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MODELLING OF A LARGE BOREHOLE HEAT EXCHANGERS INSTALLATION IN SWEDEN

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ABSTRACT

In the last years the ground source heat pump (GSHP) systems achieved resounding success in the Swedish market thanks to a growing technological and economic development. The increasing demand of cooling energy, in commercial and industrial fields, encouraged the growth of a larger market of geothermal systems with multiple boreholes.

This technology represents an important component in the strategy to reduce the energy consumption and limit the greenhouse gas emissions in order to reach Europe's climate and energy targets.

The project has been conducted from March 2015 to September 2015 at the Department of Energy Technology of KTH Royal Institute of Technology.

During this exchange period, a large scale installation of 130 boreholes with uneven pattern placed in Stockholm has been simulated. In this context, different study cases have been analysed: a single borehole, a couple of boreholes, a group of boreholes and, at the end, the whole installation divided in different thermal zones.

The first task was to check the validity of the code against relevant publications and the possible limitations of the analytical model based on the Finite Line Source (FLS).

The aim of the thesis is to simulate the thermal process of this uneven boreholes field and predict the fluid temperature's drift under different conditions in the short-term and in the long-term. The effect of the imbalance between cooling and heating demand has been examined with special attention to the starting simulation month.

As a result, the differences in the g-function values observed between the proposed method and the pre-processor increase directly with the increasing number of the boreholes.

At the end of the analysis, the decrease of the energy flow's imbalance turns out to be effective to the improvement of the system's performance, decreasing the maximum reached fluid temperature.

SOMMARIO

Negli ultimi anni i sistemi geotermici a pompa di calore hanno riscontrato un grande successo nel mercato Svedese, soprattutto grazie ad un crescente sviluppo economico e tecnologico. Specialmente nel settore industriale e commerciale, la crescente richiesta di raffreddamento degli edifici ha incoraggiato lo sviluppo di un nuovo e ampio mercato di sistemi geotermici a elevato numero di scambiatori.

Questa tecnologia gioca un ruolo chiave all'interno della strategia intrapresa dalla Svezia per raggiungere gli obiettivi europei di riduzione dei consumi energetici e delle emissioni di gas serra.

Il progetto è stato svolto da Marzo 2015 a Settembre 2015 presso il "Department of Energy Technology", presso il KTH Royal Institute of Technology. Durante questo periodo di scambio, l'incarico principale è stato quello di simulare il comportamento termico di un'ampia installazione di 130 sonde geotermiche, non uniformemente distribuite e installate nella località di Stoccolma.
L'idea è stata quella di suddividere il lavoro in diversi casi studio. Inizialmente, è stato valutato il comportamento termico di un singolo scambiatore isolato e, in seguito, di gruppi con numero crescente di sonde. Il confronto tra i diversi casi ha permesso di valutare come variano le temperature del fluido e del pozzo in relazione al numero di sonde geotermiche e di capire come le possibili interferenze termiche possano alterare le caratteristiche del sistema.

Prima di procedere con le simulazioni, bisognava verificare la validità del codice Matlab con i recenti approcci e individuare possibili limiti del modello analitico basato sulla teoria FLS.

Lo scopo principale della tesi è di studiare il processo termico per la configurazione assegnata e prevedere l'andamento della temperatura del fluido termovettore in un intero anno, con carichi orari, e l'evoluzione termica fino a venti anni, con carichi mensili.

Sono state simulate diverse situazioni di funzionamento sotto differenti condizioni. E’ stato valutato l’effetto dello sbilanciamento del carico termico nel breve e nel lungo periodo, con particolare attenzione anche al mese di avvio delle simulazioni.

Il modello di simulazione non ha mostrato una sufficiente accuratezza nel calcolo del fattore di risposta termica con gli ultimi approcci sviluppati, in particolare nel lungo periodo. La differenza tra i profili delle “g-functions” diventa sempre più preponderante al crescere del numero di scambiatori nella configurazione studiata.

Di conseguenza, l’approssimazione della geometria e la suddivisione dell’intera installazione in diverse zone termiche hanno permesso di poter simulare il comportamento termico dell’intera configurazione.

Al termine dell’analisi, la riduzione dello sbilanciamento del flusso di energia nel profilo termico si è dimostrata essere l’azione più efficace per ridurre la temperatura massima raggiunta dal fluido termovettore e, quindi, incrementare l’efficienza del sistema.

TABLE OF CONTESTS

1. INTRODUCTION

1.1 Background

One of the most innovative and attractive way to supply heating and cooling demand, in residential and commercial buildings, is represented by Ground Source Heat Pump (GSHP) systems.

In the last years the use of this technology spread gradually across the world, since it is suitable to decrease operational costs of energy supply system and to reduce as the use of fossil energy sources as the dependence on the imported fuels.

It must be said that the fossil fuels represent the major competitor with less initial investment costs, but then the decrease of oil and gas supplies and their increasing price make the ground an even more economically viable alternative source of energy.

Geothermal systems have got success in Sweden, where the geothermal energy is dominated by low temperature, shallow geothermal systems and direct use. Indeed GSHP stands for one of the most installed systems, which supply energy demand approximately to 20% of the Swedish buildings, making Sweden one of the first leading countries within this technology, not only in terms of annual energy use but also in terms of installed capacity **[1]**.

According to the study made by Andersson and Bjelm in 2013, the geothermal energy is the 3rd largest renewable energy source used in this country, thanks to an incredible growth of the GSHP systems related to their high energy efficiency potential **[2]**.

Nowadays the geothermal heat pump’s market represents the predominant market in Sweden, playing a significant role in Sweden’s dwellings to achieve a sustainable development.

Starting from the end of the 1970s, after the oil crisis, different solutions were taken in order to reduce the use of oil for heating. In the early 1980s the use of heat pumps, coupled with ground as heat source, gained suddenly popularity in Sweden and by 1985 a large number of installations were recorded.

At that time the poor reputation about available technology and the withdrawal of subsidies for heat pump technologies caused a significantly deadlock of heat pump market in the late 1980s and early 1900s. Indeed the low quality and poorly performing heat pumps led to a negative public view of the technology's reliability.

The real growth of the Swedish GHP market arrived in 1995 thanks to the strong support measures of the Swedish State and to the programme sponsored by the Swedish Agency for Economic and Regional Growth (NUTEK)**[3]**.

With the aim of developing reliable and improved heat pumps for residential buildings, this programme increased the sales of geothermal heat pumps. At the beginning of 2000s the total number of installations reached the peak around 200,000 units, covering about 90% of the residential market **[4]**.

The data from the Swedish Heat Pump Association until 2015 show that about 500,000 GSHP systems are installed in Sweden, of which in the last five years around 25,000 GSHP units have been installed per annum, especially for small power sizes. The prevalent variants of GSHPs are small systems which supply individual residential houses with an installed mean power by around 10 kW **[5]**.

In addition to the consolidated residential market, during last few years a new market for larger shallow geothermal energy systems is rapidly enhancing due to increasing interest of cooling in the commercial and industrial sector **[6]**.

1.2 Technology description

First of all, let us make clearer what a heat pump system consist on. Heat pump plays an important role for space and water heating as well as for cooling purpose in the building and industry market. Today more than one million of heat pump units are installed in Sweden, mainly in residential dwellings **[7]**.

The heat pumps use renewable energy sources from ground, air and water: everyone gets various advantages as well as disadvantages and has a strong influence on their capacity. Renewable sources of heating and cooling can also be cheaper than fossil alternatives in the long-term operation and contribute to significantly energy savings.

They provide energy from a heat source to a heat sink through auxiliary energy use, as electricity or gas, moving thermal energy in opposite way to the natural direction; from low to high temperatures. Then the extracted heat from the ambient (heat source) is supposed to be supplied at higher temperature to the building (heat sink) using a compressor. Furthermore they can provide cooling energy by operating in reverse mode.

This technology relies on a vapour compression cycle, with two simple principles: evaporation and compression. The cycle includes two heat exchangers, one compressor and one expansive valve in order to carry heat from one space to another one. Afterwards the energy is usually supplied via radiators, floor heating system or fan coil units.

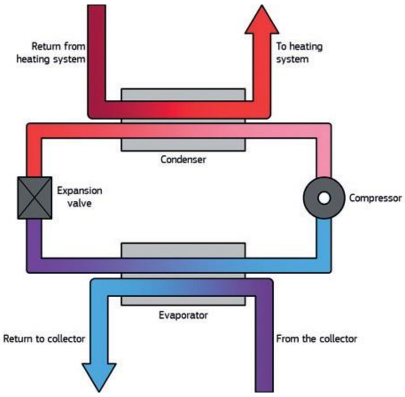


Figure 1.1: Vapour compression cycle for a Ground Source Heat Pump system

The efficiency of a heat pump unit is described by the Coefficient of Performance (COP) in the heating mode and by the Energy Efficiency Ratio (EER) in the cooling mode, which are the ratio of the output energy divided by the input energy. Heat Pumps can reach efficiency by 3 or 5, which means that one unit of electricity is transformed into three or five units of heat (in the case of heating mode).

In order to fulfil the heating and cooling demand, Geothermal Heat Pumps (GHPs) are one of the most widely used technologies in the world, since geothermal heat is an inexhaustible source of energy.

These systems could be divided in two main groups depending on the temperature level of heat source they reach.

A great amount of heat could be reached up to depths of around 5000 m by deep geothermal systems, which employ heat at high temperatures to generate electricity or for direct heat use applications. Furthermore we could obtain greater efficiency by using cascade methods, which employ the waste energy from electricity generation. Instead shallow geothermal systems, working at depths less than 300 m, use heat at lower temperature in order to supply the heating and cooling demands **[4]**.

The use of deep geothermal energy systems is limited in Sweden and only one plant is in operation. Since this country is dominated by low temperature, the market of shallow geothermal energy systems has a growing trend **[5]**.

Depending upon the type and availability of land and the possibility of drilling economically a water well, we can divide the GHPs in two different types: groundwater systems and ground-coupled systems.

The first one is open loop system, which uses ground water or lake water directly in heat exchanger. Then, depending upon the local laws, it is discharged into another well, into a stream or lake or more over onto the ground.

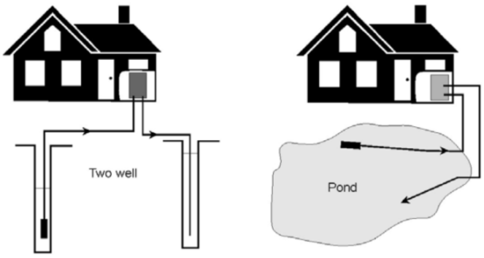


Figure 1.2: Open loop heat pump systems (source: Geo-Heat Centre)

In this kind of installation, single U-pipes are generally used in boreholes, making easier these systems, which have a slightly higher heat transfer capacity.

The second one is closed loop system installed horizontally or vertically in the ground with a heat circulating fluid through the plastic pipes.

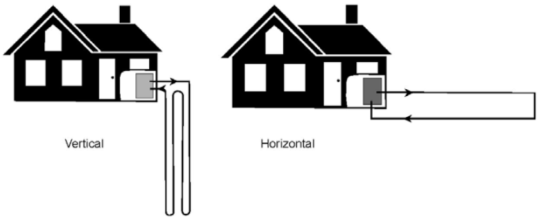


*Figure 1.3: Closed loop heat pump systems (source: Geo-Heat Centre***)**

In this case, double U-pipes are sometimes used in order to extract heat from the ground in winter or reject heat to the ground in summer.

The type of heat exchanger has a strong influence on the cost of the system and on the heat exchange. The horizontal pipes, for example, are the most common type of system since their smaller installed depth let to decrease the drilling costs. They concern the shallow layers of the ground and do not go deeper than 1,5 m, but they need large areas of installation. Anyway they have a lower efficiency since they are affected by variable heat loads cause of solar radiations and other weather conditions that influences the ground temperature change in the upper layers **[8]**.

In contrast, vertical pipes request smaller land and offer a higher efficiency, since they are affected by smaller seasonal swing in the ground temperature. Anyway they are more expensive than horizontal pipes. The cost of technology is influenced by the reached depths; indeed the deeper the borehole goes, much more expensive the GSHP is **[9]**.

1.3 Aim of the study

The technological and economical improvements make the GSHP system the main technology to supply the energy demand in both residential dwellings and large commercial buildings.

The relatively constant mean temperature of the ground, compared with the ambient air, the lower operating costs and the lower maintenance requirements, compared to ones of a conventional system, represent the main advantages related to this technology.

Solar radiations increase the efficiency of the GSHP recharging the ground and maintaining a quite constant temperature under about the first 13 meters deep, even throughout winter **[10]**. The temperature difference, between the heat source and the heat sink, is thus lower and this leads to a higher efficiency.

During last few years, larger heat pump installations are steadily growing in the commercial and industrial sector, where the cooling demands find more interest. Especially for larger borehole systems, the main point in question concerns the long-term behaviour of the borehole heat exchangers. It is important to have a long-term balance between the heat extracted from the ground and the heat injected to the ground: a remarkable imbalance could induce thermal anomalies.

It must be said that at northern latitudes the heating energy demand of residential buildings is not always balanced with the cooling energy demand, as consequence this imbalance influences the performance of these systems **[11]**.

A long term heat extraction from the ground, during the heating season, produces a ground and working fluid temperature changes along with a lesser capability of the borehole field to regenerate itself. Besides, this deviation is emphasized by borehole field geometry and by interferences between multiple neighbouring boreholes. The closer the boreholes are, the greater the thermal interference is **[12]**.

Recently research activities are focusing on the optimization of the borehole heat exchangers by studying different operational modes and different geometry arrangements.

The thermal process analysis relies on the interaction between the local process and the global process: the first one influences the heat transfer capacity of ground heat exchanger; the second one the heat losses from the store. The thermal local process involves interaction of different boreholes, while the thermal global process studies the heat losses of the whole studied volume.

The main aim of this project is to assess the performance of the borehole field and obtain an important fluid temperature prediction for different conditions of load profile and layouts. This work intends to realise a complete study on the thermal response of the installation.

Further, the idea is to compare simulated data and real data from the committed installation in order to test and validate the last developed theoretical models.

The project has been conducted from March 2015 to September 2015 in cooperation with the Department of Energy Technology, at KTH.

First of all, it is important to investigate the main topic and the technology used and then examine the current results of the last approaches, also by analysing different real cases in order to understand the theory's limitations.

For this thesis a long work is carried out concerning a real large installation placed in Stockholm and funded by Akademiska Hus and other companies. This project is financially supported by Swedish Energy Agency in collaboration with Tyréns, Skanska, Stures Brunnsborrningar and Akademiska Hus for the next three years.

It is possible to sum up the main tasks performed in these months through the following points:

- Validation of the Matlab code and design of a new arrangement geometry according to the last approach
- Simulation of the thermal process in an uneven bore field configuration
- Short-term and long-term simulations of the heat carrier fluid temperature with the given load profile
- Prediction of the fluid temperature for a balanced load profile and with special attention to the starting operation month

In this project, it will be simulated the thermal behaviour of a single borehole, of a couple of boreholes, of a small group of boreholes (manifold) and of the whole installation.

Hourly and monthly load profiles will be used in order to outline the fluid temperature profile in the short-term (1 year) and in the long-term (20 years).

Several comparisons between different cases will be carried out in the dissertation. The purpose is to understand the influence on the fluid temperature of an increasing number of boreholes, of reducing the imbalance between heating and cooling demand and of changing the starting simulation month.

The final results will give an important contribution to check the agreement of the model with the reality and to enhance the settled geothermal installation.

This is something interest for the people who are working on the control of the system, in order to find new solutions to get better the performance of the system.

From the next month (October 2015), the installation will start working and supplying the energy demand to the building. For this reason it will possible to measure the real values and compare them with the simulated results.

2. *THEORETICAL BACKGROUND*

2.1 Model of a single borehole heat exchanger

During the first months, a long work was leading in order to get as much knowledge as possible about geothermal energy, ground heat source pumps and borehole heat exchangers, by reading several sources such as reports, papers and scientific books.

Starting from an overview on the heat pump technology theory, the work was gradually focused on the ground heat exchange.

The main task is to study the thermal behaviour of the bore field and predict the fluid temperature in order to estimate the performance of the heat pumps connected to those boreholes.

First of all, it is important to explain the model of a single borehole and how it could be designed. We must bear in mind that an important part of the costs of the system is the heat exchanger in the ground. A single geothermal borehole is used to exchange heat with the surrounding ground, which acts as a heat source during winter or a heat sink during summer. For the design of the boreholes, it needs to be defined the heat transfer between the heating carrier fluid and the borehole and between the borehole and the ground. In most of the approaches, the heat transfer process is simplified taking into consideration mainly the heat conduction problem when the groundwater flow is neglected.

The amount of the heat exchanged with the ground influences the borehole wall temperature change and the temperature of the ground surrounding.

A vertical heat exchanger buried in the ground is sketched in the Figure 2.1. The most common heat exchangers are vertical and typically have one or two U-tubes, through which the heat carrier fluid circulates exchanging heat with the surrounding ground. But in this case the solution models the legs of the U-tube as a single equivalent-diameter pipe.

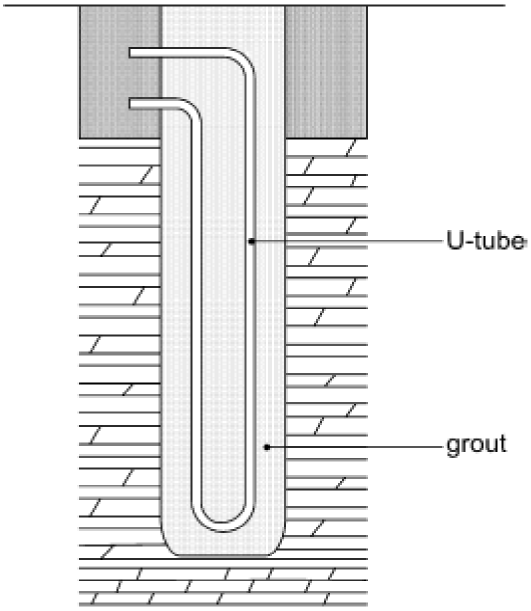


Figure 2.1: Vertical borehole sketch (Source: Lamarche and Beauchamp, 2007)

The heat carrier fluid flows down to the bottom of the borehole with an inlet temperature T_{fi} and it is heated by the rock. Then it goes upwards and exits at the temperature T_{fo}, which is influenced by the exchanger's length.

In order to simplify the model two mean temperatures are taken into account: the fluid mean temperature Tf(t) and the borehole wall mean temperature Tb(t). By considering a quasi-steady state for the inner problem, the following relation (1) models the heat transfer from the ground to the inner part of the borehole, when the heat extracted per unit length of the borehole q'(t) is negative.

$$Tf(t) - Tb(t) = q'(t)\, R'b \qquad (1)$$

With

$$Tf(t) = \frac{Tfo\,(t) + Tfi\,(t)}{2} \qquad (2)$$

This is the classical approach used to study the behaviour of vertical heat exchangers.

In the equation (1), R'b is the borehole resistance per unit length in the borehole. As in most of the classic approaches, the internal part is modelled as a simple thermal resistance. It takes into consideration the convention between the fluid and the borehole wall, the conduction in the tube walls and the conduction in the grout.

Obviously the heat flux per unit length, showed in the equation, can be positive or negative in sign depending on season. In winter, when the heat is extracted from the ground, it is negative and the fluid temperature will be lower than the undisturbed ground temperature. In summer it will be the opposite.

Then we have to talk about the last term participating in the equation, it is the borehole wall mean temperature Tb(t) and it depends on the thermal response of the soil.

The borehole wall temperature can be computed by the equation (3).

$$Tb(t) = Tg + q'(t)\ Rg \tag{3}$$

In the analysis of the geothermal system, some simplifications have been carried out for practical purposes. Pure conduction and homogeneous ground properties around the boreholes are considered, such as mean conductivity and mean diffusivity. In addition the ground is characterized by an undisturbed temperature Tg.

Depending on the heat rate exchanged, the process affects the thermal behaviour of the ground on the long timeframe. As a consequence, the borehole wall temperature becomes a key parameter which is calculated defining the ground thermal resistance R_g.

2.2 Study of the g-function

Over the years, analytical and numerical solutions were carried out in order to design the vertical and inclined boreholes, used in GCHP systems, and to investigate the long-term system performance. Basically we could split the various approaches in two main groups: short-term performance or long-term performance.

About the first group, the Duct Storage Model (DCT) proposed by Hellström, is one of the well-known numerical models. These kinds of models are used as design tools or in whole-building analyses **[13]**.

On the other hand, for large time response, the axial effect phenomena and the thermal interferences between boreholes became relevant.

Obviously a long term operation influences the ground temperature change, particularly in case of unbalanced thermal load profiles with heating or cooling predominance.

One of the first models was published in 1954 by Ingersoll, whose approach was called “Infinite Line Source” (ILS). Ingersoll used a line source model to study the vertical ground heat exchanger with some assumptions for very simple borehole field configurations, as a monthly average heat transfer rate **[14]**.

The other well-known solution is the Cylindrical Heat Source (CHS) proposed by Carslaw and Jaeger. The first edition of their work was in 1946 and then the second review in 1959. They studied the heat conduction process in the solids with the purpose of predicting the temperature distribution by spatial superposition of the infinite line source analytical solution **[15]**.

Both of these models study the distribution of the ground temperature surrounding the borehole and provide solutions to the radial transient heat transfer problem. Nevertheless they cannot model properly the borehole heat transfer and are quite inaccurate when determining the short-term response.

In the 1980s Eskilson addressed these issues and gave an important contribute to calculate the thermal response of a borehole field. He commits himself in order to improve the previous methods, introducing the non-dimensional thermal response factor, also known as “g-function”, thought to study the ground thermal resistance. Once boreholes field configuration and geometrical characteristics are known, Eskilson shows the temperature changes around the boreholes and the influences on heat transfer between the boreholes and the ground. The g-function is defined by the following relation:

$$Tb\ (t) = Tg + \frac{q(t)}{2\,\pi\,kg} * g\left(\frac{t}{ts}, \frac{rb}{H}, \frac{B}{H}, \frac{d}{H}\right) \qquad (4)$$

Where T_b is the average temperature of the borehole wall, T_g is the undisturbed ground temperature, q(t) is the given heat extraction, k_g is the ground thermal conductivity.

The g-function is dimensionless and depends on the non-dimensional time t/t_s, where t_s is the characteristic time of the bore field, α_s is the ground thermal diffusivity, r_b/H is the borehole radius to length ratio, B/H is the borehole spacing to length ratio and D/H is the active length ratio, which has a relevant impact on the g-function.

Eskilson proposed a numerical solution based on a finite difference method where he assumes a total constant heat flow in the borehole field and equal temperatures at each time step along the borehole, for all of them. The boundary condition at the borehole wall makes the analytical solution different from the numerical one, since the heat flux is constant at the borehole wall.

In the analytical solution, recalled “Finite Line Source” (FLS), the g-function is determined using a line heat source with finite length. The borehole is studied in a two dimensional way where the boundaries are $r > r_b$, with r_b as borehole radius, and $D \leq z \leq H$, where ‘D’ is the ground water level and ‘H’ is the total length of the borehole.

For the analytical process, he took the temperature at the middle point of borehole length to calculate the heat process between the borehole and heat carrier fluid.

Furthermore he divides the borehole length in the active part and inactive part, which represents the superficial layers, which do not contribute to heat exchange. By studying single boreholes, he showed that the variation of the inactive part of the borehole (D) from 2 m to 8 m barely influence boreholes with depths greater than 100m **[16]**.

Due to a long computing time of the g-function generation especially for large borehole fields, several g-functions were pre-computed numerically for different borehole configurations and then they were stored as a database in commercial software. The computing restrictions of that period do not allow to apply his solution in the g-function process.

The limiting factor in Eskilson’s work is represented by the fact that he computed the g-functions only for symmetrical and standards layouts. Sometime the available land area for installation of the ground loops does not allow to install a symmetrical or even configuration. In these cases g-functions need to be calculated separately **[17 – 18]**.

Zeng tried to find a solution for the flexibility issues introduced by Eskilson's g-functions. By a model of a line source with finite length in a semi-infinite medium, he analyses the heat conduction process of vertical boreholes in a GCHP systems. His solution is similar to the solution suggested by Eskilson and he takes into account a constant value of the borehole wall temperature in the middle of the finite line source.

The suggested method finds difficulty to be applied in some cases owing to the excess time to generate the solution and to the discrepancies with numerical values **[19]**.

In order to reduce the computation time, Lamarche and Beauchamp showed a different approach modelled on computing the "g-functions" and analyse the thermal response of vertical heat exchangers. They suggested a new analytical model by simplifying the FLS solution from a double integral to a single integral. The results are similar to the numerical values tabulated in the literature.

They obtained more accurate results using the integral mean temperature along the borehole length and introducing some more simplifications. They observed that the calculation is more accurate using the borehole's average temperature, since the temperature at the middle of the borehole overestimated the borehole wall reference temperature. In addition, the angular dependence was neglected and the mean transport properties of the surrounding ground were taken into account. The aim of their studies was to find a model able to work with any kind of borehole pattern **[20]**.

Later the FLS method was extended in order to include new configurations with inclined boreholes. The heat source is represented by a finite line source (FLS method) along the axis of the borehole.

The model cannot be simplified as a single integral as in the case of vertical boreholes but it can generate very quickly the g-functions for more different borehole field configurations **[21]**.

Following these theories the Matlab code was modelled and then validated by comparing the g-functions values generated with the results obtained by Eskilson from 1986. The thermal response factor was simulated following the FLS analytical approach for vertical and inclined BHE.

The code does not take into account the new approaches which we are going to talk on.

Recently, Javed and Claesson in 2011 developed an analytical approach to study the thermal response factor from very short times to very long times. It needs to join the long-term response and the short-response at a suitable breaking time. He uses an analytical radial solution for short time, up to the breaking point, and the long-term response is calculated using a finite line source solution.

The two legs of the U-tube are approximated to a single equivalent-diameter pipe and they take into account an average value for the heat carrier fluid temperature between the inlet and the outlet of the U-tube.

Special care should be taken to calculate the exit fluid temperature, which influences the performance of GSHP systems. It depends upon both the short-term response of the borehole and the long-term response of the surrounding ground **[22]**.

In the last few years, new methods were proposed to approximate the g-functions. Starting from the concept introduced by Eskilson, Cimmino and Bernier studied a new method based on FLS solution accounting the thermal interferences among boreholes.

In the proposed method the heat extraction rate is not constant, while the heat extraction rate of the borehole field is constant over time. In this case all boreholes have the same mean borehole wall temperature and each borehole was broken down into segments modelled by a finite line source.

The results show that this method has a good agreement with Eskilson’s numerical model, especially for small times. Instead some differences take place especially for larger times owing to two different boundary conditions used at the borehole wall. While Eskislon assumes a uniform temperature at the borehole wall, in the proposed method the heat transfer rate is uniform along the height of the boreholes **[23]**.

Later their aim was to simplify this approximation of g-functions based on the FLS solution in order to work with variable borehole lengths and buried depths. The new methodology was implemented by Matlab in order to pre-processes the hourly values of the thermal response factors for use in energy simulation programs.

By the FLS solution it is possible to value the temperature distribution around individual boreholes, seen as finite line source. Then by the spatial superposition of all boreholes' contribution they calculate the temperature variation at the borehole walls. The third step is characterized by the temporal superposition, which account for the time variation of the heat extraction rates of individual boreholes.

The values of borehole-to-borehole response factors are pre-calculated through a spline interpolation, which reduce the number of evaluations and also the number of time steps in the temporal superposition. Then the g-functions are calculated and exported by the pre-processor. Knowing the variable total heat load profiles per borehole length, the geometry configuration and the g-function, the borehole wall temperature is calculated by temporal superposition of the g-function **[24]**.

The difference between the g-functions obtained by the FLS solution and by Eskilson was less than 5% in most analysed cases of different bore field configurations.

Recently a new study about the thermal response of a borehole field was led at KTH with the idea of simulate different hypothetical scenarios thanks to a more flexible numerical model **[25]**.

Originally the aim of the work was to numerically calculate the g-function values for one borehole field geometry by means of Comsol simulations. This had been done to investigate the numerical generation of temperature transfer functions and to provide new information on the reliability of FLS generated g-functions as well as on a function obtained from the design software EED.

A borehole rectangular arrangement of 64 boreholes was simulated using Comsol. The heat flux was imposed constant at the borehole wall in all of them and an undisturbed ground temperature was set at the outer radius of the simulated domain.

The results showed a good agreement in lower time ranges with the spatial superposition of Finite Line Source and with the other results obtained by the EED commercial software. Further in time, the differences start increasing since the three different generated solutions use different boundary conditions. Moreover the Comsol generated g-function show a different profile depending on the physical domain dimensions.

In a recent work at KTH **[26]**, the study of the thermal response factor was implemented towards larger scale installations for commercial purpose. In this context, the increasing cooling demand recently led to new more flexible configurations.

These new arrangements are divided in several thermal zones and they work separately as sub-systems.

Starting from this idea, a new study on g-functions generation was proposed. In this context, the g-functions were obtained from a numerical model built up in Comsol and validated under the boundary conditions of FLS (constant and equal heat flux at the walls of the boreholes).

The same bore field of the previous work was simulated, at the beginning, under usual conditions and, then, taking into account different hypothetical scenarios, thanks to the flexibility of this model.

By imposing variable thermal loads, the g-function was calculated considering seasonal or simultaneous operational modes and different arrangements of the exchangers. In addition, the configuration was divided into extraction and injection boreholes.

The results allow to investigate the interactions among the boreholes and the optimization of the boreholes operation within the bore field.

The results from both the models (Comsol and EED) showed the same behaviour in the long-term simulations when the system is thermally balanced. Conversely, in case of two different thermal zones, energy storage is observed in the inner part of the bore field.

The location, the actions and the number of boreholes in its surrounding and the action of these surrounding boreholes influenced the thermal behaviour of the boreholes as well as the thermal properties of the ground.

2.3 Different work modelling installations

In the last years several models were developed with the purpose of decreasing the environmental impact of ground source heat pump (GSHP) system with multiple borehole heat exchangers. They were aimed at investigating the thermal interactions among boreholes and verifying the long-term GSHP sustainability.

Nowadays the intensive study about the ground heat exchanger system allow us to be well aware of the physically and thermally phenomena occurring in these systems.

A lot of works deal with the design installation and use of GSHP leading to well-defined technical solutions about typical layouts and materials in order to improve their understanding.

On the other hand, for what concerns the modelling phase, only a continuous work would fill the gap with other more developed topics.

In most of the studies different simplifications are used to make the simulation easier and decrease the difficulty linked to computational time.

Usually all the software works with even configuration which have a regular pattern only, e.g. linear, rectangular, L-shaped or other regular configurations.

Thus, a common approach is generally simplifying the real configuration comparing it with an even one: this could modify the thermal behaviour giving different results than that resulting from the real case. In order to test and validate these models, it is essential to compare models' data with the real values obtained by the installed configuration.

First of all, it must be said that geothermal gradient in the ground, the long term leakage of heat through the soil-atmosphere interface and the ratio between boreholes' spacing and length are neglected. The latter generally could affect the performance of a GCHP and a long study about these influences was conducted by Eskilson and Claesson (1998) **[27]**.

The most of works generally takes into account mean properties of the ground and the absence of the groundwater flow, furthermore the effect of the third dimension are neglected.

Recently some researches were done about real installation showing seasonal and long-term computer simulations with the purpose of validating the assumptions made by the designer and investigating the thermal performance of the study case.

In one of the most recent work, Capozza, Zarrella and De Carli evaluated the seasonal oscillations in the ground and the long-term drift of the ground temperature by seasonal and multi-years simulations, In the case of balanced load profile for two configurations located in Padova and Milano **[28]**.

They also highlighted the thermal behaviour change of the ground surrounding by three different types of simulation, starting from the originally borehole field and ground heat load, then improving the load balancing of the ground load profile and increasing the number of boreholes.

Over 10 years, the values from different approaches were compared taking into account the same heat loads.

The aim was to assess the time history of the entering fluid temperature at the heat pump in order to fulfil the heat exchange with the ground.

As a consequence several results were reached: the thermal drift of the ground results stronger influenced by reducing the heat imbalance than by increasing the number of boreholes, this outcome is not justified by the energetic-economic evaluation since it leads to less remarkable improvements.

When we find uneven configuration the simple software in the literature will be not able to compute unusual geometries far from the simple and regular one. A new approach was implemented by simulating long-term operation of a complex GCHP with multiple boreholes in various geometry arrays in order to provide the energy demand of a new building in Zagabria, Croatia **[12]**.

Two different borehole array geometries with a fixed number of boreholes were compared in order to study the more suitable solution for the study case.

The long-term simulation was carried out by two different numerical solutions: ASHRAE/Kavanaugh cylinder source solution and Lund/Eskilson line source solution, where the first one simplifies the thermal interactions in the borehole field and it is good for quick calculations, conversely the second model requires more detailed monthly or hourly data and it is more accurate. Practically, with the second model it is possible to calculate the evolution of the borehole wall temperature over time when a constant heat rate is extracted from the borehole.

Obviously, the spacing of adjacent boreholes is going to influence the required loop length for heat transfer, which changes also depending on what model is taken into account and on simulation time. Thus for 1 year of operation we find a smaller length as neighbouring boreholes’ scope don’t overlap as the spreading cold fronts don’t reach the outer boundary of the other boreholes.

In a recent study the assumptions of an adequately approximated BHE field pattern were assessed in order to evaluate the validity and the possible limitations through a long-term simulation **[29]**.

Teza, Galgaro and De Carli, starting from a irregularly shaped BHE field of 28 boreholes, investigated the performance of a regular pattern 7-by-4 grid with spacing equal to the mean value of the real case, on the basis of an equivalent areal footprint criterion, then a 6-by-2 grid near the previous one was added and studied with the same criterion.

The simulation was carried out over 25 years using a 2D FEM approach with the purpose of calculating the evolution of the annual maximum and minimum temperatures and the maximum difference of the temperature at the year 25 between the real case and the regular pattern approximation.

The assumptions don’t significantly affect the results with the equivalent areal footprint criterion.

Obviously the presence of a nearby existing or planned geothermal systems could affect the performance of the original configuration, mostly when the annual thermal load is unbalanced.

An unbalanced load profile towards heating, could decrease the ground temperature over the years and, as a consequence, the performance of the system. For this reason the mathematical optimization, in addition with reducing the number of boreholes, let to reach relevant benefits.

Especially in the core of the field the boreholes have the strongest thermal impacts and the presence of surrounding boreholes prevent the lateral conductive heat transfer, so these are removed through an iterative process until arrangements with boreholes concentrated along the fringe of the original field.

The aim of Bayer, de Paly and Beck was to optimize the workloads and also decrease the investment costs minimizing the effect on the whole field performance. The optimization procedure aims to avoid a high temperature change; indeed a maximum efficiency is achieved if the maximum temperature change is kept to a minimum **[30]**.

It must be said that the imbalance between cooling and heating load can influence strongly the BHEs field thermal analysis. In those cases, it needs to avoid a relevant overheating or undercooling of the ground.

As a consequence of ground temperature changes, the performance of the heat pump decrease since the heat process is related to temperature difference between heat source and heat sink.

Generally this happens when the ground is characterized by seasonal changing load profile, affecting the radial temperature distribution in the underground. For this reason one of the main objectives was to optimize the individually regulated energy extraction for each single BHE where the conductive heat flow is dominant and is governed by ground properties and thermal conductivity **[31]**.

A new combined optimization approach was implanted by adjusting the BHE positions as well as by a load optimization **[32]**.

In the previous studies each BHE was assumed as line-source unable to simulate the exact thermal conditions within a borehole, in this case the temperature analysis was restricted in a small radius around each BHE by discretization approach.

As results from this approach we can reach a maximum conductive heat flow towards the field getting away the BHEs from the central part of the field along the field’s border.

In the case of an even configuration with a continuous extraction of heat from the ground, a not uniform temperature distribution will appear in the field. This produces a local cooling in the centre of the field and the temperature decreases form the edge to the core. For this reason different energy extraction loads were employed for multiple BHEs.

By this load optimization, a lower central heat extraction is compensated by higher loads at the BHE field boundary and the variability of the temperature is less pronounced.

Depending on the field geometry and the relative BHE positions, which modify the temperature distribution, we will take into account different energy extraction strategy in order to guarantee lowest environmental impacts in the underground.

Different ways of optimization could be taken into account with the aim of keeping the temperature decrease in the subsurface minimal and the heat pump efficiency at high level. At the beginning three different cases were analysed: the first one is a load optimized case as a mathematical optimization problem based on simulated superimposed BHE fields, in the second case equal load was imposed to each borehole assuming the same energy extraction for all BHEs and as third an equal flow case was studied, which correspond to a typical BHE field in practice.

As results by load optimization the ground temperature change is lower than the equal flow case and also we can achieve reduced temperature anomalies and a more balanced lateral cooling of the ground making not work the boreholes in the core of the field, when the heating demand decreases, and then reactive at first external boreholes when the energy demand rise again.

3. DESCRIPTION OF THE FRESCATI INSTALLATION

The boreholes’ field, which I am going to study, is placed at Frescati, in Stockholm. The project of this new smart energy solution is funded by Akademiska Hus and other companies and it is growing up in the area of Frescati campus in order to supply heating and cooling to the new Arrhenius complex.

This joins to the actions undertaken from Sweden in order to reduce the purchased energy by 2015.

The main purpose of this work is to reach the most relevant data on the large scale installation in Frescati, analysing the thermal response of heat exchangers coupled with ground heat pump systems (GCHPs) by using Matlab code, calculated previously by Marc Derouet during his thesis.

The study case needs a long monitoring process since the installation involves a large number of boreholes drilled with different inclinations and different active lengths. The system of multiple boreholes is not yet connected with the building growing up in that zone but it is supposed to provide the heating and cooling demand from October 2015.

In the Figure 3.1 we can see the installation’s site.

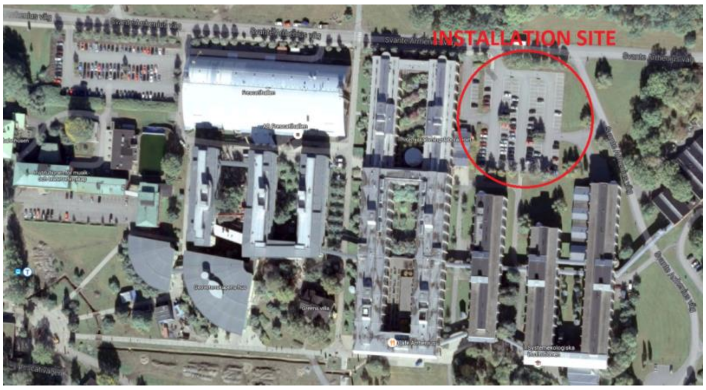


Figure 3.1: View of the installation site

My project relies on the simulation of a large ground source heat pump installation of 130 boreholes drilled surrounding the building. It is important to mention that the project will concern an uneven bore field configuration, owing to constrains related to the available space around the planned building and to the positions of the existing buildings. In addition, so many other factors often don't allow to have a regular borehole configuration.

The total length of the whole installation is by 29980 m, where each borehole has a length by 230 m, except for two of them by 270 m. All of these have different inclination, with different values of alpha and beta angles, where alpha represent the angle with the vertical line and beta represents the angle with the ground surface.

In this original configuration the distance between different boreholes is quite small and thermal influences among them could be modify the thermal behaviour of each exchanger.

The radius of each borehole is equal to 0.0575m and fitted with a plastic tube through which the heat carrier fluid is transported to the bottom, and then goes upwards through the second tube. The closed loop system studied is a double U-tube shaped. As showed in the following map, the legs of the U–pipes shaped are approximated as a single equivalent diameter pipe.

The cooling requirement of the building is about 4574 MWh with higher temperature of 31/25 °C in summer period. During the winter season the heating requirement is about 3630 MWh with temperature swinging between 2.5 °C and 6 °C.

In the last few years, the development of larger systems in commercial applications led to the idea of a more flexible configuration for multiple boreholes fields. The whole borehole field is divided in 14 thermal zones, where the boreholes of each zone are connected to the same manifold. The aim is to have several sub-systems able to operate together or separately.

The several thermal zones, which the configuration is divided, and the different positions of each borehole are given in the figure 5 and figure 6. In order to realize the input configuration, all the characteristics of each borehole were taken from original documents about the drilling procedure.

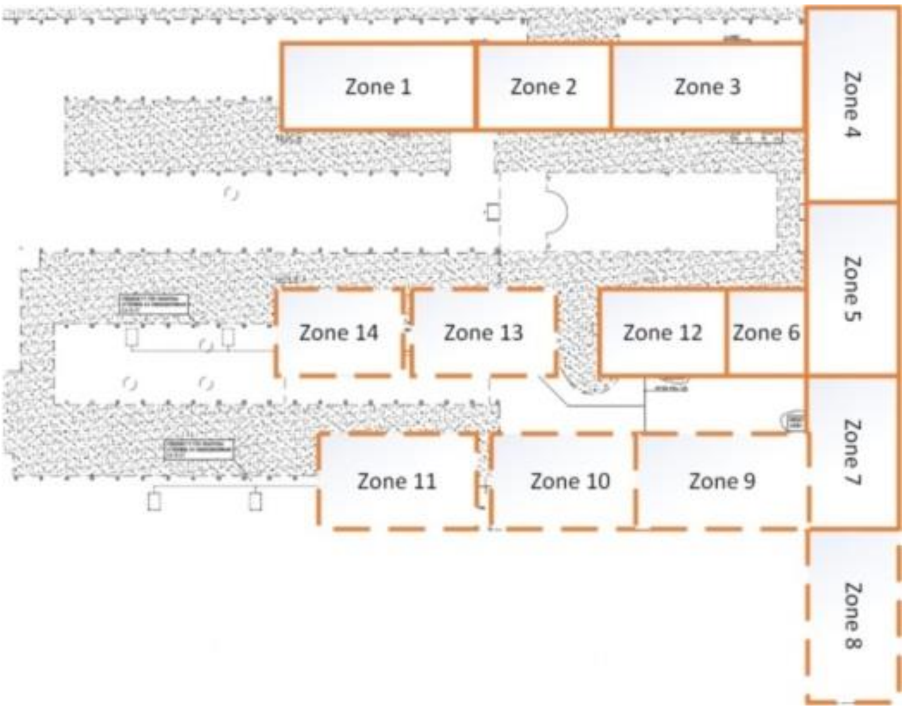


Figure 3.2: Configuration of several zones

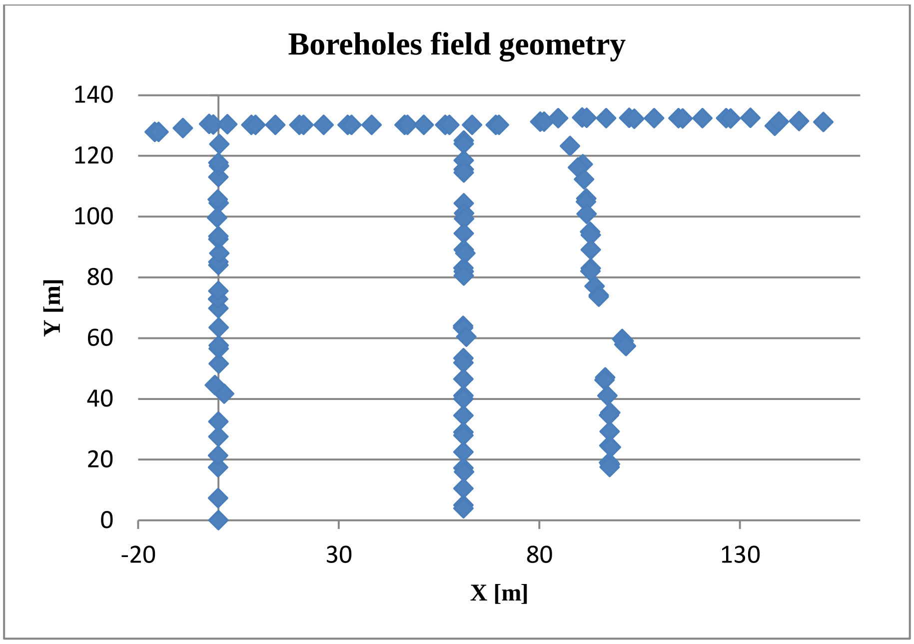


Figure 3.3: Sketch of the borehole field geometry to be studied

Each coordinate (x,y) has been found by locating the centre of the borehole in the middle point between the U-pipes. The inclined borehole required to know the alpha and beta inclination.

Alpha represents the angle from the perpendicular line to the ground surface (z axis) and beta is the inclination of the borehole in the x,y plane.

In the different drilling descriptions available, the groundwater level was measured for each borehole in all manifolds. The measured values of this level range from 4.2 m to 9.05 m. This level describes where the heat exchange starts, and is used to define active part of the borehole in the heat exchange.

It need to take into account the different values of the ratio D/H, since it could influence the simulation and the results.

In addition, each borehole is characterized by a measurement system with a yellow pipe and cables all along these pipes, as showed in the following photo.

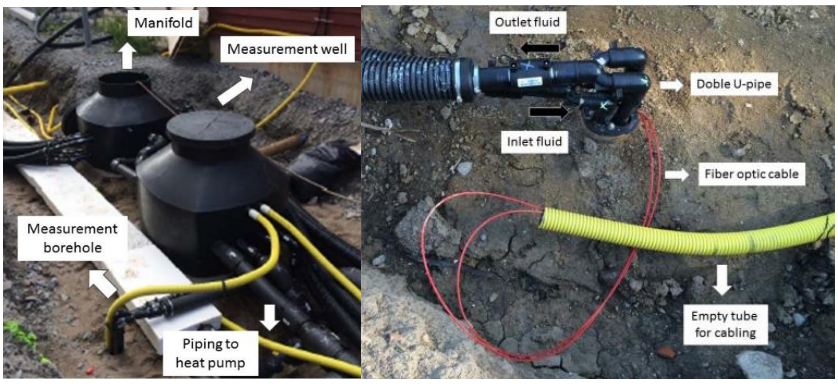


Figure 3.4: Measurement system

In every zone we can find the “measurement well” or “measurement manifold”, which measures the flow rate and the temperature difference to each specific borehole.

4. METHODOLOGY

4.1 Approach carried out in the study

The work, started In March 2015 in cooperation with the Department of Energy Technology of KTH, was led until September 2015. It represents a preliminary study about the new settled system in Frescati area, which is going to fulfil the new building’s energy requirement starting from the next month.

One of the aims of this work is to study the performance and the effects of the use of GSHPs in a commercial building for both short and long time step operation.

In GHSP systems, which uses the ground as key source or sink to supply the heating and cooling demand, it is really important to study the ground behaviour where such system is placed. The change of ground temperature, and as a consequence the fluid temperature, will modify the heat pump system’s performance.

In order to simulate the thermal process in an uneven bore field configuration and predict the fluid temperature for the predicted case, it is important to explain clearly the methodology carried out.

At the beginning, a preliminary literature review was required to be familiar with the body of science about the topic of the assigned work and follow the main theories up.

The Lamarche and Beauchamp’s theories gave an important contribution in this field and stand for the base which my work relies on. Earlier the main theory was proposed by Eskilson in 1987, who was the first to introduce a method based on non-dimensional thermal responses called “g-functions”. He takes into account only even borehole configurations and for this reason his theory is characterized by a lack of flexibility.

Then, in 2006, Lamarche and Beauchamp showed a different approach modelled on computing the “g-functions” in an analytical way, for the medium and long time analyses of bore field configuration. They provided many scripts for g-function calculations.

Gradually new models, either numerical or analytical, were also proposed in order to generate the "g-functions" and analyse the thermal response of vertical heat exchangers.

Later than their first approach, Lamarche and Beauchamp developed a new analytical solution giving an important contribution to the modelling of geothermal heat exchangers for short time transient response. All these works were proposed for vertical boreholes. Following, they introduced a new method for the calculation of time response factors for inclined boreholes.

A new technological development is placed in the last studies of Bernier and Cimmino. In addition, an important contribution was given by KTH in the last few years.

Once I got familiar with the theory, the second task was to get along with the Matlab code. I started observing and studying the code in order to understand how it works and to simulate the concerned field.

The code was designed by Marc Derouet, in his previous master thesis, and then I had to update and adapt it for my new configuration.

In the meanwhile, I started designing part of the real installation, previously described, in order to arrange the input data about the bore field. I drew the configuration in order to know the right coordinates and inclinations of each borehole.

At this stage, a large scale installation of 130 boreholes can be modelled and simulated following a specific criteria.

The aim of this simulation was to assess the borehole wall and fluid temperature changes by increasing the number of borehole studied in each of the simulations done. For this reason, firstly only one borehole was simulated, and then a couple of boreholes close to each other. Gradually the whole installation was simulated by evaluating separately the single manifolds and taking into account the couples of closest manifolds.

The main purpose is to compare the behaviour of one borehole to a group of them in order to know how neighbours could influence each other.

Each of these cases was simulated by dividing proportionally the total heat load, depending on the total active length in each of them. It means to subtract the ground water level from the total length of the simulated boreholes.

Once the methodology was clarified, the following task, before starting the simulations, was to check the validity of the code with the last approach (FLS – Uniform Temperature). This preliminary check was necessary to find possible mistakes.

The code is validated by imposing a constant heat flux at the borehole wall in all the boreholes, as boundary conditions. The model, given for this project, was built up according to the boundary conditions described in the FLS method. For this reason, the values obtained from the code are compared with the FLS solution for a reference geometry with 2x3 BHEs in a rectangular pattern (rb/H = 0.0004, D/H = 0.0343).

Figure 4.1 shows the g-function obtained from the code, named in the figure as “FLS – constant q”, and that from the pre-processor, named “FLS – constant q reference”.

It is important to mention that the code gave different results in comparison with the values obtained by pre-processor. Both of the approaches, for the generation of the g-function, use the boundary condition of a uniform heat extraction rate along the length of the boreholes.

The difference, between the g-function calculated by the pre-processor and the g-function obtained by the implemented code, increases with the value of ln(t/ts).

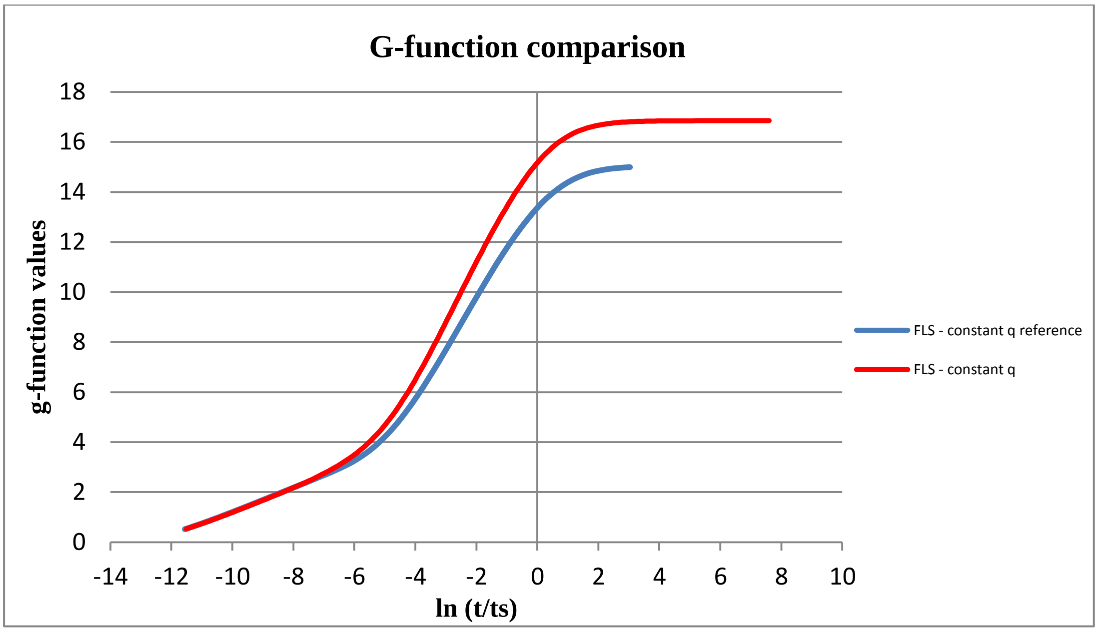


Figure 4.1: Comparison between the g-function values obtained with the Matlab code and the FLS reference case for a configuration with different values of D/H for all the boreholes

It is clear as the difference, between the two curves, starts still before one year step operation, which is placed up to a time ln(t/ts) = -4,6.

These curves were calculated in case of a vertical boreholes configuration with different values of D/H.

Hereafter, using the same values of D/H for every boreholes, the gap between the two curves start to be noticeable after one year operation, as shown on Figure 4.2.

In case of similar boundary condition at the borehole walls, the comparison with the FLS reference case shows a perfect match between the two curves. Instead a small difference is observed for a different reference case, with uniform borehole wall temperature along the length of the boreholes.

The g-functions are linear up to a time ln(t/ts) = -5 and then the slope of the curves increases. They start to stabilize toward their steady-state value around time ln(t/ts) = 0, when axial effect become significant.

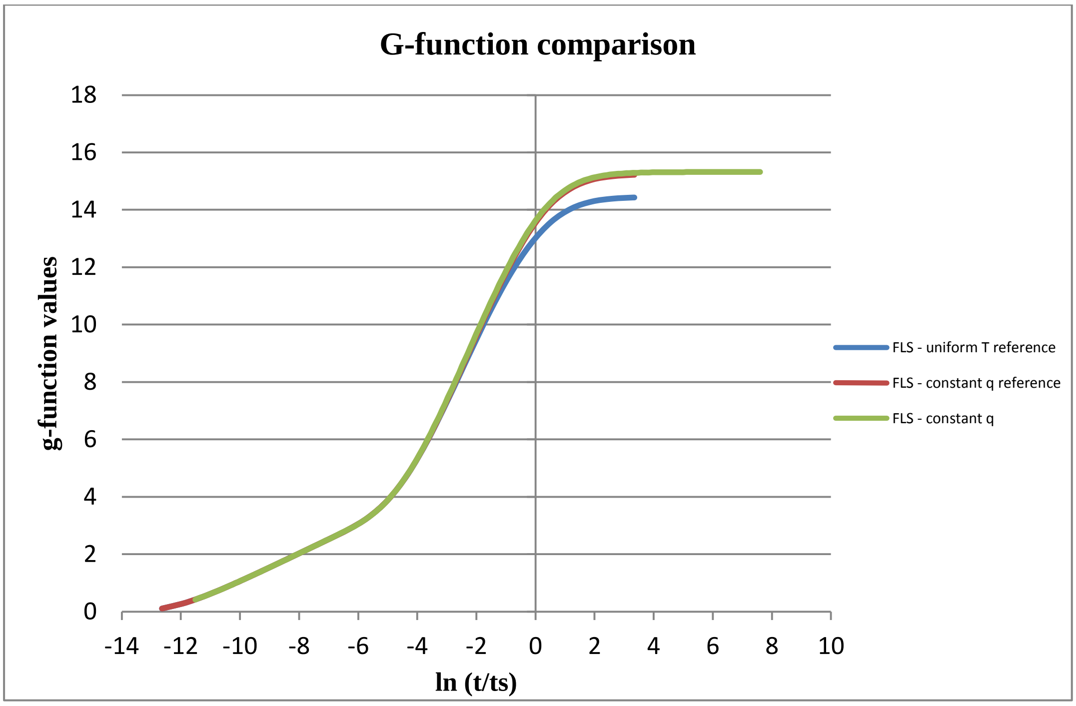


Figure 4.2: *Comparison between the g-function values obtained with the Matlab code and the FLS reference case for a configuration with the same values of D/H for all the boreholes*

In order to continue working with this code, a new arrangement geometry was designed, following the pre-processor for fields of vertical boreholes. Once defined the new geometry, it was possible to determinate the g-function for both of the studied cases.

The g-functions are not the final goal of this work. The following step was to define the heat load profile in order to assess the borehole wall and fluid temperatures for each case.

These temperatures were calculated for short and long term operation. The simulation time for short term operation is 1 year, using an hourly load profile. For long term simulation of 20 years, the same load profile was used by means of a monthly step heat load profile.

4.2 New BHEs arrangement

As the comparison shown previously, the Derouet's code was not able to calculate accurately the g-functions' values, owing to different values of the ratio D/H for all the boreholes.

For this reason, it was necessary to come up with an alternative resolution. The whole installation was studied taking into consideration separately each manifold, after ensuring that no thermal interaction occurs among them.

The new arrangement geometry was designed taking each borehole coordinates (x,y) in the middle point of the real boreholes. This configuration is shown in the Figure 4.3.

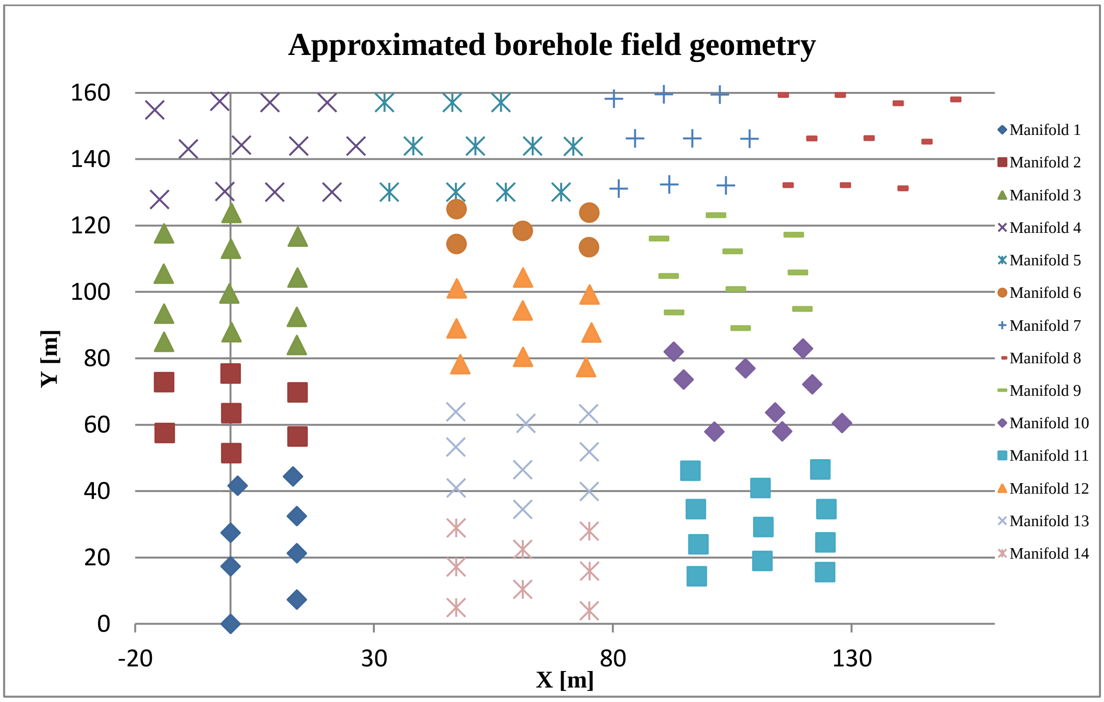


Figure 4.3: BHE configuration for straight boreholes taking into account the middle point for each borehole of original geometry

The spacing among boreholes was increased with this approximation. For this reason, the distance between two different manifolds has to be verified thereby ensuring the spatial temperature distributions would not cross to avoid any interactions.

If the boreholes from different manifolds don’t see each other in the timeframe of 6 months to 1 year, it will be possible to study separately the manifolds to assess the whole installation.

According to the theory of Göran Hellström (1991), the penetration depth for each couple of manifolds was calculated and compared to the spacing among adjacent heat exchangers in order to assess the thermal influence between manifolds. It is a characteristic length for the periodic temperature variation in the ground and can be expressed as:

$$dp = \sqrt{\frac{\alpha tp}{\pi}} \qquad (5)$$

It depends on the thermal diffusivity α and the period time t_p and only 5% of the amplitude remains at a depth 3dp from the boundary **[33]**.

Each manifold is judged with a hexagonal duct pattern, so in this case the influence is negligible when:

$$r'1 = r1\sqrt{\frac{2\,\pi}{a\ tp}} \geq 3 \qquad (6)$$

Where “r1” is the outer boundary for each manifold, “a” is the ground thermal conductivity and “t_p” is the period time.

Taking the ground thermal conductivity equal to $1.62*10^{-6}$ m^2/s and r1 equal to the distance between two boreholes from different manifolds, we found that just for two couples of manifolds the spacing is comparable to the penetration depth. It means that a moderate thermal influence is observed after 1 year step operation between these two couples. For all other cases it is possible to study separately each manifold in order to analyse all installation.

Since the value of r’1 is less than 3 for the couples of manifolds 3-4 and 5-6, both of them will be simulated separately and then also together in order to show how change the thermal behaviour.

4.3 Assumptions made

Many parameters used to model the heat transfer need to be defined for the GSHP system at Frescati. All of them can be seen in the following table.

Ground and borehole properties	**TRT - BH1**	**TRT - BH2**
Diffusivity [m^2/s]	$1.62\ 10^{-6}$	$1.62\ 10^{-6}$
Thermal conductivity [W/mK]	3.9	3.95
Undisturbed Temperature [°C]	9.8	8.9
Groundwater level [m]	$4.2 < d < 9.05$	
Borehole Radius [m]	0.0575	
Borehole Thermal Resistance [mK/W]	0.065	
Depth [m]	$230 < H < 270$	

Table 4.4: Summary of the main ground and pipes parametres

Some data were obtained following the research background study done mainly during the literature review; the remainders were taken by the installation's table.

The ground and borehole properties are divided in two groups, where TRT-BH1 corresponds to the borehole number 7 (zone1), while the TRT-BH2 represent the borehole number 63 (zone 7).
Following the previous table, the thermal properties determinated in TRT-BH1 are applied to zone 1,2,3,4,5,6,12,13 and 14. The remaining zones are characterized by ones evaluated in TRT-BH-2.

4.4 Load profiles for the installation in hourly and monthly cases

One of the main parts of this project consisted in determining the load profile of the studied building, as well as the borehole wall temperature and the heat carrier fluid temperature.

At the beginning, the simulation was conducted over a one-year period with an hourly time step calculation, in case of short term operation. The power extracted or injected from or to the bore field is given for every hour in 1 year and these data are related to 2011.

The total heat load of the building in 1 year is shown in the Figure 4.5.

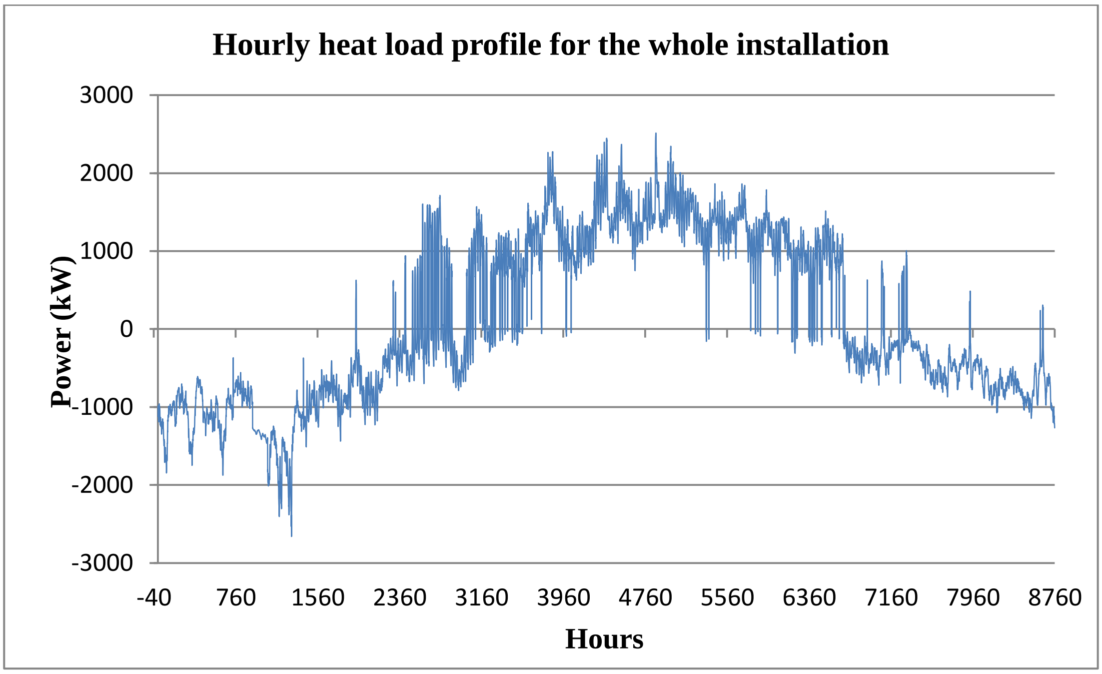


Figure 4.5: Power extracted/injected from/to the borehole field

Regarding the previous equation (3), we gather the fluid temperature is lower than the undisturbed ground temperature in heat extraction. Since the heat is extracted from the ground, we consider it negative in sign in that equation.

Afterwards I simulated the installation over 20-year period with a monthly time step calculation. About the long term simulation, the load profile was built taking into account the same load profile in 2011 for all of the following years and repeating it over the 20-yearperiod.

The monthly load profile for 20 years of simulation is shown in the Figure 4.6.

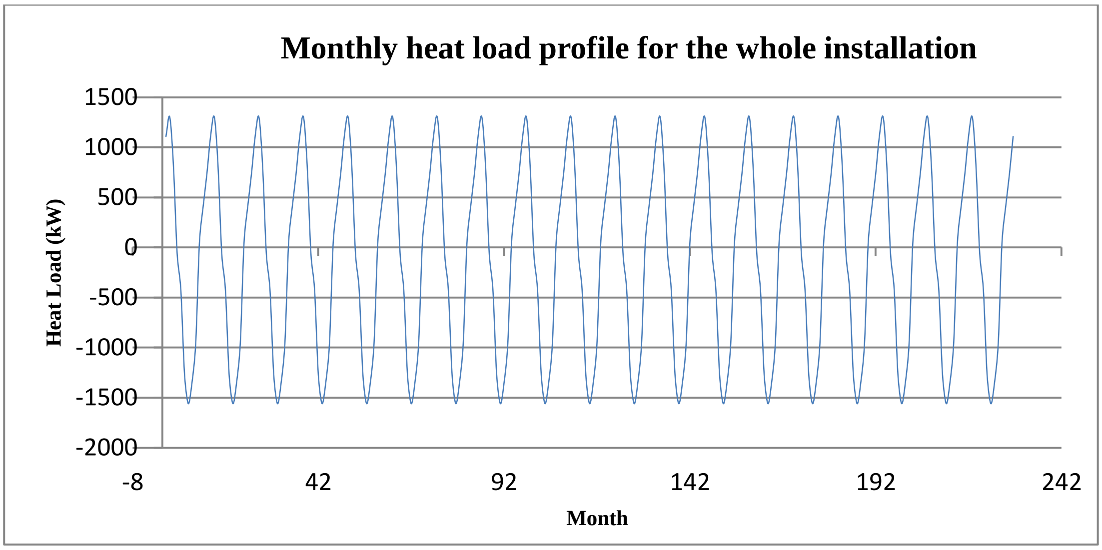


Figure 4.6: Monthly heat load profile for 20-year simulation

It is important to mention that in 1 year the warming demand during winter is not similar to the cooling demand of the building. This fact leads to an imbalance towards cooling by 944 MWh of the total heat load profile.

The compensation between heating and cooling influences the long-term simulation and the fluid temperature depending on the starting point of the simulation. For this reason another thermal load profiles was considered.

In particular, an hypothetical condition of decreased unbalancing was obtained.

It was interested to simulate the same configuration with a balanced load profile in the short and long term operation. In this case the geothermal energy system is supposed to work coupled with a supplementary system with the aim of fulfil the cooling peak in some hours of the year.

The balanced heat load profile is shown in the Figure 4.7.

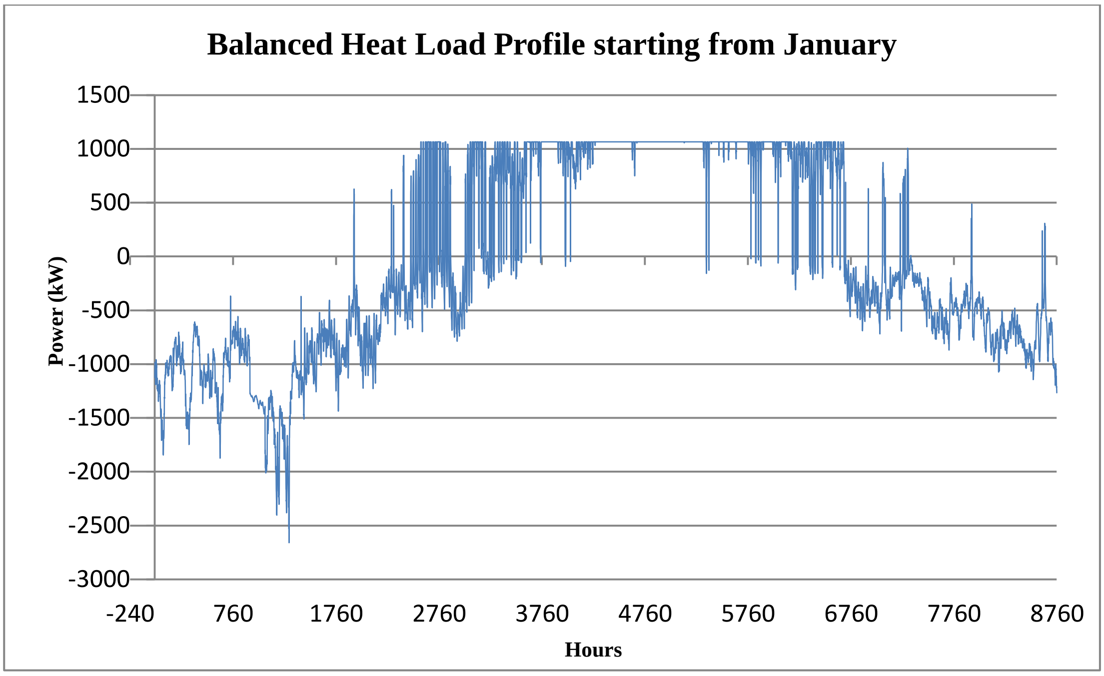


Figure 4.7: Balanced heat load profile

For short and long term simulations, both the unbalanced and balanced heat load profile was used with special attention to the starting operation month.

The aim is to minimize the fluid temperature and therefore maximize the heat pump performance.

5. RESULTS

With the purpose of figuring out clearly the results, a brief introduction to the executive procedure is presented.

For each case study, the short and long term simulations were carried out considering different hypothesis and all of the results obtained from the simulations done can be summarized in three following steps:

- *First step:* the new geometry arrangement was simulated with hourly and monthly load profiles for the predicted case (Unbalanced load profile).
- *Second step:* A special attention to the starting operation month was given in order to evaluate the performance improvement.
- *Third step:* A Balanced heat load profile was supposed in order to decrease the long-term effect of the thermal drift.

5.1 G-function for the borehole field in Frescati

Once validated the code with last approaches, after a long comparison, and designed the new geometry arrangement, the g-functions for each study case were calculated using the updated Matlab code.

The code, previously updated and validated, allows for uneven bore field with vertical boreholes and same values of ratio D/H. The positions of all boreholes were illustrated earlier and the g-functions are presented as a function of the non-dimensional time ln(t/ts) on Figure 5.1.

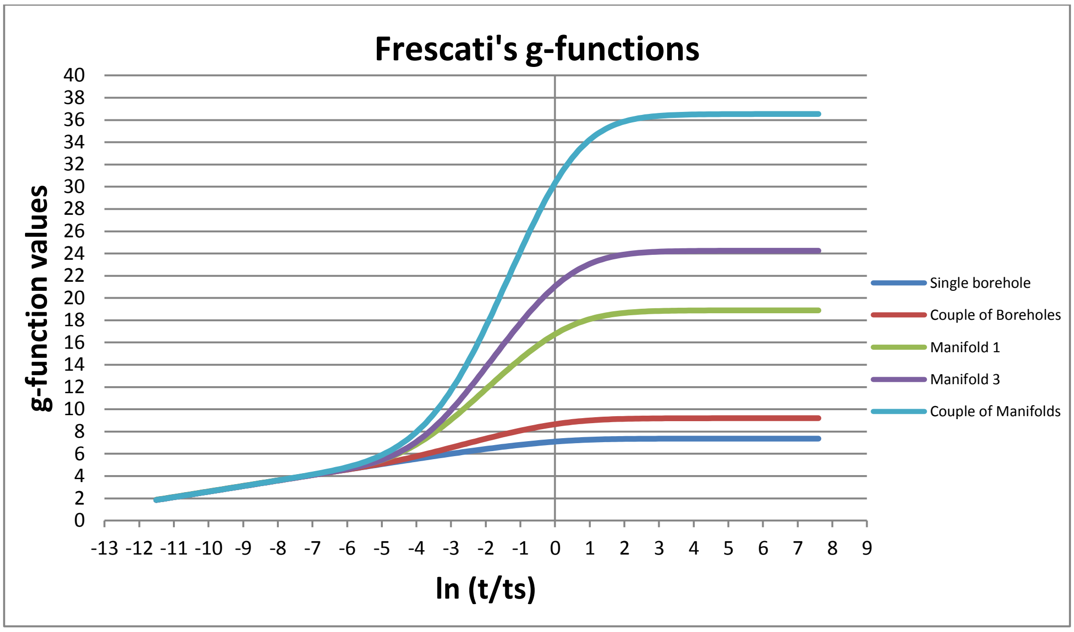


Figure 5.1: G-function of the Frescati installation for each study case

For single borehole and couple of boreholes, the curves are linear in the first region of the graph, up to a time ln(t/ts) = -5, which is about 1-year period. In this part the axial conduction effects are negligible for small values of time and the heat transfer is only in the radial direction. In addition the distance B among boreholes was rather increased after the approximation done to vertical boreholes.

These factors ensure that thermal interaction among boreholes is negligible and the g-function for couple of boreholes is similar to the g-function for a single borehole.

For the other cases, the slope of the g-function curves increases before ln(t/ts) = -5 and the thermal interactions among boreholes become important. In this second range time, until when the curves don’t reach the steady-state, the heat transfer is studied in radial and axial direction. The g-function value increase depends on the number of the boreholes in the relative case and on the geometrical layout, as it can be seen between Manifold 1 and Manifold 3.

The last part of the graph represents the steady-state heat transfer and it starts from ln(t/ts) = -2, which corresponds to 16 years. For very long time the bore field and the ground are in equilibrium and the extraction does not affect the borehole wall temperature.

5.2 About the short term simulation with hourly heat load profile

At this stage, after validated the code concerning the new approximated configuration, it was possible to use the pre-calculated g-function in order to simulate the bore field and obtain the hourly and monthly variation of the borehole wall and fluid temperatures.

The temperatures were calculated for a variable heat load profiles by temporal superposition to account for the time variation of the heat extraction rates of individual boreholes.

Since there are no interactions between manifolds, according to the calculation of the penetration time, the load is distributed proportionally to the total length of each manifold. Thus, the total load profiles will be divided equivalently depending on the ratio between the total length of the examined boreholes and the total length of the whole borehole field.

At the beginning, the system has been studied in 1-year time operation, dividing the simulation in different cases:

- Simulation of one borehole (the borehole number 1 in the zone 1 is taken as reference);
- Interactions between a couple of boreholes in the same manifold;
- Simulation of one manifold;
- Simulation of a couple of close manifolds (manifold 3 and 4).

The variation of the heat carrier fluid temperature, due to a variable heat extraction rate for 1 year of hourly simulation, is shown for all study cases.

All of these cases are summarized in the Figure 5.2:

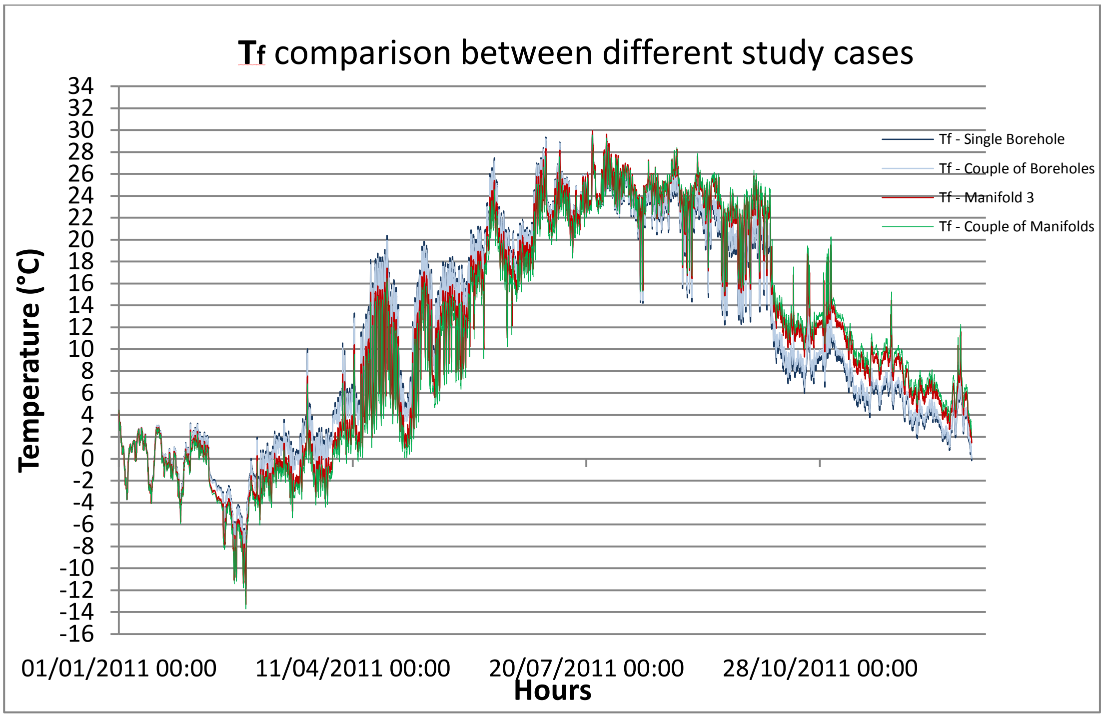


Figure 5.2: Heat carrier fluid temperature profile from the simulation starting in January with an unbalanced load profile

	Single Borehole	**Couple of Boreholes**	**Manifold 1**	**Manifold 3**	**Couple of Manifolds**
Tf max [°C]	29.94	29.98	30.13	29.93	29.55
Tf min [°C]	-11.85	-12.07	-13.1	-13.39	-13.72

Table 5.1: Maximum and minimum values of the heat carrier fluid temperature for a simulation starting in January with an unbalanced load profile

The attention is focused on the temperature of the heat carrier fluid, which represents a key parameter. A synthesis of the annual minimum and maximum temperature of the fluid is outlined in Figure 2 and summarized numerically in the Table 5.1.

Since the annual amount of heat extracted from the ground is lower than that which is injected into the ground, the long term fluid temperature inside the ground heat exchangers increase, as it is noticed by the simulation.

By and large, a similar shape of the curves can be observed for all cases. The maximum temperature of the fluid is quite similar for all of the cases, amounting to 30 °C.

Obviously, the maximum efficiency is achieved when the maximum temperature change is kept to a minimum. In addition an extreme local heating of the ground is not desirable, since it could modify the efficiency of the heat pump.

For these reasons the idea was to use different heat load profiles in order to assess the fluid temperature change in comparison with the predicted case and determine the possible improvement by a more balanced use of the ground.

Two ways were proposed in this project:

- The first way was to start the simulation in October, maintaining the same hourly energy profile.
- The second way was to use a balanced heat load profile, by coupling the geothermal system with a supplementary system which would be started up during the hours of cooling peaks.

5.2.1 Starting point in October

With the same unbalanced heat load profile, the same study cases were simulated moving up the starting operation month in October.

The results of the new simulation were compared with that originally simulated. The difference temperature (in Kelvin) was plotted in the Figure 5.3.

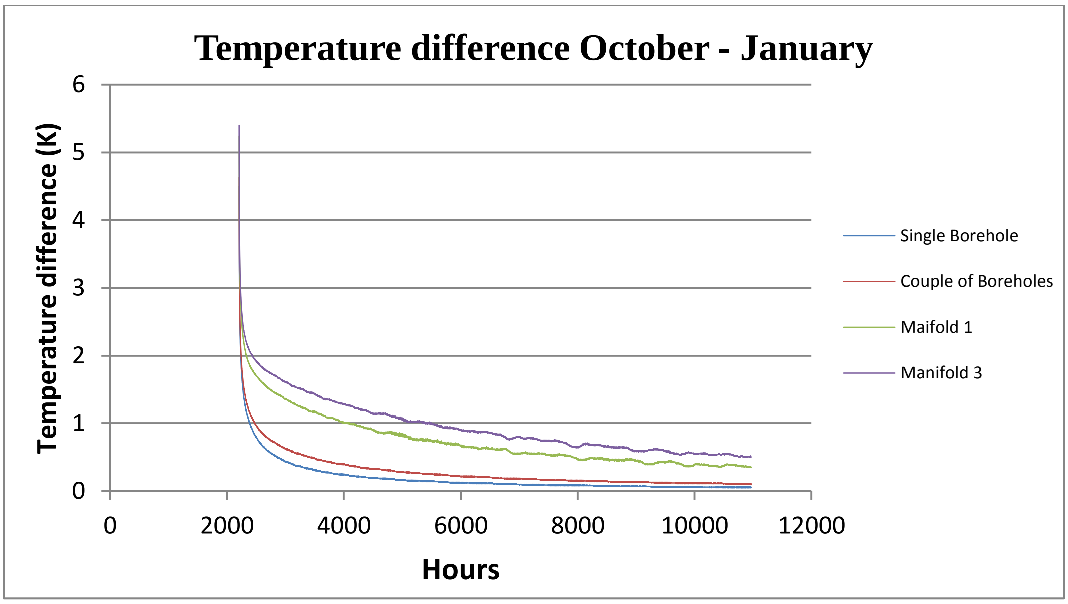


Figure 5.3: Comparison between two simulations starting in October and in January with an unbalanced load profile

The hourly values of fluid temperature in 1-year time operation decreased by about 5,2 K at the beginning of January (after 2000 hours). The temperature difference decreases quickly and in April (after 5000 hours) it is less than 1 K for all of the cases.

Concerning only the annual maximum value, no improvements are obtained with this strategy.

5.2.2 Balanced load profile

When the energy flow imbalance was reduced and the unbalanced load profile was replaced with a balanced load profile, the maximum fluid temperature was decreased by around 9 K from the original value.

Comparing the results obtained by simulating a balanced load profile starting in January with the original result in same starting operation month, the hourly temperature difference between these two cases is shown in the Figure 5.4.

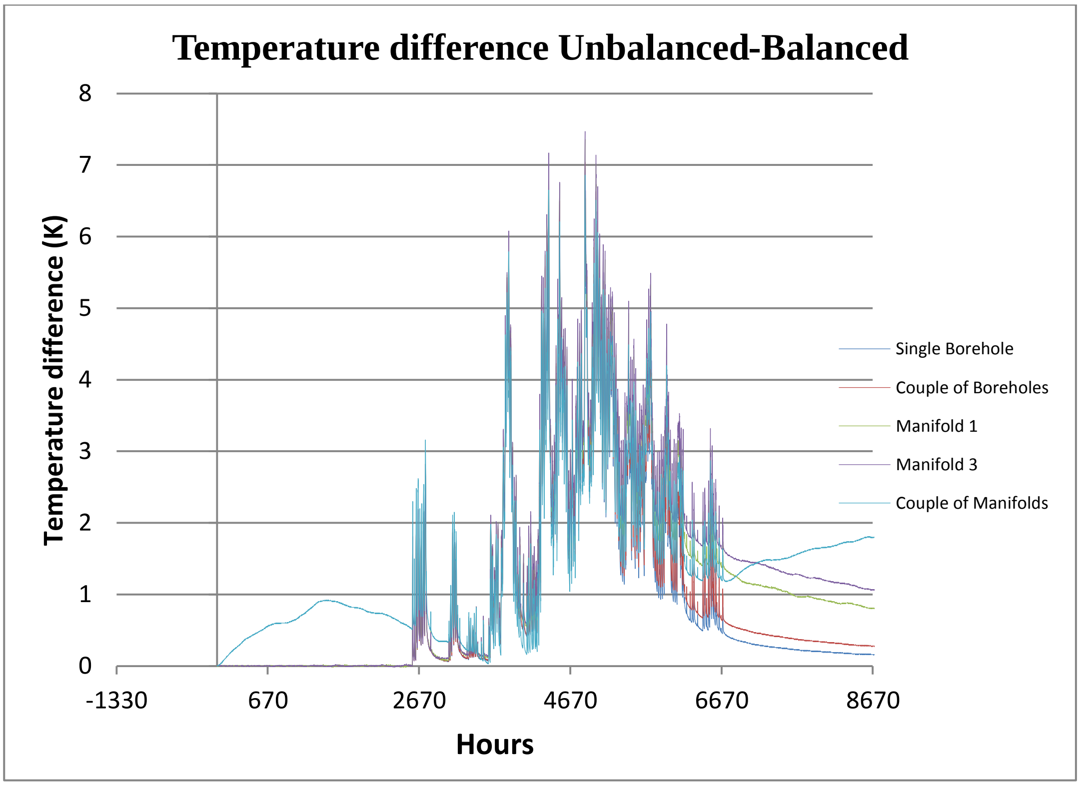


Figure 5.4: Comparison between unbalanced and balanced load profile in the same starting operation month

In the time frame when the cooling peak was supplied by the alternative system, the hourly temperature difference can reach the value of 7 K, leading to a great improvement of the heat pump efficiency.

When the extracted energy flow is equal to the injected energy flow, a good improvement of the maximum fluid temperature is reached and shown in the Table 5.2.

		Single Borehole	**Couple of Boreholes**	**Manifold 1**	**Manifold 3**	**Couple of Manifolds**
Unbalanced Load Profile	**Tf max [°C]**	29.94	29.98	30.13	29.93	29.55
	Tf min [°C]	-11.85	-12.07	-13.1	-13.39	-13.72
Balanced Load profile	**Tf max [°C]**	20.22	20.5	21.57	21.91	22.85
	Tf min [°C]	-11.85	-12.07	-13.11	-13.4	-14.58

Table 5.2: Maximum and minimum values of the fluid temperature in case of unbalanced and balanced heat load profile

Then, the same balanced heat load profile was used to simulate the temperature changes starting in October. But the difference between the two cases is the same we recorded in case of unbalanced load profile.

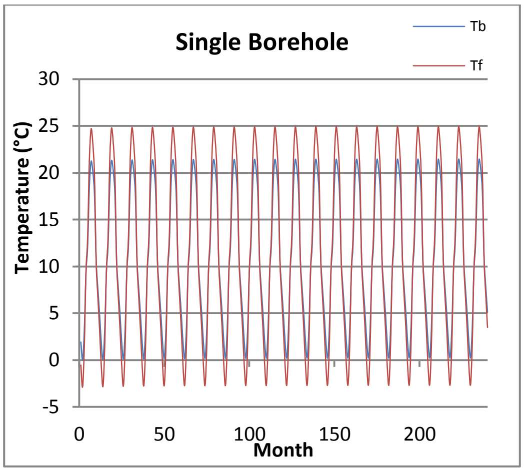
5.3 About the long term simulation with monthly heat load profile

In the previous paragraph, the short-term simulation, with an hourly time resolution, allowed to assess the minimum and maximum temperature of the heat carrier fluid, which represents a relevant design parameter.

Now the attention shifts to the long-term simulation in order to evaluate the effect of a periodic heat load in each study case under the same considerations previously introduced.

In this section, a monthly time resolution is required in order to outline the evolution of the fluid temperature in 20-year time operation. The results have been calculated considering the predicted heat load profile of the first year, used in the short-time simulations, for all following 20 years of operation.

The borehole wall temperature and the heat carrier fluid temperature are plotted together and they are presented in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8, for the cases of single borehole, couple of boreholes, manifold 3 and couple of manifolds.



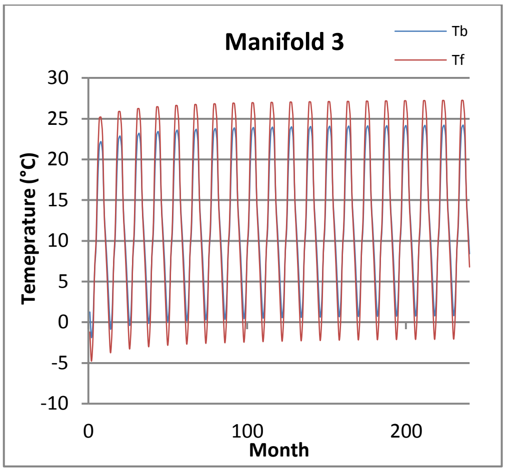
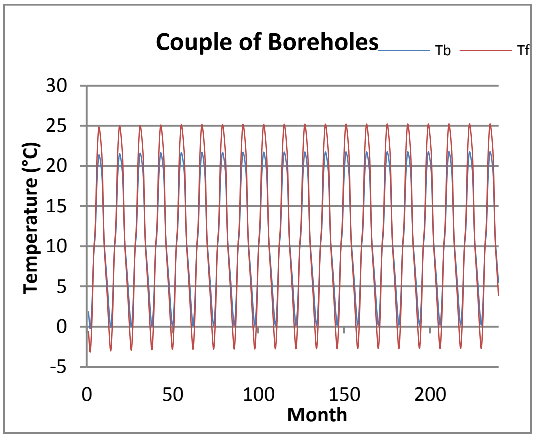


Figure 5.5: Borehole wall temperature and heat carrier fluid temperature profiles for a single borehole with monthly loads

Figure 5.7: Borehole wall temperature and heat carrier fluid temperature profiles for the manifold 3 with monthly loads



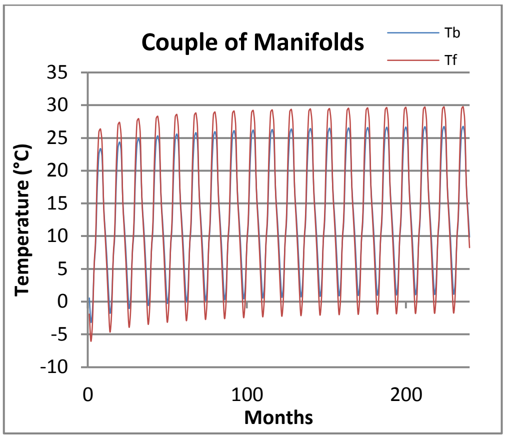


Figure 5.6: Borehole wall temperature and heat carrier fluid temperature profiles for a couple of boreholes with monthly loads

Figure 5.8: Borehole wall temperature and heat carrier fluid temperature profiles for a couple of manifolds with monthly loads

Several observations arise from these results. At first, the tendency of the periodic curves is quite similar for both the single borehole and couple of boreholes cases. This is due to the huge ground volume surrounding each borehole after having taken the approximated geometry.

Since the borehole separation distance is about 15 m, in case of studying a couple of boreholes, thermal interferences doesn’t affect the behaviour of individual boreholes in a long-term heat process.

In the other examples, the increasing number of boreholes leads to a notable temperature increase by about 2-3 K over 20 years. The greater the number of boreholes is, the higher the fluid temperature value is reached at the end of simulated period.

A short comparison of the fluid temperature values among different cases can be noticed in the Figure 5.9 and Figure 5.10, which show respectively the maximum and minimum temperature tendency.

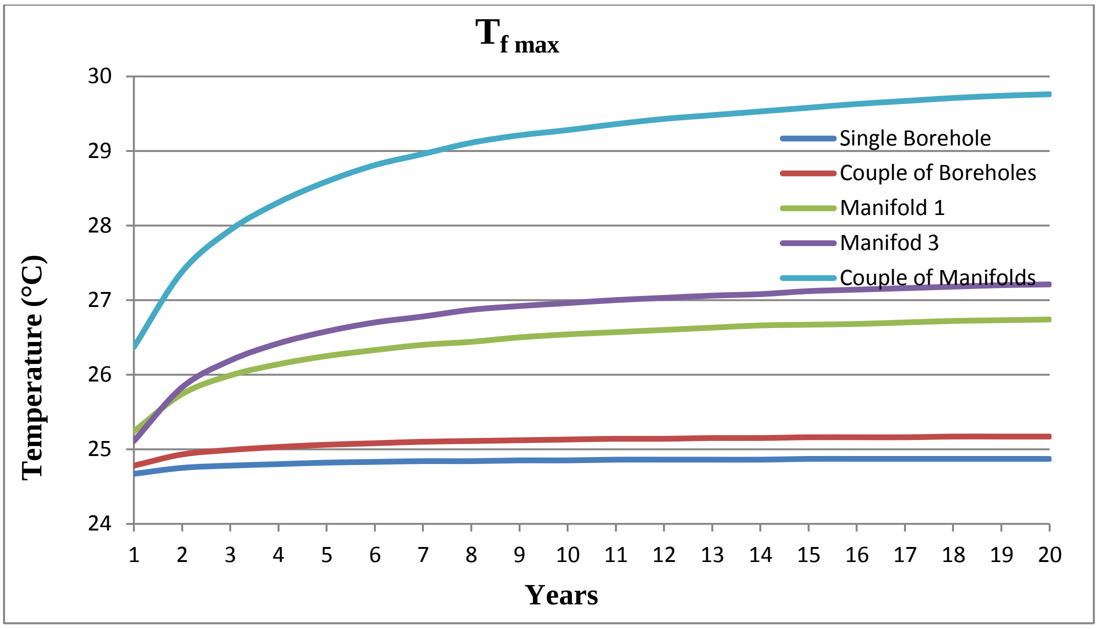


Figure 5.9: Maximum heat carrier fluid temperature with unbalanced load profile for long-term simulation

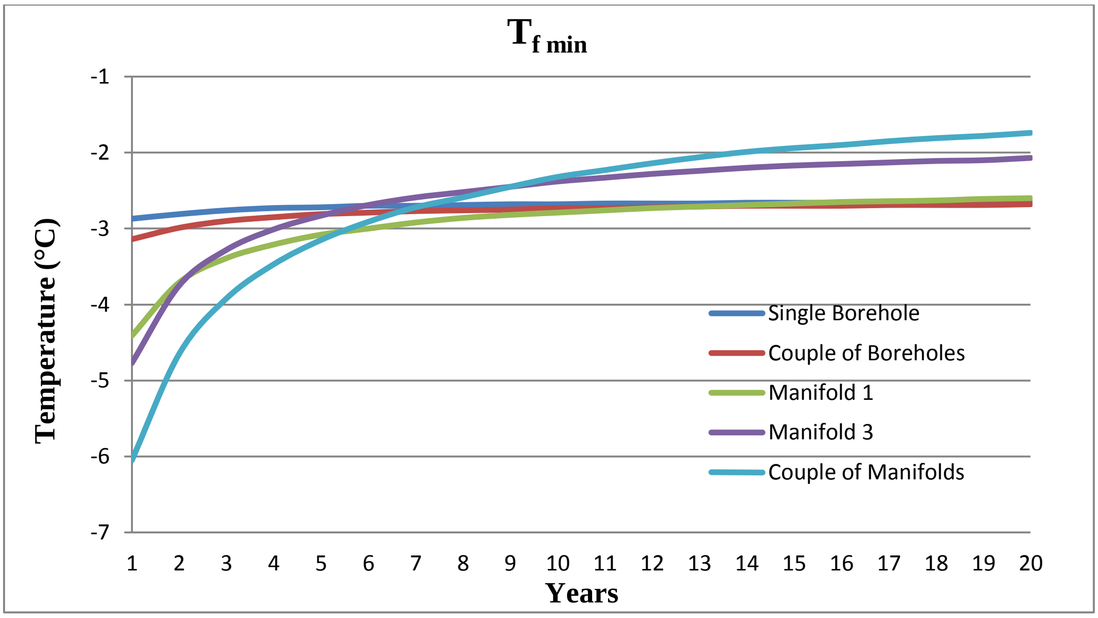


Figure 5.10: Maximum heat carrier fluid temperature with unbalanced load profile for long-term simulation

5.3.1 Starting point in October

In order to reduce the curve of maximum fluid temperature values, the long-term simulation was started up in October. Since the building still requires cooling energy in this month, it is expected to have a noticeable difference in the first period of the simulation.

The comparison between the two simulations with the same unbalanced heat load profile but different starting operation months is provided in the Figure 5.11.

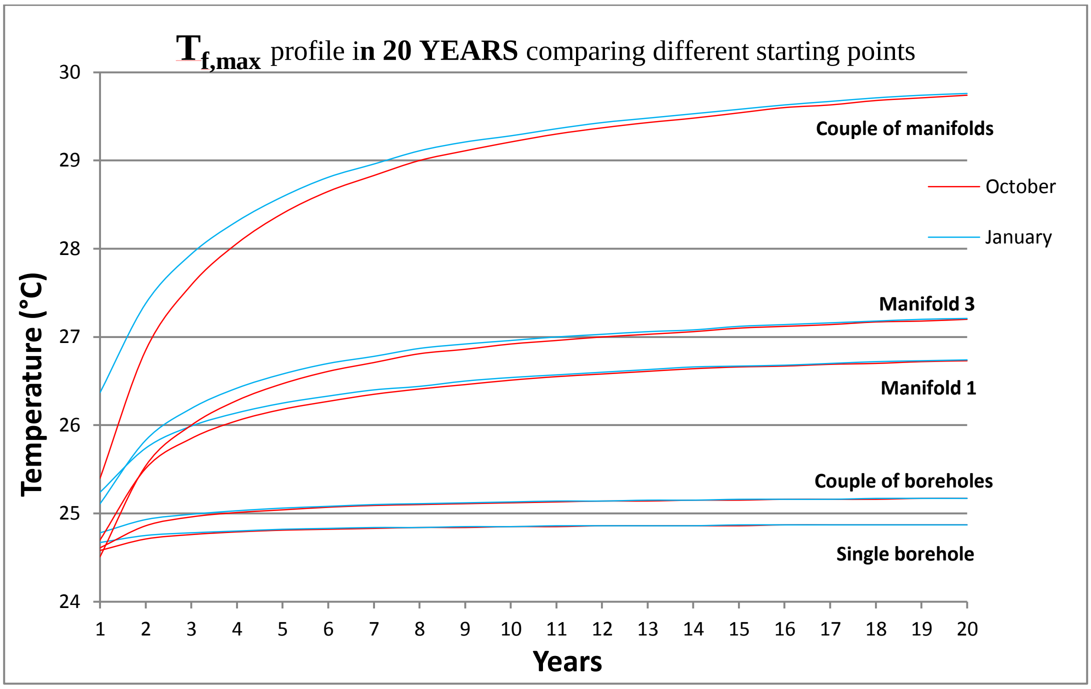


Figure 5.11: Comparison of the maximum fluid temperature tendency between two different starting month operation

All of the study cases are plotted in the same graph and the two different results are discriminated for each of them. The results of the simulation with the start up point in January are outlined by the blue line, instead the red line shows the tendency of the maximum fluid temperature in 20 years' timeframe.

It can be noticed that in the first period the fluid temperature decrease is remarkable, especially for cases with a greater number of boreholes as "Manifold 1", "Manifold 3" and "Couple of manifolds". For "Single Borehole" and "Couple of boreholes", there are not relevant discrepancies between the two curves on the long period and really small, almost negligible, on the short period.

These observations attest that the starting operation month doesn't affect the results neither in the short period nor in the long period and when considering an increasing number of boreholes there are more interactions.

5.3.2 Balanced load profile

As last result, it is worthwhile to compare the maximum fluid temperature tendency in 20–year operation in case of unbalanced and balanced load profile.

For both load profiles, the simulations started in October and all of the study cases are shown in Figure 5.12.

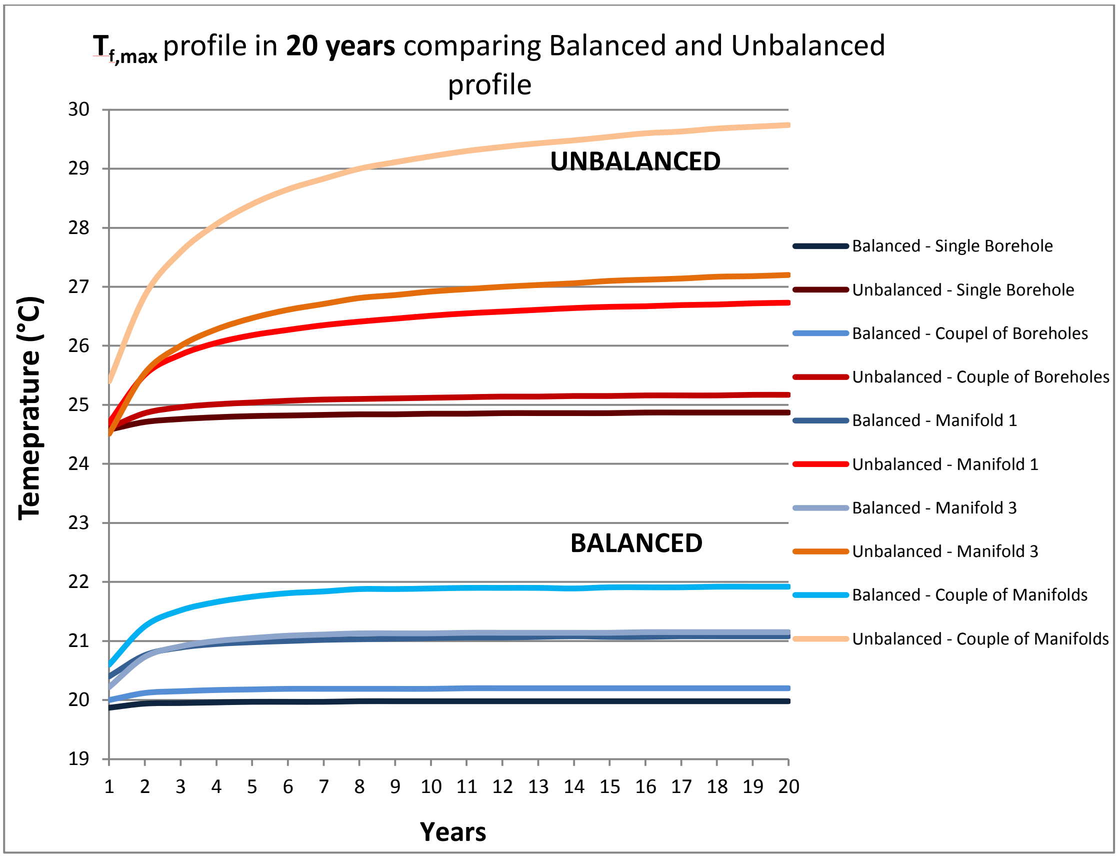


Figure 5.12: Comparison of the maximum fluid temperature tendency between unbalanced and balanced heat load profile

In the plot, the red lines outline the fluid temperature tendency over 20 years using the original and unbalanced load profile. The fluid temperature, reached at the end of each simulation, change considerably going from “single borehole” case to “manifold” case, and from “manifold” case to “group of manifolds” case as well.

On the other hand, the blue lines show that a balanced load profile reduce the distance between them and the fluid temperature difference between the “single borehole” case and “couple of manifolds” case is lower than 2 K during the long-term simulation.

It is interesting to notice that using a balanced load profile allows to have a good efficiency improvement since the heat carrier fluid temperatures are much lower than that obtained with an unbalanced load profile.

Moreover the different load profile influences the slope of the curves in the first period of the simulation. As regards to the unbalanced cases, it can be also noticed that the temperature increases up to about 2 K in the first 4 years. Instead it is less than 1 K when the heat load profile is balanced.

Concerning the minimum fluid temperature, the tendency for both unbalanced and balanced load profile is shown in the Figure 5.13.

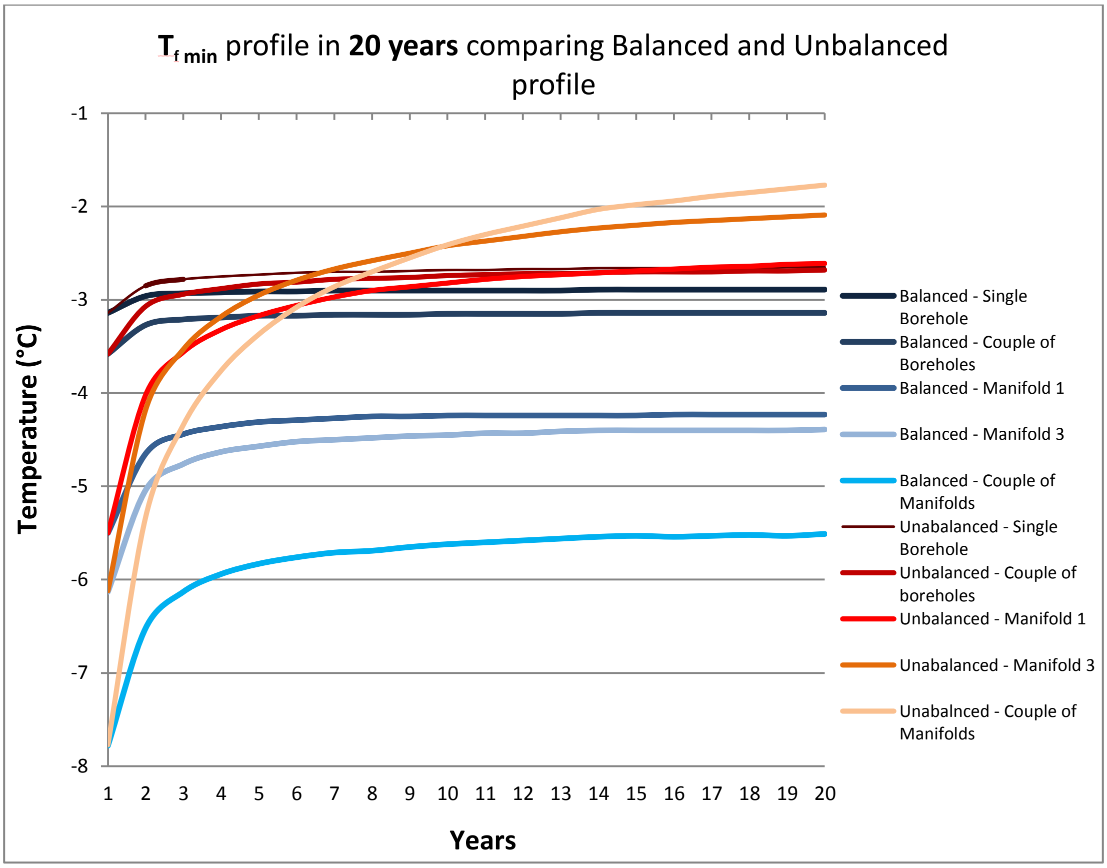


Figure 5.13: Comparison of the minimum fluid temperature tendency between unbalanced and balanced heat load profile

As we expected, the balanced load profile reduce the slope of all curves in the first years of operation and then all of the curves tends to become linear after few years.

Reducing the heat injected in the ground in summer time increased the impact of the heat extraction process in winter time, with a decrease of the minimum fluid temperature. This decrease is remarkable when the number of boreholes simulated is high. The minimum temperature can decrease up to 4 k in the case of “group of manifolds”.

6. DISCUSSION AND LIMITATIONS

This experimental study where alternative operational modes have been introduced provided many useful results in order to have a notable evaluation of a real GSHP installation in Stockholm. These results allow us to investigate on the thermal interactions among boreholes and on the optimization of the GSHP system's performance. They represent the baseline for beginning to discuss possible solutions.

The aim of the study was to judge the accuracy of the simulation code in the perspective of describing properly the thermal response of the borehole heat exchangers configuration. For this reason it is important to explain the assumptions done and their influences on the final results.

The code has been taken from a previous work. In that case, it was developed to evaluate the thermal response of a GSHP installation of 26 boreholes arranged in a symmetrical pattern and divided in two different thermal zones.

The given simulation code, run with the software Matlab, showed initially a small inaccuracy in the computation of the g-functions related to committed bore field.

The code was built up according to the boundary conditions described in the FLS approach of Lamarche and Beauchamp (constant heat flux at the borehole's wall). For its validation, the model was compared with the new FLS analytical solution proposed by Bernier and Cimmino, taking into consideration two different boundary conditions (constant heat flux at the borehole's wall and uniform borehole wall temperature equal for all boreholes).

The g-function calculated by the code was compared with those calculated by the new FLS method. This comparison was carried out for two kinds of standard configurations (2x3 BHEs with vertical boreholes in a rectangular pattern), one having same values of D/H and the other having different values of D/H.

Only in the first case the comparison gave satisfying results throughout the timeframe.

Since the geometry presents different values of groundwater levels and borehole depths, it must be said that the given model overestimates the configuration committed in this project.

Thus, a new solution was found with the purpose of solving this problem and continuing to work with the given code.

The real geometry was approximated according to the theory of Hellström and the new arrangement was designed. This is a crucial point since the hypothesis on the geometry will influence the results at end of the work.

In the approximated geometry the distance between boreholes is rather larger than that in the real case and, as a consequence, this mitigates the thermal interferences between them.

For this reason, it is necessary an additional validation of the model with the on-site measurements data. A limitation, highlighted also in the previous work, is that such projects need the data acquisition on the installation.

It has been important to have pointed out these assumptions related to the new geometry's arrangement and the limitations found on the code, since they could influence the final results.

Another aspect to mention is that the thermal behaviour of the bore field was simulated considering hourly steps in the short-term modelling. In spite of the increasing computational time, the choice to work with hourly steps gives more accurate results instead of using daily or monthly ones as in the previous modelling.

Once the critical points are overcome, it was possible to start the simulations in order to predict how the ground will behave.

7. CONCLUSIONS

The project, which was entrusted to me during my exchange period in Stockholm, mainly concerns the study of a large scale GSHP system. The installation is composed of 130 boreholes with different inclinations and groundwater levels.

The boreholes are arranged in an uneven geometry divided in 14 thermal zones, each one are connected to a different heat pump. It is important to mention that the thermal influences among most of them were estimated negligible.

The simulation of the thermal process for the given bore field configuration aims at predicting the heat carrier fluid temperature for short-term (1 year) and long-term (20 years) simulations, considering respectively hourly and monthly load profiles. The knowledge of the borehole exit fluid temperature is important to assess and optimize the performance of the GSHP installation.

The thermal response of the borehole is studied by a short-term simulation. Conversely, the study of thermal interactions among boreholes is a slow process and takes more time, and it depends upon the extraction and injection periods of the ground heat.

After becoming familiar with the simulation software, the second step was to design the field layout and, at the same time, check the validity of the code. This preliminary check was required to find possible mistakes in the model.

Since the code was not able to simulate properly the whole installation, it was necessary to come up with an alternative resolution.

For this reason, the uneven configuration was approximated, taking into consideration only vertical boreholes, and simulated considering separately the different thermal zones with the unbalanced heat load profile.

In addition, different cases were studied considering an increasing number of boreholes in order to assess the thermal influence among the exchangers on the fluid temperature drift.

Once the different study cases were defined and the field layout was acquired, the g-functions were calculated for each case. The following step was to predict the heat carrier fluid temperature circulating in the boreholes.

As regards the unbalanced load profile, the fluid temperature change due to an increasing number of boreholes is notable, especially in the second part of the year.

In the long-term simulation, the thermal behaviour of a single borehole shows that the system seems to be thermally balanced. The fluid temperature profile presents repetitive responses over the simulation time. In fact, the peak-to-peak variation of the heat carrier fluid temperature is about 27 K (maximum temperature around 24°C and minimum temperature around -3 °C) throughout 20 years.

In the first years, a greater number of boreholes increase the difference between the maximum and the minimum value of the fluid temperature. After 5-6 years, the fluid temperature levels continue to increase slightly until the end of the simulation time.

As a result, the minimum fluid temperature reached after one year for a couple of manifolds is about -6 °C and the maximum one about 26 °C. At the end of the simulation period they are respectively about -2 °C and 30 °C at the end of the simulation period.

On the basis of the results obtained, two hypothetical scenarios were introduced in order to point out potential ways to improve the performance of the GSHP system. With this objective in mind, the configuration was simulated using balanced load profiles and by changing the starting month operation.

Firstly, starting the simulation in October, and not in January, does not lead to a notable improvement of the system performance. This is partly due to the fact that the heat extracted, from October to January, is around 20% of the heat injected during the rest part of the year.

In this case, the fluid temperature decreases by about 5 K at the beginning of January, while after March the gap starts to be negligible.

The second alternative was to reduce the heat imbalance and simulate the approximated configuration with a balanced load profile. In order to have the same cooling and heating demands supplied by the geothermal system, a new supplementary cooling system was coupled with the GSHP system.

As expected, the hybrid GSHP system led to an improvement of the heat pump efficiency, especially in summer time when the auxiliary technology is called to supply the cooling peak.

In 1 year of operation the maximum temperature decreased by 5 K and up to 8 K in the long-term process.

With respect to the economic evaluation, it needs to assess the costs for potential auxiliary system (for example solar panels or other solutions) to know the energetic and economic feasibility.

Further experimental analysis should be carried out in order to verify if the given model describes the real behaviour of the system with sufficient accuracy.

The approximation done for the new geometry arrangement seems to be acceptable to simulate the thermal process of the real configuration, even if the spacing between boreholes is larger with respect to one of the real case.

Nevertheless a better validation of the model could be done by comparing the obtained results with real values, which can be measured starting from October 2015.

Furthermore a new way of resolution was thought during the last meetings. The increasing interest of cooling in the commercial buildings is leading towards more versatile configurations in order to fulfil cooling and heating demand by dividing the ground into different thermal zones.

The usual way of operating multiple borehole fields today is to use all the BHEs to extract heat during winter and inject it during summer.

As alternative operation mode, the manifolds of the same configuration could be split in two different groups, extraction BHEs and injection BHEs. The idea is to use the boreholes of a group to supply the heating energy and those of the other group to fulfil the cooling demand.

The purpose is to increase the spacing between groups of boreholes and reduce the thermal interference in the long-term heat process.

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