TEMPERATURE STRATIFICATION OF CIRCULAR BOREHOLE THERMAL ENERGY STORAGES

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Abstract: Circular borehole field geometries are sometimes preferred when designing borehole thermal energy storage systems, including controlled radial temperature gradients from the center and across the borehole field. A numerical model has been described in this paper in order to study the influence of connecting boreholes in radial zones with different thermal loads. The studied geometry consists of 3 concentric rings having 6, 12, and 18 boreholes, and the boundary condition at the wall of all boreholes can be flexibly changed. In this case, a realistic quasi-uniform temperature condition, observed using distributed temperature measurements, was applied at the borehole wall, giving a temperature gradient of 1 K from bottom to top in all boreholes. The boreholes are thermally connected with each other. Thermally connecting the boreholes is one of the alternatives of the Superposition Borehole Model (SBM). A few control strategies for using the circular borehole field are studied, both for balanced and unbalanced thermal load cases.

Key Words: g-function, borehole thermal energy storage, ground source heat pumps, borehole heat exchanger, circular fields, ground temperatures, stratification

1 INTRODUCTION

Shallow geothermal energy systems based on vertical boreholes aim at exploiting the energy contained or stored in the bedrock. The energy is often extracted or injected by circulating a fluid through vertical borehole heat exchangers. Systems where either heat or cold are stored are often called Borehole Thermal Energy Storage (BTES), an underground structure for storing heat collected in summer for use later in winter, for example. As this thermal energy is collected, it can be distributed with various strategies in order to deliver either cold or heat.

When designing a BTES system, the designer needs to determine the number of boreholes required, the borehole depth and the geometry of the borehole field (distance between boreholes, borehole location, inclination, etc.). In order to achieve this, the designer considers the location of the system, the ground properties, the available drilling area and the thermal loads, and decides a size and form of the borehole field which satisfies the temperature requirements of the system to be built. The sizing of the borehole field is important and determines whether the installation is profitable or not. It is important to examine the thermal response of the bedrock due to varying thermal loads with different time horizons. Especially for the long-term perspective (decades), it is vital that the bedrock is not depleted of thermal energy so that the lifetime of the system is not limited. Stratifying and controlling the temperature levels in the borehole field may enable a better utilization of the ground as a source of cold and/or heat.

There are several tools to calculate the thermal response of borehole fields. The most popular commercial software, EED and GLHEPRO, by (Hellström and Sanner 1994) and

(Spitler 2000), respectively, are based on pre-calculated thermal response factors called g-functions, originally presented in SBM by (Eskilson 1986). Having a g-function for a borehole field, the linear properties of the heat equation can be utilized to investigate the effects of varying heat pulses, i.e. study borehole systems with variable extraction and injection. The technique for doing this is often referred as temporal superposition.

By calculating the average temperature of the boreholes as a function of time, the g-function is established for a specific borehole field. Every borehole geometry field has its own g-function. SBM calculates the thermal response of the bedrock based on the spatial superposition of partial solutions for a two-dimensional numerical calculation of a borehole in a homogeneous surrounding material. A uniform borehole wall temperature at all-time instants is normally assumed (other possible boundary are also possible in SBM), but the heat flux can vary in time and is different between the boreholes.

Eskilson suggested also an analytical method for approximating the g-function, the Finite Line Source (FLS). The advantage of this method, also presented in (Zeng et al. 2002), is that it does not require as much computing power and it is more flexible from the borehole geometry point of view. Some newer tools based on the FLS approach allow for a very fast calculation of the g-function, especially after the improvements by (Lamarche and Beauchamp 2007). The FLS approach assumes a constant heat flux along the borehole wall. Although this boundary condition may be limited, boreholes can be connected as done by (Lazzarotto 2014) allowing for more flexibility and a more realistic approach for multiple borehole systems. FLS approach can be even used to consider the variation of the heat flux along the length by dividing the boreholes into segments (Cimmino and Bernier 2014).

In this paper, we investigate the thermal response of a circular geometry borehole field containing 36 boreholes arranged in concentric rings of 6, 12, 18 boreholes. Somewhat similar borehole field geometries have been studied in (Chapuis and Bernier 2009) using TRNSYS. In our case the heat transfer problem is solved numerically with the Finite Element Method (FEM) software COMSOL Multiphysics©. The model is built in such a way that the boundary condition at the wall of all boreholes can be flexibly changed. In this case, a realistic quasi-uniform temperature condition is applied to set a temperature gradient of 1 K from bottom to top of borehole depth at in all boreholes, as observed in the experiments by (Acuña 2013).

Our boreholes are thermally connected with each other and they are thought to be run in parallel, i.e. with the same inlet temperature (at least for a given ring). It is also possible to use borehole connections in series in circular (or hexagonal) borehole field geometries as a way to stratify temperatures in the ground. An example of this is the Drake Landing Solar Community Project (Sibbitt et al. 2007), a large project where groups of 6 very shallow holes were connected in series from the center to the outer part of the borehole field (see also the reference for the Drake Lake Solar Community). There are also some projects with circular BTES in Sweden (SEEC 2014) and in the United States.

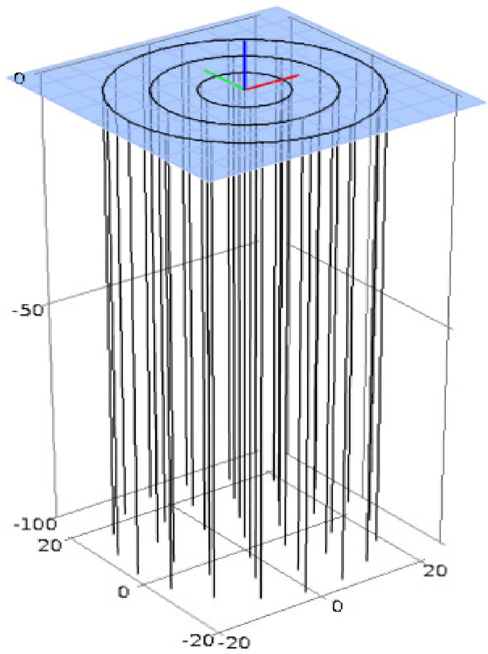
We show how ground temperatures are affected when the boreholes are connected in radial thermal zones with different thermal loads. The zones consist of the previously mentioned rings. Both balanced and unbalanced thermal load profiles are studied, using boundary conditions similar to those mentioned above. The borehole geometry is illustrated in Figure 1. Heat transfer is considered from the borehole wall and into the surrounding bedrock that is homogeneous and has no groundwater flow.

The impact of temperature zones is examined by using a given load profile and study some different charging strategies when different share of energy supplied to the different radial zones. For the unbalanced case, the thermal load profile is scaled so that the heat charge is twice as large as the outtake. Similar control strategies have been studied in an 8x8 square borehole (Lazzarotto 2014) and (Monzó et al. 2013).

2 MODEL OF A CIRCULAR BOREHOLE FIELD GEOMETRY

A circular and a square borehole field model with the same amount of boreholes are created. In the former, the boreholes are placed in three concentric rings consisting of 6 holes in the innermost ring (r_1), 12 in the middle (r_2), and 18 in the outer ring (r_3). A drawing illustrating borehole locations for the circular geometry is shown in Figure 2. The central borehole is not used in the simulations in order to keep 36 active boreholes (same amount of in the square geometry). The square geometry is used as benchmark in some parts of the study.

To reduce the calculation time, only the minimum symmetry for the borehole field is simulated. Only 1/12 of the total geometry was simulated (the reduced model corresponds to a sector of 30 degrees of the whole borehole field as shown in Figure 3). The same result was obtained as if the entire geometry would have been built and simulated.



geometry

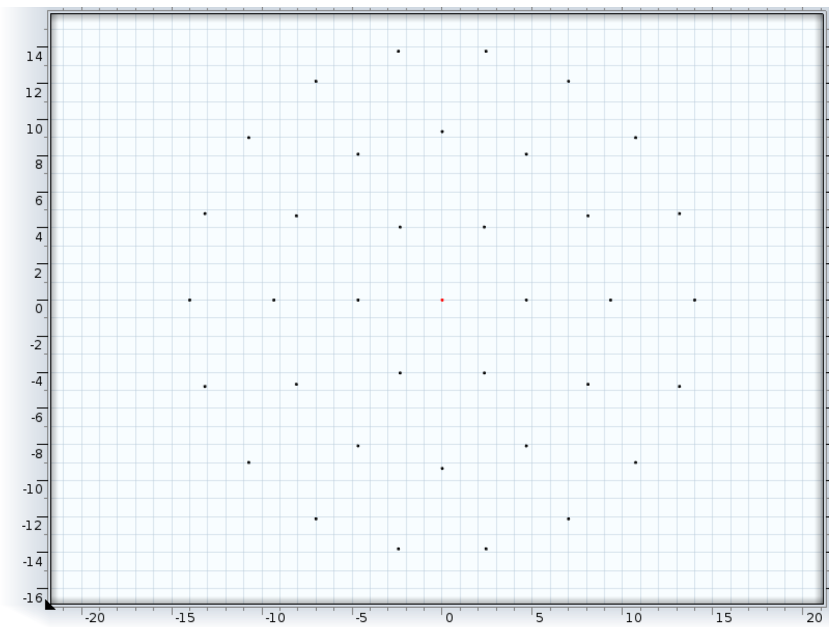


Figure 2: The circular geometry consisting of 36 boreholes*.

***** The dimension shows the location of the boreholes in meters [m].

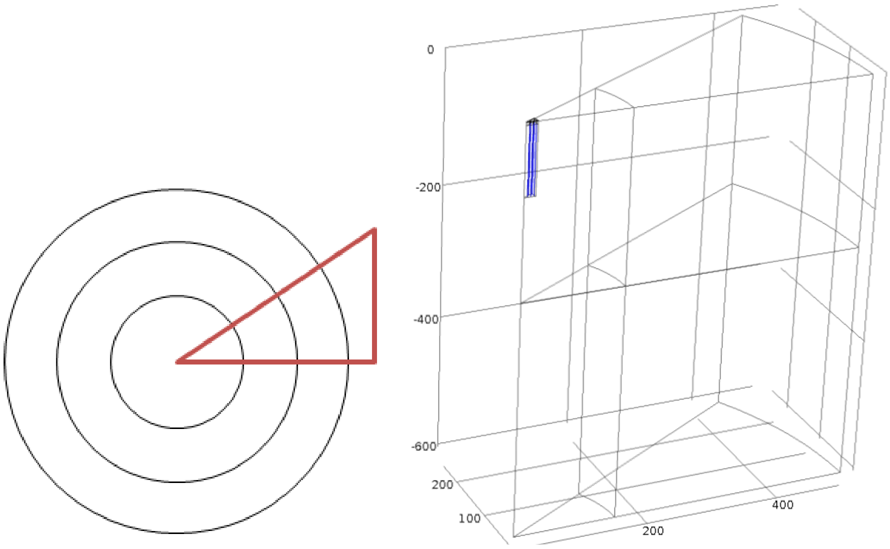


Figure 3: Actual simulated section of the circular geometry*.
* The dimensions of the borehole field are shown in meters [m].

The boundary condition at the borehole wall is defined by considering a total constant heat flow in the borehole field and setting a quasi-uniform temperature gradient of 1 K along the borehole wall. This temperature gradient is based on experimental observations as of (Acuña 2013). This type of temperature gradient as boundary condition at the borehole wall may be closer to the reality and may depend on the type of collector pipes installed in the boreholes.

Since the boreholes are connected in parallel, all the boreholes will share the same temperature condition. Thus, the heat flux is distributed to each borehole and along the borehole length according to the conditions on the surrounding ground, always satisfying the boundary condition at the borehole wall. A description of how this can be accomplished in COMSOL can be found in (Penttilä 2013). The methodology to apply the aforementioned boundary condition is described in detail by (Monzó et al. 2014a) and validated against experimental data in (Monzó et al. 2014b). The thermal properties used for the ground are presented in Table 1.

Table 1: Thermal properties for materials used in the model

Density, ρ, $\left[\frac{kg}{m^3}\right]$	**Specific heat capacity,** C_P , $\left[\frac{J}{kg \cdot K}\right]$	**Thermal conductivity,** k, $\left[\frac{W}{m \cdot K}\right]$
2300	870	3.1

The bottom surface takes into account the location of the simulated installation having boundary condition "Thermal Heat Flux", Stockholm city, with a geothermal flux of 0.05 W/m^2. The top ground surface has a temperature, also location-specific, representing the annual air temperature at the chosen site.

At the uppermost 4 m, a boundary condition with a thin thermally resistive layer is used in order to simulate the adiabatic depth, i.e. account for groundwater level and soil between bedrock and ground surface. All domains in the model have temperature as an initial condition, corresponding to a temperature gradient from the bottom of the model to the surface caused by the geothermal gradient, ground surface temperature, bedrock thermal conductivity and the depth.

The mesh of the circular model with interconnected boreholes has a 2-D triangular grid on the top surface of the plate, which are then swept along borehole depth. The distribution along the borehole depth is 20 elements. The remaining surrounding rock volume is made of elements with tetrahedral shape. Total number of elements of the reduced model consists of approximately 156000. A presentation of the mesh is shown in Figure 4, showing smaller elements in the mesh near the boreholes and the increase in size in the direction away from the borehole field. A similar mesh is done for the circular geometry.

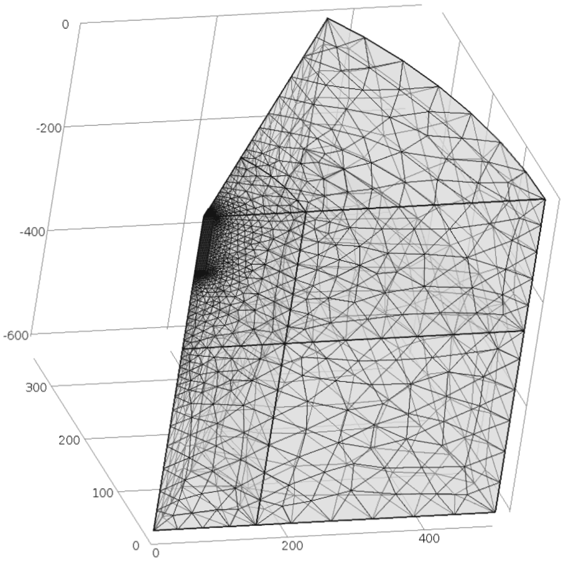


Figure 4: Mesh of the circular configuration*.

* The dimensions of the borehole field are shown in meters [m].

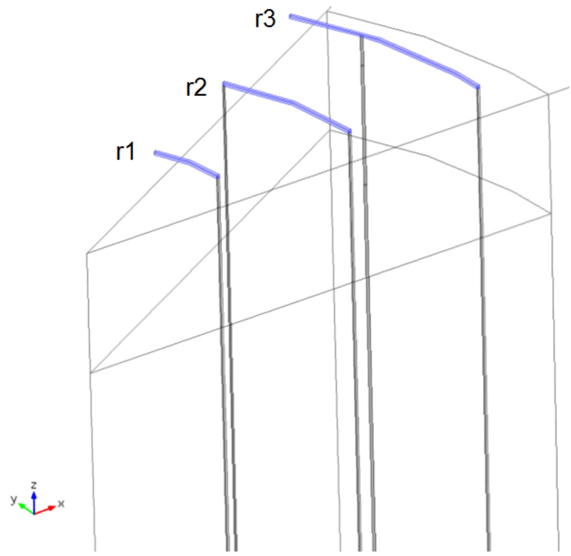


Figure 5: The circular borehole field connected in 3 concentric rings

A reduction of the modeled rock volume to 150 m in radius and 350 m depth in the cylindrical case is found to not affect the result. This reduction aimed at reducing the number of elements in the model, which results in shorter computing time.

Once the model was built, a g-function for the borehole field is calculated in order to be able to use it for more rapid calculations in the future, and as a way to validate with reference square solutions, both from COMSOL (using the same approach) and EED. In EED only the study of the square pattern is possible.

When comparing to the EED result, the g-functions obtained with COMSOL in 6x6 square and circular borehole field are slightly lower than generated with EED (Penttilä 2013). The difference may be partly explained by the temperature gradient of 1K along the borehole depth imposed in our models. The g-function behind EED assumes uniform temperature along the borehole depth. Also, it is somewhat unclear what the buried depth (adiabatic depth) is in the g-functions behind EED.

Regarding the comparison of our square and circular model, the g-function representing the circular borehole field is slightly higher than in the square case. At a constant heat flow, this difference gives a slightly higher temperature at the borehole wall for the circular geometry as time goes towards infinity. The circular borehole field has an outer mantle with the shape of a cylinder, while the square field has the shape of a cuboid. The cylinder has thus a smaller area exposed to the surrounding ground, possibly implying fewer heat losses and higher storage possibilities. However, when simulating real thermal loads (i.e. different than generation g-functions), the latter statement will depend on how the borehole storage is controlled.

3 TEMPERATURE ZONES IN CIRCULAR BOREHOLE FIELD GEOMETRIES

As mentioned above, the boreholes in the circular borehole field model are connected together in three separate rings to create different radial temperature zones. The reason for separating and grouping the boreholes in radial zones is to control of the amount of energy that goes into each zone and perhaps optimize the temperature distribution in the BTES. The design of the rings is presented in Figure 5.

Two cases have been studied, a balanced and an unbalanced thermal load. The active borehole depth is set to 200 m, according to the geometrical characteristics of a real system built in Sweden. The balanced load profile is also based on this installation, while the unbalanced case is hypothetical. The simulation time is selected to 30 years but the results are shown up to the 15th year of operation. The time steps in the simulation are automatically selected by COMSOL with the restriction of a maximum step of 15 days.

3.1 Balanced thermal load profile

The balanced thermal load profile is shown in Figure 6. To investigate how the varying energy extraction affects the radial zones, six different control strategies were tested. For each strategy, the radial zones have their own load profile which can vary in power and over time. The sum of the load profiles for the three zones corresponds to the given total load profile in Figure 6. In this paper only some of the control strategies for the temperature zones are reported. The result of all strategies can be found in (Penttilä 2013).

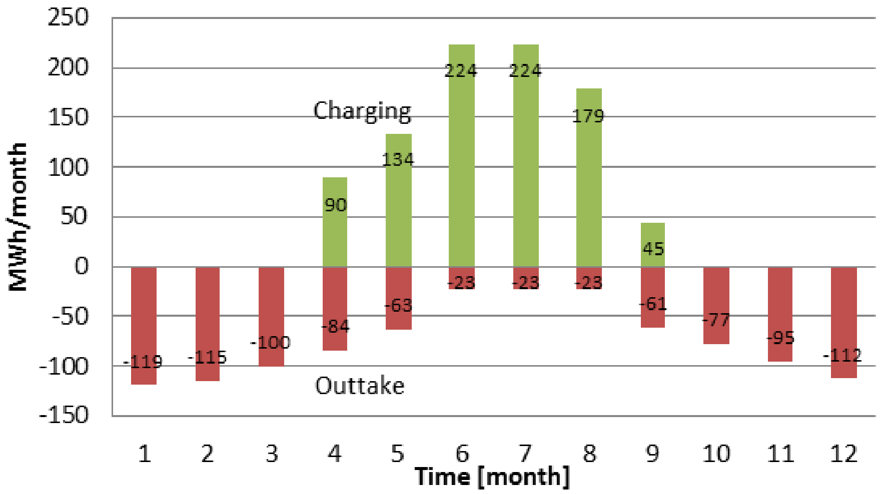


Figure 6: Balanced load profile

The control of energy that goes to the different zones is done in such a way that, during the first charging (injecting heat) month, both the inner zone and the middle are (r_1 and r_2) activated. However the boreholes in the middle zone receive less charge per meter borehole during the first month. During the second month, the load is equally shared between the boreholes in the two zones. Along the following three months, the boreholes in all zones receive charging. During the last month of the heat injection season, charging stops in the outer zone while the holes in the middle zone receive less charge per meter borehole than the inner zone. The outtake is equally distributed on all boreholes. The process is illustrated in Table 2.

Table 2: Charging strategy by month for respective ring

Charging (green shaded)			
Month	r_1	r_2	r_3
1			
2			
3			
4	2/3	1/3	
5			
6			
7			
8			
9	2/3	1/3	
10			
11			
12			

The above settings for the load profile for each zone result in reasonable charge at approximately 40 W/m. Figure 7 shows the amount of MWh/month that goes into each ring in the borehole field.

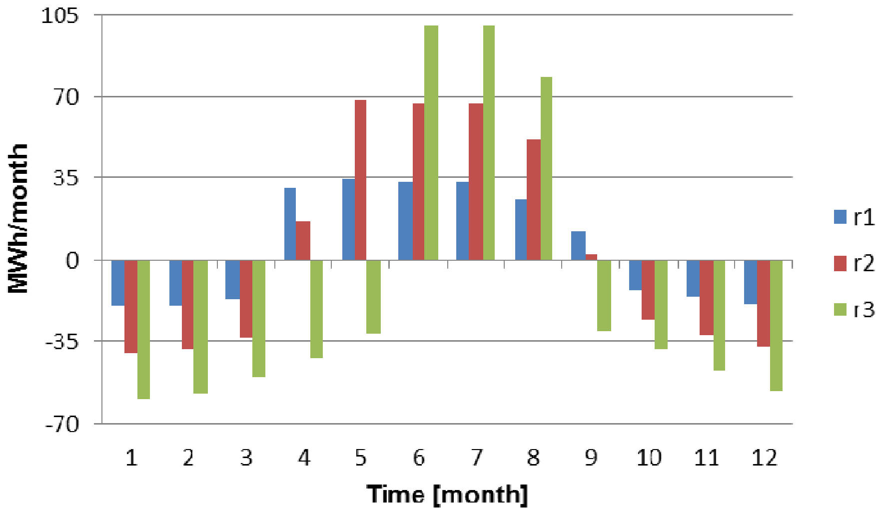


Figure 7: Load profile imposed to each of the rings, balanced cases

Figure 8 shows the temperature response of the boreholes in the respective rings during year 15, together with a calculation from EED for the quadratic 6x6 geometry, showing that the temperature in all zones has a smooth variation without major fluctuations as the charge in the different zones are started and stopped. The temperature level of the inner zone is highest at all times and varies between 5°C to 20°C. The middle zone temperature variation follows the inner zone variation. The minimum and maximum temperature in the middle zone is 4°C and 19°C, respectively. For the outer zone the temperature range is between 4°C to 18°C. The latter are time shifted.

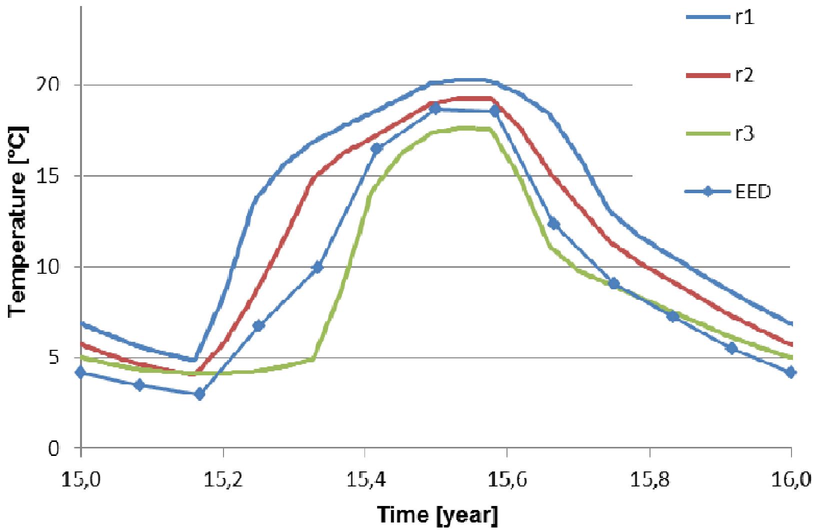


Figure 8: Borehole average temperature during year 15 for the three rings compared to EED solution for the quadratic geometry, balanced cases

3.2 Unbalanced thermal load profile

An unbalanced load profile character is based on the former balanced case. The charge was increased by 15% and the outtake reduced by 23.5%. The modified load profile over the years is shown in Figure 9. The borehole field has the same geometrical design as in the balanced case. The charging control strategy is the same as before. Figure 10 shows the amount of MWh/month that goes into each ring.

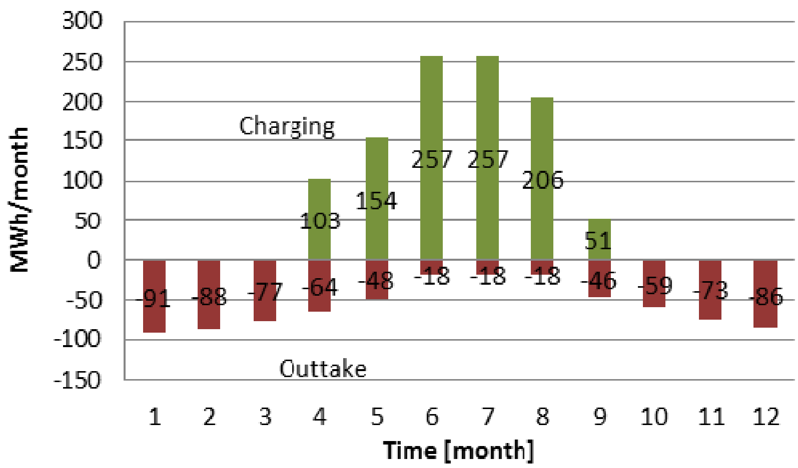


Figure 9: Unbalanced load profile

Figure 11 shows the temperature response of the circular borehole field during the first 16 years of operation, together with an EED calculation. The EED series start at year 1 and show the minimum and maximum temperatures coming from the 6x6 square borehole field (without temperature stratification).

Different temperature levels at each of the thermal zones (rings) are observed from Figure 11, showing the temperature stratification of the ground where higher temperatures can be kept in the middle of the storage along the years. Different temperature zones can be used for covering separate needs at the site where the boreholes are used. The same applies to the balanced cases, differing by the fact that temperatures are the same year after year.

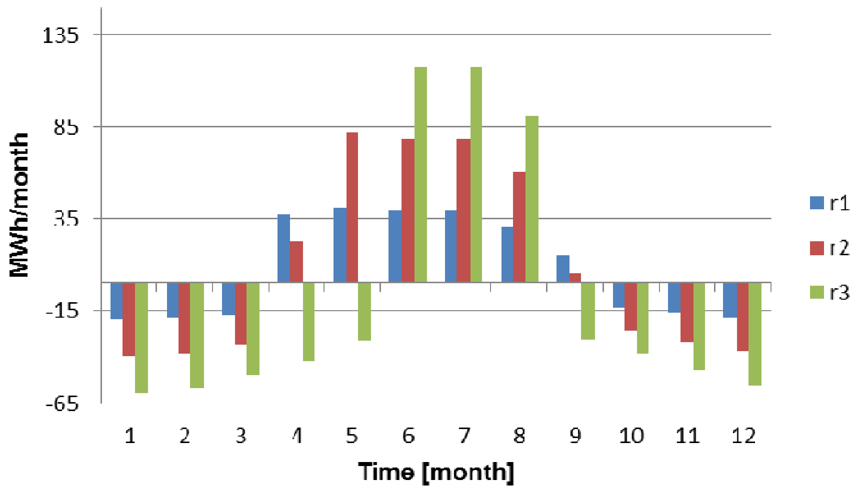


Figure 10: Load profile to the rings, unbalanced case

All borehole temperatures shown in Figure 11 have a tendency to flatten somewhat after several years, but they keep increasing in time due to the unbalanced loads. An interesting control strategy would be to shift the use of the different zones after some years. This strategy would hypothetically keep the temperature levels of all rings within the design limits of the installation, providing both heating and cooling at all times. The amplitude of the temperature changes at each ring could also be optimized by different thermal load strategies. A mean temperature taken from all rings would be in acceptable accordance to the square case simulated with EED. The latter would, however, result in slightly higher values for the circular geometry likely due to fewer losses to the surrounding ground.

Future work will be devoted to finding optimum temperature stratification strategies for given standard applications and load profiles for this type of borehole field.

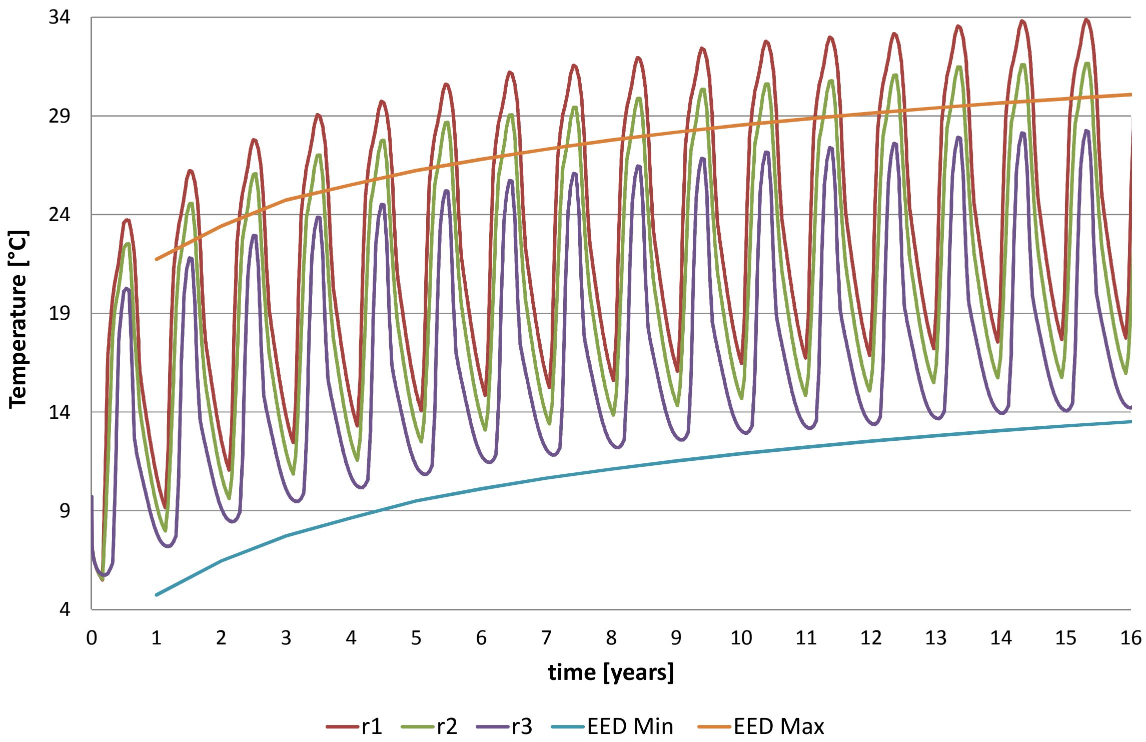


Figure 11: Borehole average temperature, unbalanced case

4 CONCLUSIONS

The long-term temperature response of a circular borehole field consisting of 36 boreholes has been investigated through a numerical model developed in COMSOL. The studied geometry consists of 3 concentric rings having 6, 12, and 18 boreholes.

A quasi-uniform temperature condition with a gradient of 1K is set at the borehole wall of all boreholes, allowing the total heat flux to the borehole field to be naturally distributed in the ground. This type of temperature gradient as boundary condition at the borehole wall may be closer to the reality and may depend on the type of collector pipes installed in the boreholes.

The temperature response of the circular geometry is compared in terms of the g-function to that of a square borehole field with the same amount of boreholes. For the circular borehole field, the g-function presents higher values in the asymptotic part of the curve, which may imply fewer losses to the surrounding ground for this geometry as compared to a square geometry.

An annual balanced and unbalanced thermal load profile with varying output over the year have been used to test the possibility of controlling heat transfer in three radial zones in the circular borehole field. Some control strategies have been tested and presented, showing that it is possible to stratify and control various temperature levels in pre-established ground zones. Different temperature zones can be used for covering separate needs at real borehole sites. In future studies, an optimization method for controlling these temperature zones will be investigated.

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