and use more flexible and energy efficient heating and cooling solutions.

Under above-mentioned circumstances, ground source heat pump (GSHP) systems have emerged as an attractive option for the heating and cooling of buildings. Lately, the high energy efficiency potential of ground source heat pump systems (GSHP) has resulted in rapidly growing numbers and sizes of such installations. The attraction of this application is that, below a certain depth, the ground temperature is not affected by seasonal changes. This enables ground to be used as a heat source or a heat sink in a dissipative system. Alternatively, ground can also be used for seasonal storage of heat. The dissipative GSHP systems are designed to maximize heat transfer between the ground heat exchanger (GHE) and the neighboring ground. Storage systems, on the other hand, are designed to store thermal energy in the ground at a time of energy surplus and extract it at a later time. The energy efficiency of the GSHP systems can be further enhanced by optimized design of the ground collector and storage systems. A key parameter in this regard is the brine temperature.

In this paper, we firstly look at the reasons for identifying brine temperature as a key parameter and we present various methods to evaluate this temperature. Secondly, we calculate brine temperature for a case study. Thereafter we present key numbers to characterize GSHP systems. Finally, we illustrate how different building load patterns and borehole system designs affect brine temperature and consequently the overall system efficiency of the GSHP system.

2. BRINE TEMPERATURE

A higher brine temperature in winter and a lower in summer will increase heat transfer and positively influence the heating performance of the heat pump. However, an optimal design must be found as the winter and summer temperatures are interconnected. In addition, the design of a GSHP system requires input values of inlet and outlet brine temperatures. The design of the GHE and the capacity of the heat pump are decided based on the desired brine temperature. The GHE design method by ASHRAE [1] and software programs like EED and GLHEPRO also require brine temperatures as an input.

The actual brine temperature leaving a borehole depends on various factors including heat flux, soil and grout properties and heat transfer outside the borehole boundary etc. A common approach to model the heat transfer mechanism inside a borehole GHE is by assuming a mean borehole wall temperature (T_w) and a mean brine temperature (T_b). Heat transfer inside the borehole is generally considered as quasi-steady-state. Under these conditions the mean brine temperature can be calculated as:

$$T_b(t) = T_w(t) + \dot{q}_B(t)R_B + T_p \qquad (1)$$

where $\dot{q}_B$ is the heat flow per unit length of the borehole, R_B is the thermal resistance of the borehole and T_p is the temperature penalty because of temperature influence from surrounding boreholes.

Calculation of T_w and T_p in equation (1) is quite a challenge. Various analytic and numerical models have been developed over the years to determine T_w and T_p. The simplicity and flexibility of analytical models, like the line source and the cylindrical source, have prompted many researchers to use these models to calculate T_w, particularly for single borehole GHEs. The classical line source (LS) method models a borehole as a line source of constant heat output and of infinite length surrounded by an infinite homogeneous medium. The cylindrical source (CS) method, on the other hand, models the borehole as a cylinder surrounded by an infinite homogeneous medium. The cylinder, which usually represents the borehole outer boundary in this approach, is assumed to have a constant heat flux across its outer surface. These two analytical solutions can be applied, with few limitations, to calculate T_w for a single borehole under steady-state conditions. These models have also been used [2, 3] to calculate T_p for multiple borehole GHEs by applying the superposition principle. However, the obtained solutions are not very precise because of the inherent limitations of these models and there is still scepticism among researchers regarding the application of these models for multiple borehole GHEs.

Numerical models of varying complexity have also been developed and employed to determine for instance T_w and T_b. The work of Eskilson [4] is regarded as state-of-the-art and is the only method which accounts for the long-term influence between boreholes in a very exact way. The method called the Superposition Borehole Model (SBM) numerically models the thermal response of the GHE using non-dimensional thermal response functions, better known as *g-functions*. The thermal influence between boreholes is considered by intricate superposition of numerical solutions with transient radial-axial heat conduction, one for each borehole.

Lately, the classical LS theory has been extended and incorporation of the finite-length heat source has considerably enhanced the accuracy of the method to calculate T_w. Some researchers [5, 6] have used the finite-length LS to investigate T_w and T_p for single and multiple borehole configurations. For multiple borehole configurations, analytical g-functions are derived using the finite-length LS and the superposition principle is applied to account for thermal interaction between boreholes. Two different approaches have been used. Lamarche and Beauchamp [6] have used the integral mean temperature along the borehole depth as the representative temperature when calculating heat transfer between the borehole and the brine. For the same calculation, Diao et al. [5] instead propose the middle point temperature of the borehole. The first method, due to its superior approach, provides a better match to the numerically calculated g-functions. Both these approaches have been used [6, 7] to determine the thermal response of multiple borehole GHEs but the applications have mostly been limited to relatively simple configurations.

To summarize, various analytical and numerical solutions can be used to determine T_w and correspondingly T_b for single borehole GHEs. However, the SBM is the only method which can determine these for multiple borehole GHEs in a precise way. Other methods must be further tested and validated before they can be used to model multiple borehole GHEs.

In the following sections we will calculate brine temperatures for a case study using a few of the above-mentioned methods. The objective is to compare the methods in order to evaluate their fitness for use in multiple borehole GHE design calculations. Thereafter, to illustrate the effect on brine temperature, a sensitivity study is done in section 5.

3. CASE STUDY

The Astronomy-House building at Lund University in Sweden is selected as a case study. The building has a gross floor area of around 5,300 m^2. The GHEs, consisting of twenty 200 m deep boreholes in rectangular configuration, provide about 475 MWh of heating and 155 MWh of cooling. The monthly heating (Q_h) and cooling (Q_c) demands of the building are given in Table I.

Table I: Monthly heating and cooling demands of the case study building.

Month	**Q_h [MWh]**	**Q_c [MWh]**
Jan	97.9	-
Feb	89.3	-
Mar	69.8	3.4
Apr	40.9	7.3
May	20.9	15.0
Jun	-	25.7
July	-	33.2
Aug	-	31.3
Sep	-	19.2
Oct	31.4	13.3
Nov	47.5	6.4
Dec	77	-
Year	**475**	**155**

Brine temperature has been simulated using 5 different approaches. The first two approaches use the CS method to evaluate T_w. In the first approach T_p from surrounding boreholes is calculated using the infinite-length LS method. In the second approach, however, the finite-length line source method [6] is used. The third and fourth approaches use the infinite-length line source and the finite-length line source respectively to calculate both T_w and T_p. The fifth and final approach calculates brine temperature using the state-of-the-art SBM.

Figure 1 shows results of the simulations in terms of minimum and maximum mean brine temperature. Taking state-of-the-art SBM simulation results as the reference indicates that all five approaches provide reasonably close results. The biggest deviation for maximum as well as minimum temperature for the 15th year is less than 1 ºC. The SBM simulations were conducted using a commercial software which uses a highly accurate multipole method to determine R_b. In contrast, all other approaches used a simple analytical method [8] to calculate R_b.

Approaches 2 and 4, both of which involve the finite-length LS, gave more accurate results than approaches 1 and 3, which involve the infinite-length LS.

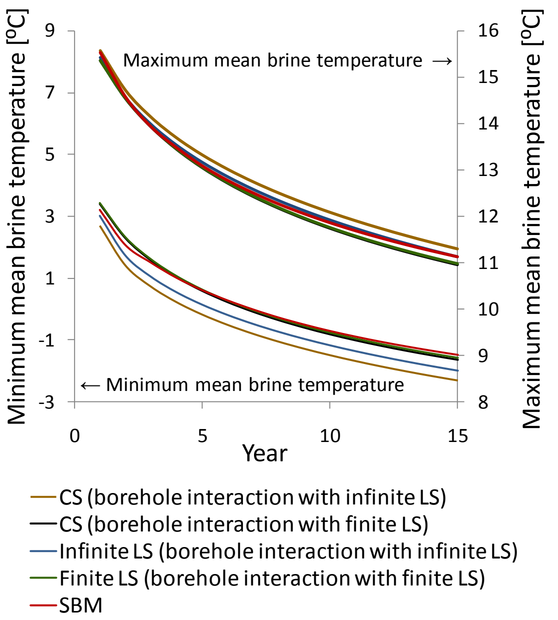

Figure 1: Mean brine temperatures using different approaches.

4. CHARACTERISTIC KEY NUMBERS

To synthesize the sensitivity study, three characteristic key numbers have been used. These numbers were first introduced by Naumov [9] to characterize GCHP systems.

The first key number, the load factor l, is the ratio of the net heating and cooling demands of the building to the sum of their absolute values:

$$l = \frac{Q_h + Q_c}{|Q_h| + |Q_c|} \; [-]$$

The concept of load factor is useful to characterize buildings based on their heating and cooling demands. Its value lies between -1 and +1. The two values indicate the extreme conditions of cooling only and heating only requirements respectively.

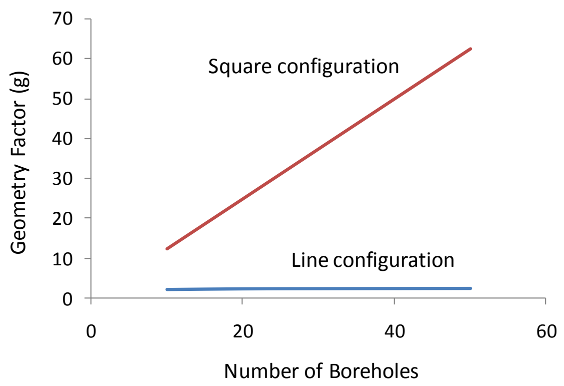

Figure 2: Geometry factor for line and square configurations.

The second key number, the geometry factor g, is defined as the ratio of the volume V of the ground system and its heat exchange area A:

$$g = \frac{V}{A} \; [\mathrm{m}]$$

The significance of g is illustrated in Figure 2, where g is plotted for the two contrasting cases of line and square configurations. For the line configuration g remains almost constant while for the square configuration g increases linearly with increasing number of boreholes.

Lastly, to characterize the correlation between building load and the GHE, the concepts of specific borehole load for heating, q_h, for cooling, q_c, and in total, q_{tot}, are introduced:

$$q_h = \frac{Q_{B,h}}{L_{tot}} \quad , \quad q_c = \frac{Q_{B,c}}{L_{tot}} \quad \text{[kWh/year/m]}$$

and

$$q_{tot} = |q_h| + |q_c| = \left|\frac{Q_{B,h}}{L_{tot}}\right| + \left|\frac{Q_{B,c}}{L_{tot}}\right|$$

where $Q_{B,h}$ and $Q_{B,c}$ represent heat removed from the borehole during heating and heat injected to the borehole during cooling respectively. L_{tot} is the total length of the GHE.

The specific borehole loads q_h and q_c are used to indicate the heat transfer load on the boreholes for heating and cooling respectively. They are standard key values for sizing boreholes. The total specific borehole load q_{tot} is a utilization measure of the total useful heat transfer in relation to the borehole investment. The use of the complementary value q_{tot} is beyond the scope of this paper and will be discussed in future publications.

5. SENSITIVITY STUDY

In this section, the effects of variations in characteristic key numbers on the brine temperature are presented.

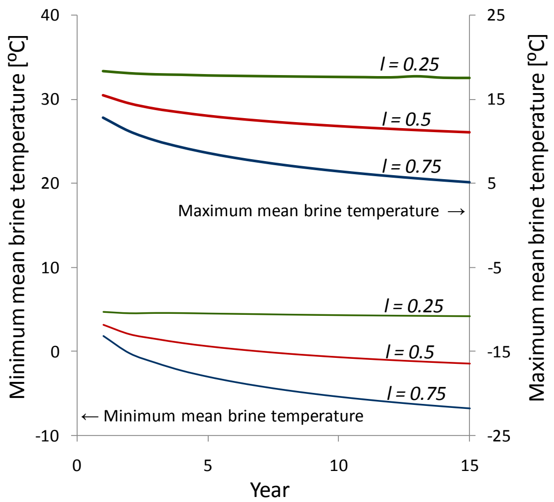

Figure 3: Brine temperatures for different load factors.

The Astronomy-House has a total load factor of l=0.5, which indicates that it is a heating dominated building. In Figure 3 the actual situation in the building is compared with two scenarios of l=0.75 and l=0.25. These scenarios are developed by varying values of heating and cooling demands while keeping the sum of their net absolute values equal to the original case.

For l=0.25, both maximum and minimum mean brine temperatures remain unchanged throughout the simulation time period. This is because, for values of l around zero, the rectangular configuration ground system, if designed appropriately, acts like a heat storage system and brine temperatures do not deteriorate over time. However, for l=0.75, there is a sharp decline in both maximum and minimum mean brine temperatures with time. This is due to a decrease in the ground temperature because of consistent unbalanced heat extraction from the ground.

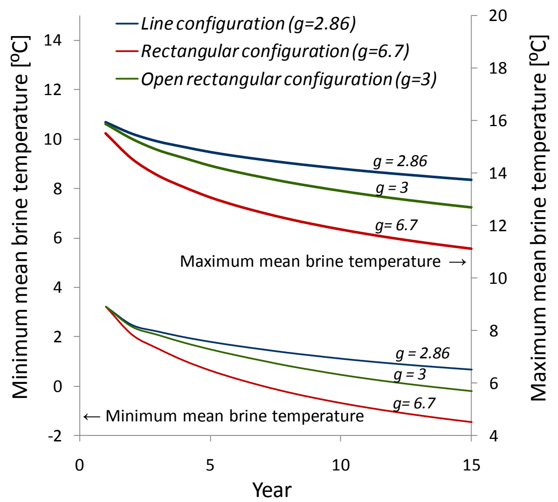

Figure 4: Brine temperatures for different geometry factors.

For predominant heating or cooling loads, as for l=0.75, the performance of the GSHP system will deteriorate significantly if a rectangular ground system is selected. In such cases, a dissipative system with more open ground configuration will result in more desirable brine temperatures. This can be seen from Figure 4 which presents brine temperatures for various geometry factors (*g*). As seen, a line configuration has the lowest *g* value. This represents the most open configuration and will ensure maximum heat transfer with the ground. It will result in a minimum decline of the brine temperature. This, however, is undesirable in the Astronomy-House case as the objective of this system is to exploit the ground's heat storage ability and hence a rectangular configuration was chosen. The selected system was designed to take care of the expected decline in borehole temperature with time.

5. CONCLUSION

In this paper, an evaluation of different methods to simulate the brine temperature in GSHP systems was presented. The evaluation showed that even simple analytical methods can be used with reasonable accuracy to evaluate brine temperatures both for single borehole and multiple borehole GHEs. The effects of variations in building load patterns and borehole system designs and configurations indicate major effects on the resulting maximum temperature during cooling and minimum temperature during heating. To synthesize the findings, three characteristic key numbers were presented. The simulation results endorse the well established practice of using the rectangular configuration for storage systems and more open configurations for dissipative systems.

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