Analysis and modeling of a large borehole system in Sweden

Alberto Lazzarotto[1], José Acuña[1], Patricia Monzó[1]

[1] KTH - Royal Institute of Technology, Department of Energy Technology, Brinelvägen 68, S-100 40, Stockholm

alberto.lazzarotto@energy.kth.se

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ABSTRACT

This paper presents a study on the thermal simulation of a large existing borehole thermal energy storage (BTES) system located in Stockholm, Sweden. The bore field investigated presents an uneven pattern, which comprises vertical and inclined boreholes, for a total of 130 units. Such complex bore field geometry cannot be modeled with the current available commercial design tools. The test case presented is utilized to explore the influence of boundary conditions and level of detail utilized for representing the model geometry on the output of the simulation. Two boundary conditions and three geometrical configurations were studied. The results show that, in the considered case, the results obtained with the tested models give a marginal difference, hence also the greatest level of simplification can be utilized without loosing accuracy in the analysis.

1. INTRODUCTION

The design of bore field systems for shallow geothermal application requires the use of mathematical models for the long term prediction of the thermal behavior of these systems. Many of the available modeling tools for the thermal simulation of bore fields (Blomberg et al., 2015; Spitler, 2000) are based on the so-called Eskilson's g-function approach (Eskilson 1987). In this method the ground is modeled as a semi-infinite solid with uniform and isotropic thermal properties. Under these conditions, the heat transfer process is governed by a linear partial equation and superposition of the effects can be applied. As a result the so-called borehole temperature, a key variable that influences the overall performance of bore field systems, can be computed by using convolution methods which are fast from a computational point of view, hence suitable for design.

An important novelty introduced in the work of Eskilson was the idea of determining a suitable borehole temperature response for an entire borehole field. In particular he focused on the evaluation of the borehole response temperature to a unitary step heat injection for bore fields in parallel arrangement. This condition was approximated by imposing uniform temperature along the boreholes and among the boreholes as heat is injected in the bore field (Cimmino et al., 2013). Eskilson utilized a numerical code (Eskilson, 1986) to calculate these temperature responses in non-dimensional form and built a database containing responses for a large number of bore field configurations (the g-functions). This database constitutes the foundation of state of the art design tools.

A parallel path to the studies performed by Eskilson on numerical modeling has been taken by several authors who worked on the development of models based on analytical solutions given their computational efficiency, robustness and flexibility. These models were firstly explored by Ingersoll, Plass (1948) and by Carslaw, Jaeger (1959) who introduced respectively the infinite line source and the cylindrical line source models. Claesson and Eskilson addressed the problem of the three dimensional nature of the heat transfer in the surrounding of a borehole heat exchanger and proposed a finite line source model in the unpublished journal article "Conductive Heat Extraction by a Deep Borehole. Analytical Studies." contained in Eskilson's PhD thesis (Eskilson, 1987). In the last decades many researchers (Claesson and Javed, 2011; Lamarche and Beauchamp, 2007; Zeng et al., 2002), further developed this analytical solution in order to make it usable for calculation regarding multiple borehole systems. Cui et al. (2006), Marcotte, Pasquier (2009)and Lamarche (2011) utilized finite line sources to simulate borehole systems with inclined boreholes showing the variety of conditions where these kind of methods can be applied.

In a recent development by Cimmino, Bernier (2014) a semi-analytical method based on finite line sources has been employed to reproduce the boundary conditions used by Eskilson for the generation of g-functions. The authors compared their results with g-functions from Eskilson for a large set of configurations and found good agreement between the two methods. A similar methodology has been then utilized by Lazzarotto, Björk (2016); Lazzarotto (2016) to study the case of arbitrarily inclined borehole systems.

As it is clear from the literature review given so far, the modeling technique within the field of borehole systems has been evolving over the years to provide fast computational tools capable of a greater level of detail both in regards to the physical description of the system as well as in regards to its geometrical representation. In this paper we present a study where a few selected modeling strategies with different level of complexity are applied to simulate the thermal behavior of a large existing bore field system characterized by a relatively articulated geometrical configuration. The objective is to evaluate the effect that the choice of boundary conditions and the detail utilize for the geometrical representation of the system have on the simulated results for the given study case.

2. METHODOLOGY

This section presents the system object of study and the set of modeling strategies that have been investigated within this work. The conditions reviewed comprises two sets of boundary conditions and three different geometrical configurations.

The analysis of the dynamic behavior of the bore field has been performed using the g-functions methodology. g-functions have been calculated for each of the modeling strategy investigated using the methodology reviewed by Lazzarotto (2016). The computed g-functions along with the design loading condition for the actual borehole system have been then utilized for the calculation of the temperature of the brine circulating within the borehole heat exchangers after a life-time horizon of 25 years.

2.1 The bore field

The bore field analyzed is an existing system that has been recently built at the Stockholm University Campus to supply heating and cooling to a group of offices and laboratories. The analysis provided in this paper is relative to design condition..

The geometrical configuration of the system consists of 130 boreholes unevenly distributed within the available ground volume. Two of these boreholes are 270 meters long while the remaining ones are 230 meters long. A plan view of the configuration is shown in Figure 1a: the blue dots represents the drilling point at the surface while the blue segments represents the projection of the boreholes into the surface for those boreholes that are inclined in comparison with the vertical direction.

2.2 Simplified geometrical configurations

The design configuration described in section 2.1 is relatively complex and the calculation of the g-function for such a system is a challenging problem that can be tackled only using advanced research tools. It is therefore of interest studying the g-function of the original configuration, but also of simplified geometrical configuration which are easier to compute.

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"Mid point geometry". The first simplification introduced consists in eliminating the difficulty of studying arbitrarily inclined boreholes. Each non-vertical borehole has been substituted by a vertical one placed at the mid point of its projection on the plan view. An illustration of the plan view of this system is given in figure 1b. The boreholes in this case are vertical and are marked with red triangles. The original borehole field is plot in transparency for reference.

"Hexagonal pattern". The second simplification introduced consists in placing the boreholes uniformly in the storage area. The 130 boreholes of the system are placed in hexagonal pattern as illustrated in figure 1c (green squares). The distance between neighboring boreholes in this case is uniform. The choice of this distance has been made in order to get a good match between the green area in figure 1b and the red area in figure 1c. Both areas are the ones delimited by the convex hull relative to the set of points representing the boreholes for the considered bore field configuration. The main idea behind this choice is studying two system that occupies roughly the same volume but have a slightly different borehole distribution.

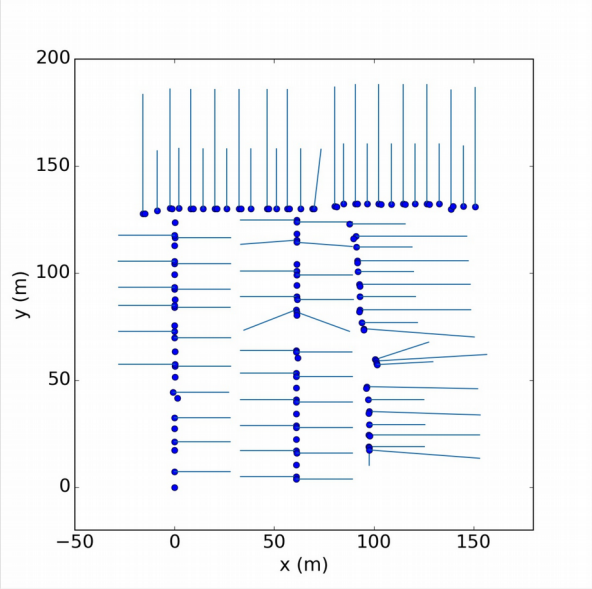
2.3 Boundary conditions

A key aspect in the thermal analysis of bore field system is the set of boundary conditions utilized for the calculation of the g-function. In this study two classical boundary conditions are investigated. The notation utilized is coherent with the one introduced by Eskilson (1987)

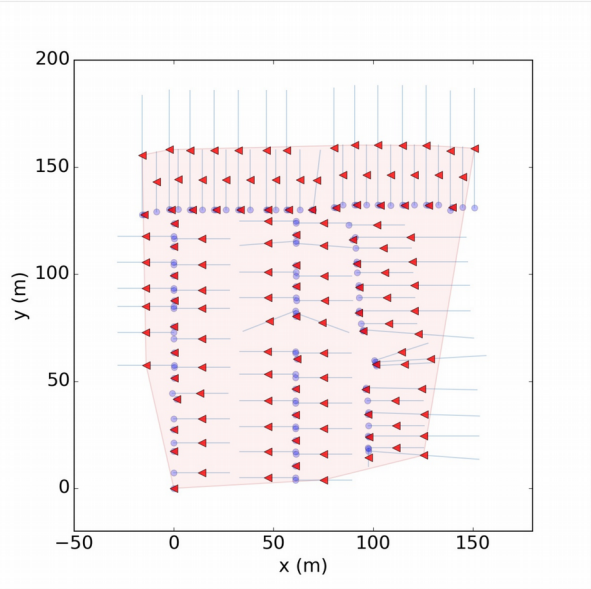
BC1. Boreholes are modeled as finite line sources. The heat flux injected along the boreholes is uniform. The temperature along the boreholes is not uniform and the borehole temperature T_b is computed as the mean temperature along the boreholes.

BC3. Borehole are modeled as finite lines, but in this case the distribution of heat in not uniform. Instead, heat is distributed so that the temperature along the borehole and among the boreholes is uniform and equal to the borehole temperature T_b.

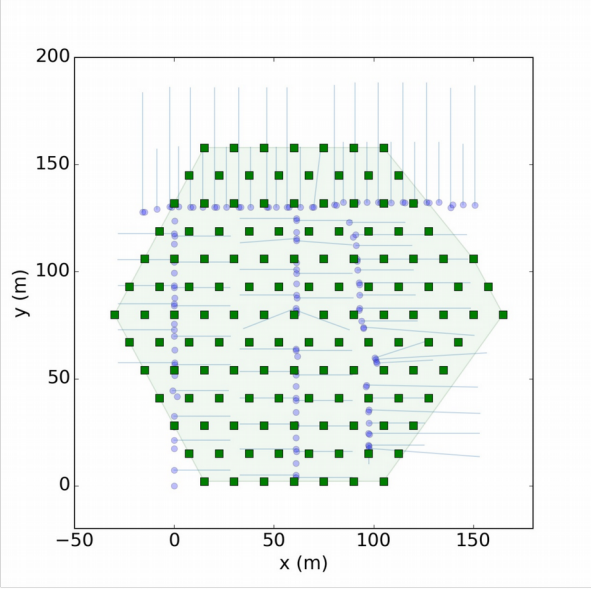
BC3 is the boundary condition utilized by Eskilson for the calculation of g-functions and is regarded as the reference condition. An in depth review on boundary conditions for the calculation of g-functions has been recently done by Cimmino, Bernier (2014).



(a) Design Configuration



(b) Mid point configuration



(c) Hexagonal pattern

Figure 1: Plan view of the bore field geometrical configurations considered within this study.

2.4 Fluid temperature calculation

Given the g-function g(t) for the system object of study, the fluid temperature is calculated as follow. Time is discretized into hourly steps and for each step j, a correspondent value for the borehole temperature $T_b[j]$, a value for the g-function g[j] and a value for the heat per meter injected into the ground $q_0[j]$ are defined. The unknown borehole temperature is calculated by applying the superposition of effects according to the following expression:

$$T_b[j]-T_0=\frac{1}{2\pi k_g}\sum_{i=2}^{j}(q'[i]-q'[i-1])\,g(t[j]-t[i]) \qquad [1]$$

Where T_0 is the undisturbed ground temperature and k_g is the thermal conductivity of the ground. Since the load q'[i] with i = 1,⋯,j is given, this calculation has been performed using an equivalent method based on FFT (Marcotte and Pasquier, 2008) that ensure great computational performance.

Once the temperature $T_b[j]$ is given, the fluid temperature is then calculated using the following expression.

$$T_f[j]-T_b[j]=q'[j]R_b \quad [2]$$

where R_b^* is the effective borehole thermal resistance. The value of the resistance R_b^* and of thermal conductivity utilized for the calculations within this paper are respectively 0.06 m K/W and 3.9 W/m K.

3. RESULTS AND DISCUSSION

3.1 g-function analysis

The results of the calculation of the g-functions for the six cases investigated are given in figure 2. Purple curves are relative to calculations performed using the BC1 boundary condition while light blue curves are relative to calculations performed using the BC3 boundary condition. Solid lines, dash-dot lines and dashed lines are relative respectively to the design geometry, to the 'mid point" configuration and to the "hexagonal pattern" configuration. Finally the black solid line with triangle markers is the infinite line source solution for a single borehole system which is displayed for reference. The g-functions are plotted in the classic fashion as a function of $\ln(t/t_s)$ where t_s equal to $H^2/9\alpha_g$ is the time when the system approach steady state conditions.

Figure 2 shows that the six systems analyzed can be clustered into three groups with distinguishable g-function:

• ***group 1***: BC1 - design configuration, BC1 - "mid point" configuration, BC1 - "hexagonal pattern".

• ***group 2***: BC3 - "mid point" configuration, BC3 -"hexagonal pattern".

• ***group 3***: BC3 - design configuration.

Moreover, three time regions can be distinguished within the plot:

• $-8 \leq \ln(t/t_s) < -6$: All the g-functions are coincident and equal to the infinite line source solution. At this stage there is no mutual thermal influence between neighboring boreholes.

• $-6 \leq \ln(t/t_s) < -3$: The g-functions are still coincident but they deviate from the infinite line source solution. In this region the thermal influence effect is noticeable but the set of configuration and boundary conditions investigated yield negligible difference in the thermal response.

• $\ln(t/t_s) \geq -3$: The three groups of g-functions introduced in this section start to deviate. The effect of boundary conditions and geometry plays a role in the thermal behavior of the system.

The results show that the major factor that affects the response temperature for the systems investigated is the choice of boundary condition. For boundary condition BC1 all the three geometrical patterns studied yield roughly the same g-functions showing that in this case the simplifications introduced in the geometrical pattern do not affect the thermal calculation. For boundary condition BC3 there is a deviation between the g-function of the original configuration and the ones relative to "mid point" and "hexagonal pattern" configurations: the original configuration with inclined boreholes yields significantly greater g-function values for $\ln(t/t_s) > -2$ suggesting that the heat distribution in the ground for this case is noticeably different in comparison with the one relative to the simplified geometrical patterns.

3.2 Time frame of interest

Traditionally g-functions are represented as a function of the non-dimensional time $\ln(t/t_s)$. This is a useful representation that enables the description of the temperature response for families of configurations with a given set of common characteristics. The drawback of this representation is that it is arguably not so intuitive from a physical perspective. For this reason an extra axis with a time scale in years has been added to Figure 2. The time scale is relative to the system object of study where $\alpha_g = 1.875e^{-6}$ m^2/s and H = 230 m.

The introduction of the new time scale is functional to analyze the g-functions considering that by design the installation life-time horizon is typically set at around 25 years. For the case study considered the 25 years time threshold corresponds to $\ln(t/t_s)$ equal to -1.38. Although this value of $\ln(t/t_s)$ is within the region where the three groups of g-functions considered mutually diverge, their difference is still relatively small and therefore the three groups of systems are expected to behave in a similar fashion.

3.2 Bore field system simulations

In order to quantify the effect of the choice of model for a time-horizon of 25 years, an hourly simulation of the dynamic variation of the temperature of the secondary fluid circulating within the ground loop has been performed. The thermal loading condition considered for this test (Figure 3) is the load that has been utilized for the design of the installation.

Figure 4 displays the results of the simulation. The yearly mean borehole temperature for the systems investigated increases with time since the yearly injection load is greater than the yearly extraction load. Even though a discrepancy between the fluid temperatures obtained with the different models is present, this difference is relatively small: the maximum difference between group 1 and group 3 is 1°C and the maximum temperature difference between group 2 and group 3 is 0.45 °C.

The divergence between the models increases with time as the effect of the yearly unbalanced becomes more relevant.

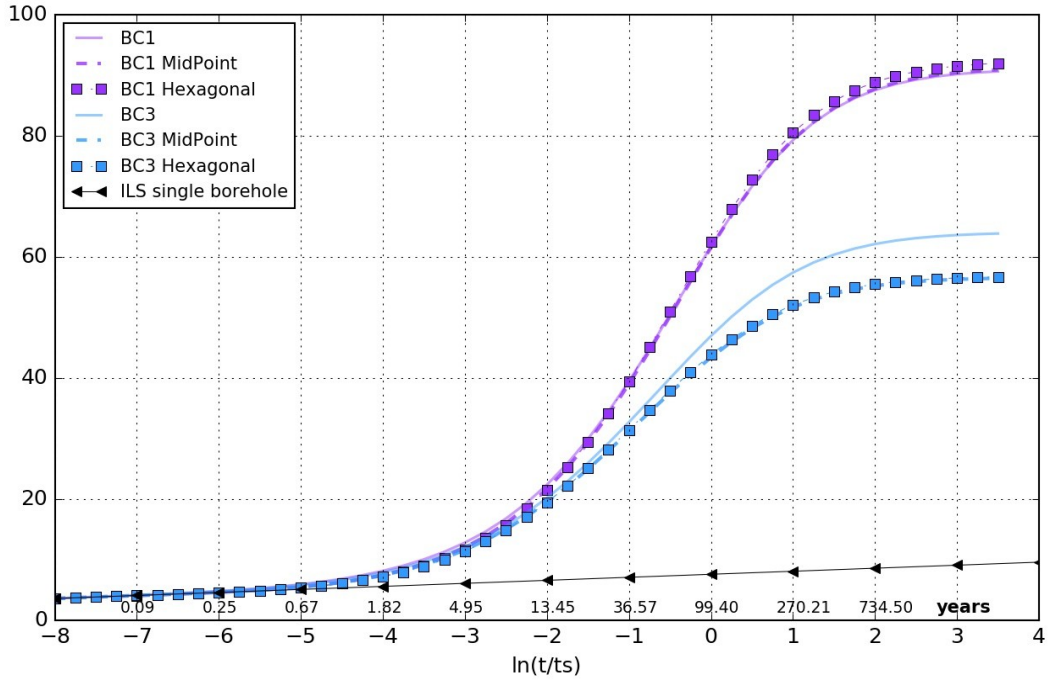


Figure 2: g-functions computed using BC1 and BC3 boundary conditions for the three geometrical configurations investigated. The g-functions are plotted as functions of the non-dimensional time $\ln(t/t_s)$ with t_s equal to $H^2/9\alpha_g$. An additional axis has been added to visualize time in years for $\alpha_g = 1.875e-6$ m^2/s and H = 230 m.

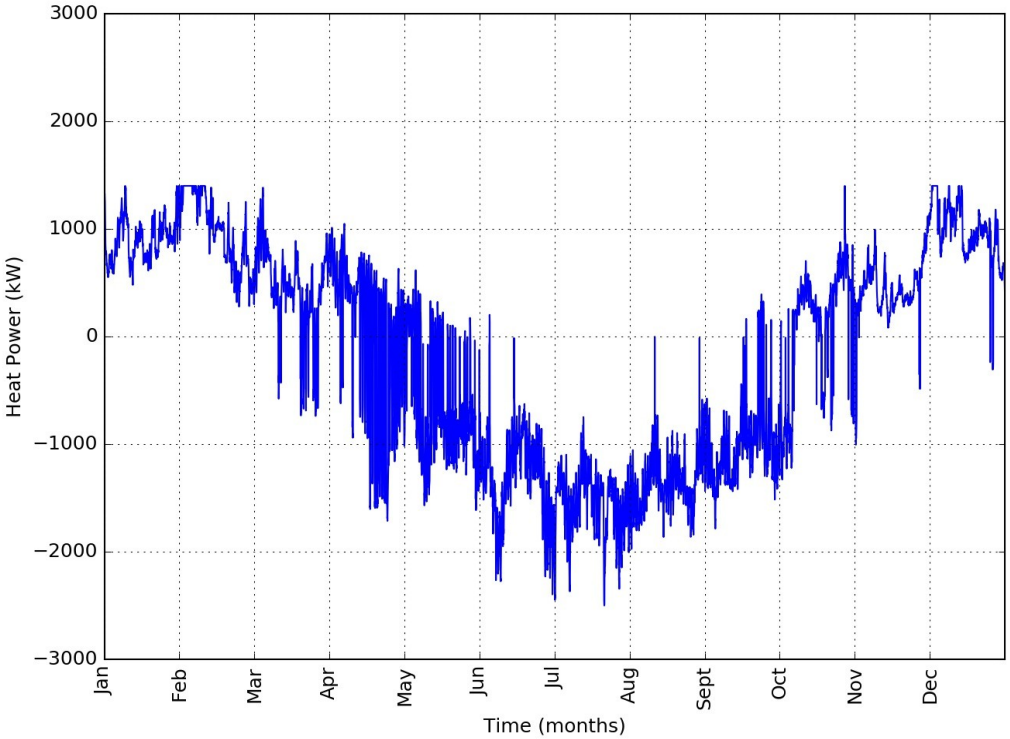


Figure 3: Design ground loading condition

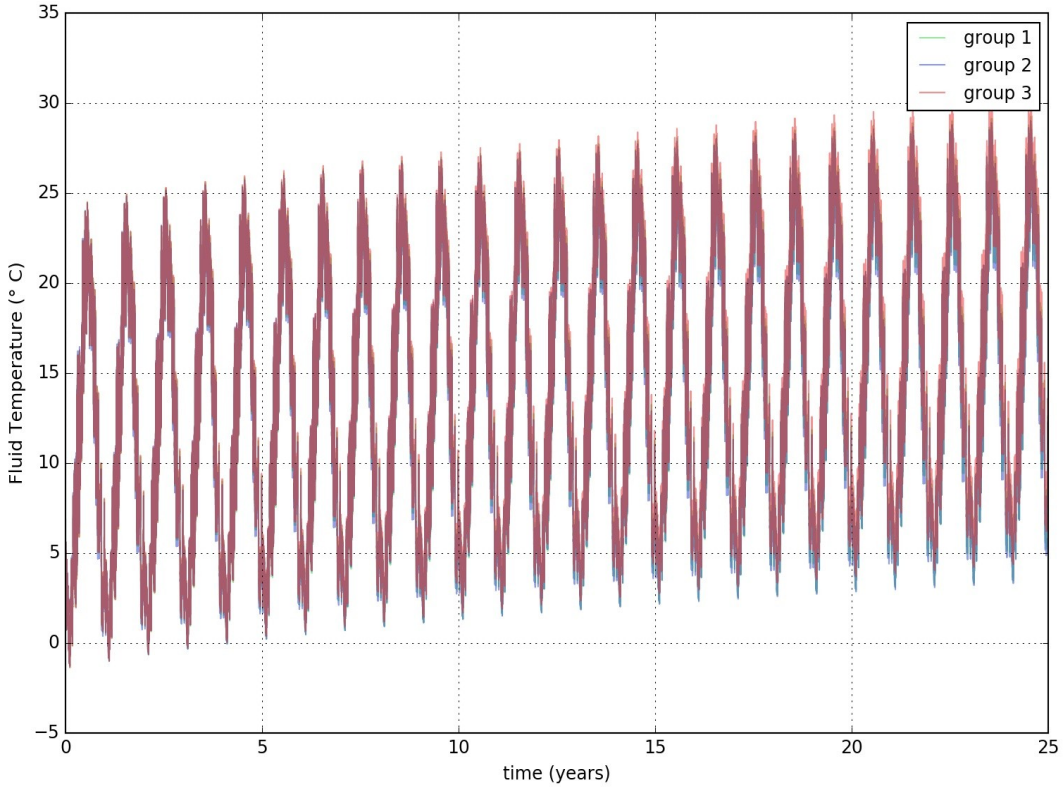


Figure 4: Fluid temperature resulting from a 25 years hourly simulations. The three curves are relative to the three groups of bore field systems considered yielding distinct g-functions (section 3.1).

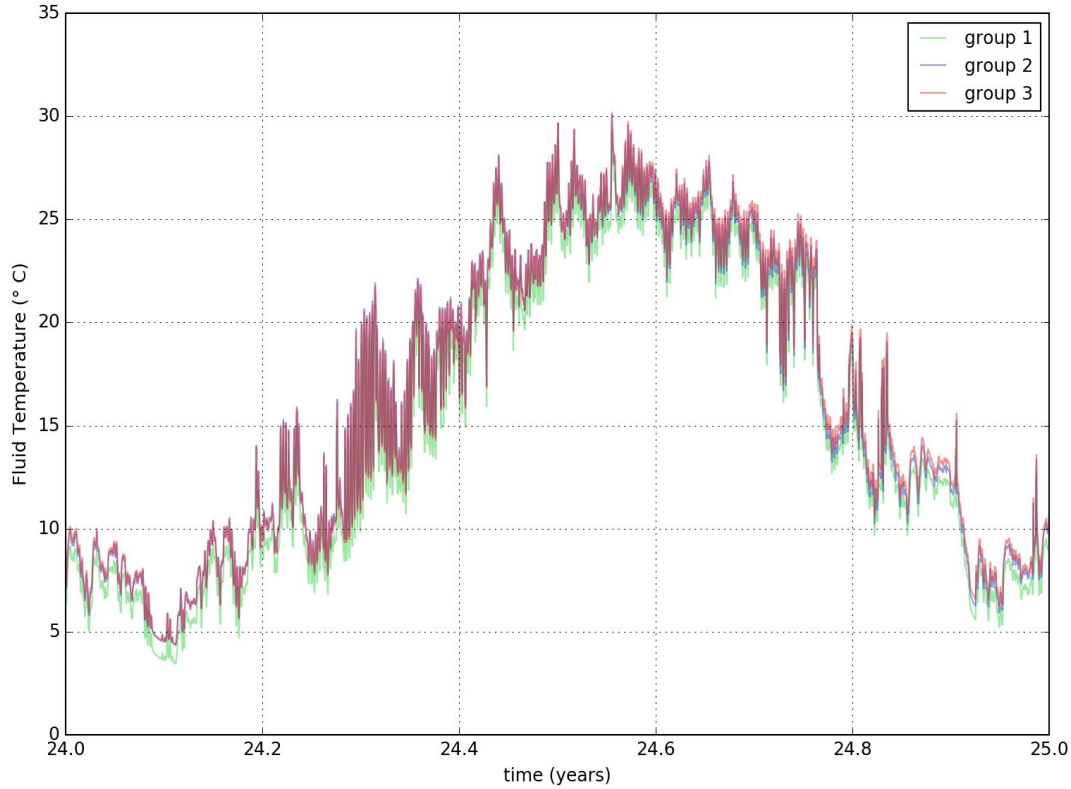


Figure 5: Fluid temperature during the 25th year of operation.

Figure 5 shows the fluid temperature for the three groups of systems investigated during the 25th year of operation which is the period when the models yields the greatest differences within the design time frame. The divergence between the models will tend to increase also after the 25th year as it can be easily derived from figure 2.

4. CONCLUSIONS

In this paper we investigated the effect of the choice of boundary condition and geometrical configuration on the modeling of an existing large bore field system. The configuration studied presented a relatively complex geometrical pattern with both vertical and inclined boreholes. Such system cannot be studied with standard simulation tools commercially available and requires advanced research tools. Two simplified configurations were proposed as possible substitute to the original configuration for modeling purposes. Concerning the physical modeling of the system, both uniform heat flux boundary condition (BC1) and uniform temperature boundary condition (BC3) were investigated.

The six models studied showed similar thermal behaviors and negligible temperature differences from a bore field design perspective. In conclusion for this particular study case the proposed approximations of the geometrical pattern and of the boundary condition are acceptable and yield results that are comparable with the ones obtained with more sophisticated models capable of a more detailed description of the system. A major reason for this result is the fact that the 25 years life-time horizon utilized for bore field design is a relatively short time in comparison with the dynamic of the bore field configuration analyzed within this study.

4. ACKNOWLEDGMENTS

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