Use of Comsol as a Tool in the Design of an Inclined Multiple Borehole Heat Exchanger

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Abstract: A field of connected boreholes drilled in the ground can be used both for cooling, heating and storage purposes. The boreholes can either be straight or inclined. The latter case is common when the drilling area is limited. Inside the boreholes, a secondary fluid circulating through heat exchanger pipes imposes a heat transfer process to or from the ground, which over time changes the ground temperature, changing the performance of the ground source system over the years. An undersized borehole field will be exhausted before the projected lifetime, and a too large field will give higher costs. Because of this, it is important that the borehole field is properly sized and evaluated before the construction.

This study presents results from evaluations of inclined boreholes used for cooling purposes, modeled with the software Comsol. Uniform ground temperature, a ground temperature gradient, and a geothermal heat flux, are considered as boundary condition, together with values from field measurements and literature.

The three dimensional problem is solved with the transient heat conduction equations and the average borehole wall temperature is obtained during several years of operation. Using a measured borehole resistance, the fluid mean temperature in the boreholes is calculated. Temperature distribution in time and space as well as heat flow directions illustrates the results.

A correct borehole length and configuration that meets the temperature requirements of an existing system can be determined from the simulated cases.

Keywords: Ground Source Cooling, Inclined Boreholes, Design.

1. Background

With increased focus on reduction of energy consumption and decreased environmental impact, the technique of using free cooling from ground source systems has risen up as an alternative to conventional cooling machines. Also protected sites like military or telecommunication facilities have to take the aspects of energy efficiency and environmental impact in consideration when planning their operation.

The problem that arises when designing system with free cooling from borehole heat exchangers is that the ground temperature becomes exhausted and has a restricted cooling life length if the heat exchangers are used too heavily. In protected sites such as military or telecommunication facilities, exhausted boreholes will lead to temperatures in the system higher than those the system has been designed for, which could cause damages to the equipment being cooled. This problem could be solved by having a large amount of boreholes, by using auxiliary free cooling from ambient air or other sources as a relief, or by using the excess heat for other purposes in combination with other storage applications and/or heat demands. Inclining the boreholes away from each other will also decrease the degree of thermal interaction between them.

Using ground source cooling has the advantage that it is reliable, cheap to operate and can be secured inside a protected facility. One downside is the high investment cost for the boreholes. This could be decreased by combining the boreholes with free cooling sources, giving a smaller borehole field with lower investment cost and less land use.

The design of the borehole field, which is based on short and long term dynamic heat transfer analyses in the ground, requires consideration of the time varying heat loads from/to the ground due to the installation requirements. Sometimes, the heat load can be constant but distributed in time depending on the need. The results of how the heat loads affect the ground depend on the borehole field geometry, the ground thermal properties, time, and the size of the loads, among others.

The most computational effective method for performing ground response simulations consists of superposing in time the effects due to different heat loads by pre-calculated temperature response factors or g-functions (Eskilson, 1987), which represent the dimensionless temperature variation of a ground volume (with respect to the undisturbed ground and evaluated at the BHE periphery) to a stepwise, continuous and constant heat pulse lasting in time. Any particular borehole field geometry has its own response and its own g-function. Databases including results from this work are behind several popular commercial calculation software such as Energy Earth Designer (EED).

There is also the approach where a single BHE solution, the Finite Line Source (FLS), is superposed in time and space to describe the ground response of any BHE geometry. FLS generated g-functions were presented by (Zeng et al, 2002) and later by (Lamarche and Beauchamp, 2007). This approach is significantly more flexible regarding the field geometry and allows accounting for inclined boreholes (Lamarche, 2011).

Solving the 3-D transient heat conduction differential equation with Comsol allows finding the solution of such problems by, for example, imposing a constant heat flux as a boundary condition at every single BHE periphery. This is what is done in this study for a particular inclined borehole field geometry.

2. Methodology

This study intends to evaluate the performance of a borehole thermal energy storage system by using the software Comsol. This is done for two operation modes where the boreholes are combined with a free cooling source running in either unloading or recharging mode. In the unloading mode the boreholes are inactive during the winter period when the free cooling has a high capacity. While recharging, the free cooling system generates excess cooling during the winter period which is used to recharge or cool down the boreholes during this period.

To evaluate the performance of a ground source cooling system the average fluid temperature inside the BHE, T_f, is an important parameter. If T_f becomes too high, the cooling requirements cannot be met. The average fluid temperature T_f can be calculated using an effective borehole thermal resistance R_b, introduced by (Hellström, 1991), being a function of the borehole heat flow per unit length q, and the temperature of the borehole wall T_{bhw}, as expressed in Eq. 1.

$$T_f = T_{bhw} + R_b * q \qquad (1)$$

R_b is the thermal resistance between the mean fluid inside the BHE and the borehole wall. A standard conservative value of 0.1 K/(W/m) is used based on previous experiences (Soil Cool/Rekyl Project, 2004). This value is consistent with hundreds of field measurements previously published. The specific heat exchanged between the borehole wall and the ground is calculated by dividing the known total heat load by the total borehole length.

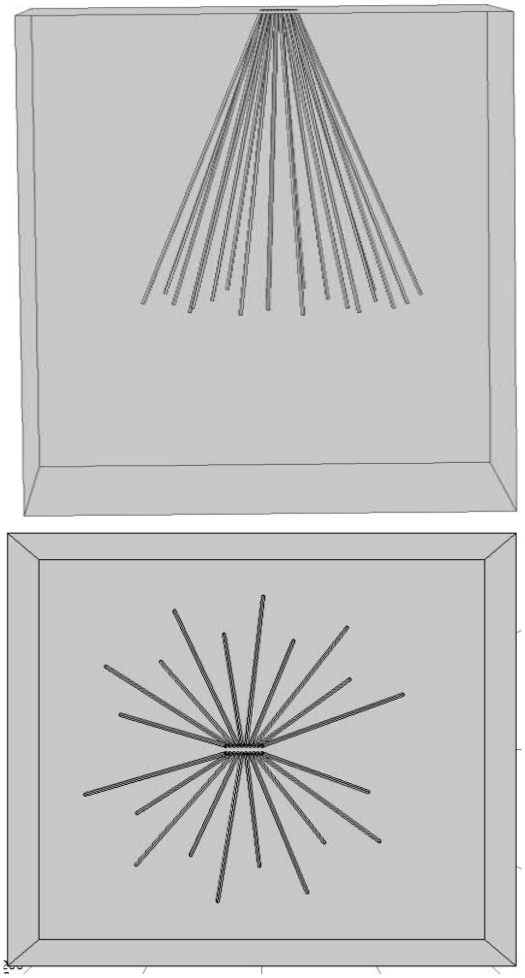

Figure 1. Borehole configuration from the side and from above.

Comsol is used to quantify the borehole wall temperature T_{bhw}. This is done with simulations of the heat transfer in the ground around the boreholes during a 20 year time period with 30 day time steps.

A total of 20 boreholes are modeled as hollow cylinders with 140 mm diameter and alternating lengths. The configuration used is shown in Figure 1 and is shaped as to fit inside an entrance tunnel to an underground facility. The boreholes are tilted alternating 15 and 20 degrees with 1.6 m spacing at the surface.

The borehole heat load is applied uniformly on the borehole surfaces as a heat flux that changes in time. The heat load varies throughout the year as shown in table 1. The negative heat load in the recharging case indicates that heat is removed from the ground (recharging) at these time periods.

Table 1. Heat load for the Unloading and Recharging cases

Month	Unloading case [kW]	Recharging case [kW]
Jan	0.00	-117.96
Feb	0.00	-100.74
Mar	1.79	-58.47
Apr	27.51	4.25
May	66.68	56.19
Jun	93.52	91.57
Jul	100.00	100.00
Aug	95.77	94.67
Sep	78.17	71.89
Oct	31.07	6.68
Nov	4.53	-52.34
Dec	0.00	-112.53

The ground thermal properties are shown in table 2. The boundaries in the ground around the boreholes are set to have a constant temperature of 6.6 °C which is a normal ground temperature in the Stockholm area according the software EED. This temperature is also used as an initial ground temperature. Absolute temperature measurements of at least a couple of degrees higher from the Stockholm region have been recently reported in (Acuna, 2010). In the simulations, a temperature profile based on the shape of these measurements is used. The exact values are shown in table 3. These were used as boundary and initial temperatures. The profile is adjusted to fit the 6.6 °C for comparison reasons with EED.

The ground surface has a temperature that alternates according to the average outdoor temperature (SMHI, 2012), see table 4.

Table 2. Thermal properties of the ground

Density [kg/m^3]	2700
Cp [J/kg K]	830
Thermal Conductivity [W/m K]	3.1

Table 3. Ground Temperatures of different depths

Depth [m]	Temp [°C]	Depth [m]	Temp [°C]
0	8.14	120	7.15
10	7.4	130	7.26
20	6.43	140	7.31
30	6.33	150	7.41
40	6.28	160	7.53
50	6.33	170	7.67
60	6.41	180	7.8
70	6.57	190	7.9
80	6.62	200	8.1
90	6.64	210	8.23
100	6.78	220	8.45
110	6.94		

Table 4. Ground surface temperatures.

Month	Temperature [°C]
Jan	-3.5
Feb	-3.7
Mar	-0.5
Apr	4.3
May	10.4
Jun	15.2
Jul	16.8
Aug	15.8
Sep	11.4
Oct	7
Nov	2
Dec	-1.8

A normal sized physics-controlled tetrahedral mesh with 107 000 cells was used.

Calculations with the software EED are used for comparison. Here, the boundary and initial conditions were set to correspond to those used in the Comsol simulation. Since this software does not contain g-function calculation for inclined boreholes, the geometry was approximated and modeled as closely as possible by using the spacing at the middle depth as borehole spacing for straight boreholes.

3. Results and Discussion

3.1 Ground Temperature Profile

The temperature distribution in the ground with tilted boreholes is shown in Figures 2 to 4. These figures show the results for unloading case with 212 m boreholes after 5, 10 and 20 years.

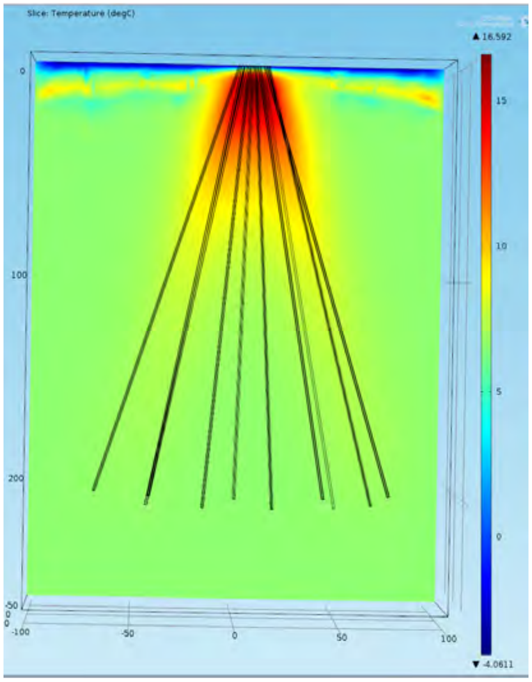

Figure 2. Temperature distribution in the ground after 5 years.

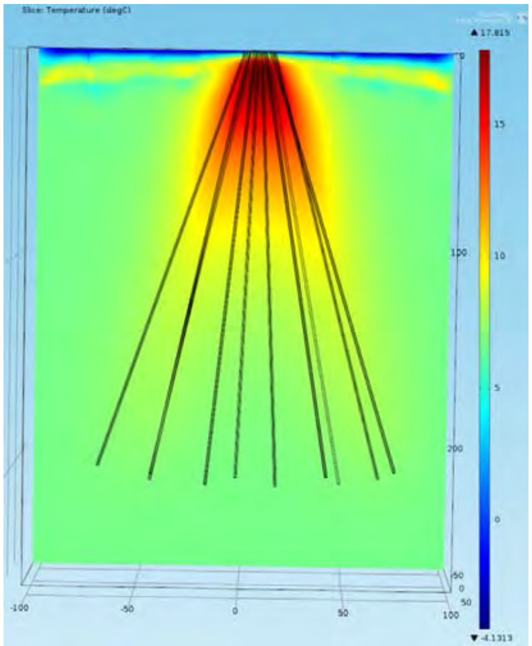

Figure 3. Temperature distribution in the ground after 10 years.

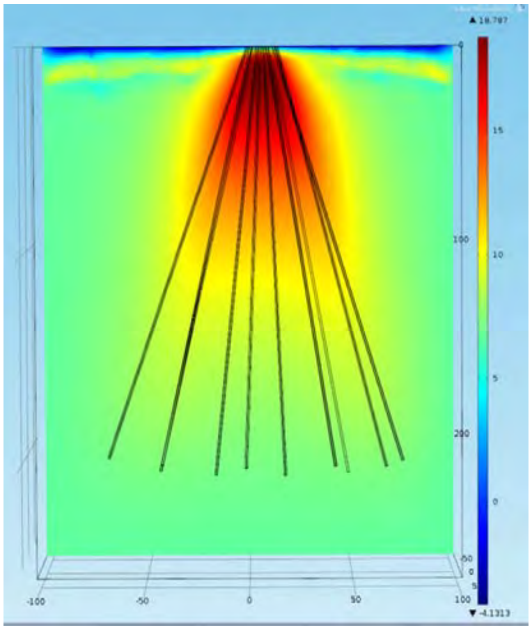

Figure 4. Temperature distribution in the ground after 20 years.

The temperature is highest in the top of the boreholes where the boreholes and the heat source are most concentrated. The rest of the volume around the boreholes, deeper in the ground, is fairly unaffected by the heat injection. With time, the rock volume that is affected expands downwards.

The boreholes are located densely at the top. The heat that is released at the top while using the ground as a cooling source is distributed to a smaller volume which is heated up more rapidly than the rest of the ground volume. The ground temperature around the top of the boreholes is 14-16 °C after 5 years, 15-17 °C after 10 years and 17-18 °C after 20 years. With a fluid incoming temperature of 18 °C the heat transfer in the top of the boreholes will be substantially worse than in the bottom of the boreholes where the ground temperature is affected less. When the ground temperature is 18 °C the heat transfer at that point will be zero and that part of the borehole will not be used. To avoid this phenomenon the boreholes could be placed with a larger distance or another type of heat exchanger could be used. A next step for the further development of this study will be to use a temperature as a boundary condition at the borehole wall instead of a heat flux, allowing to take care of this overheating effect at the top of the borehole in a better way.

3.2 Fluid Temperatures

Temperatures of the fluid coming out of the boreholes, T_f, vary with the length. In Figure 5 the temperature profile over 20 years is shown for unloading case for different lengths of the boreholes.

The temperature profiles show that a shorter borehole length gives both higher fluid temperatures and a higher temperature difference between the maximum and minimum temperatures. The temperature profile for 212 m seems to almost have flattened out, indicating that it soon will reach it equilibrium, while the profile for 150 m still increases at a rapid rate after 20 years. Increasing the amount of boreholes or the borehole depth will help on achieving better thermal balance, but will also increase the installation cost.

Figure 6 shows the fluid temperature profile for the recharging case after the initial heat up period for two lengths of the boreholes.

From figure 6 it is clear that the fluid temperature varies much more over the year than in an unloading case in figure 5. The variation over the year is around 10 °C in a recharging case while it is 5 - 7 °C for an unloading case. Figure 6 shows that the temperature decreases with time since the net yearly heat load is slightly negative. The longer borehole length gives less yearly temperature changes and also higher minimum temperatures in the winter.

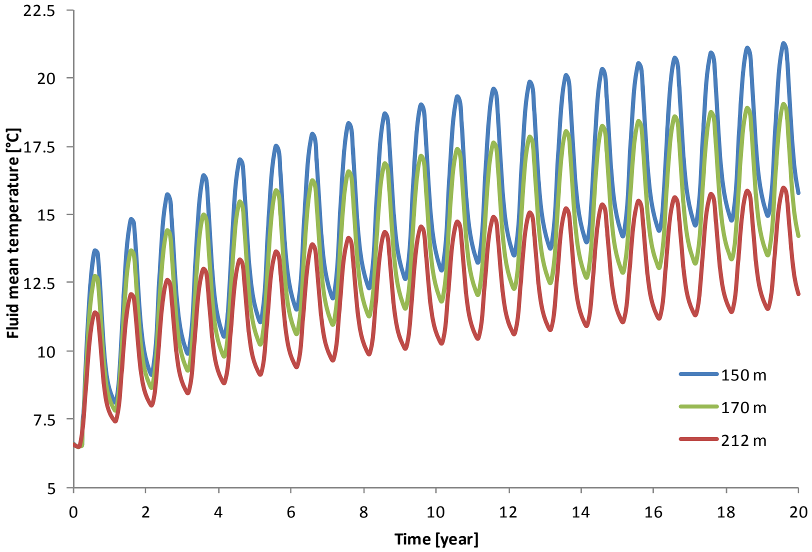

Figure 5. Temperature profiles of the fluid mean temperature for different borehole lengths for the unloading case

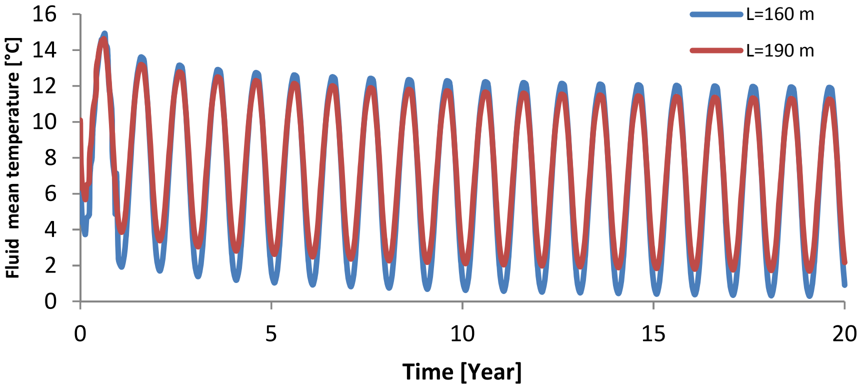

Figure 6. Fluid mean temperature profiles for different borehole lengths for the recharging case

For the unloading case, the temperature varies around 3 °C between the summer and the winter with 212 m boreholes which is the required length to reach the design parameters in this case. With shorter boreholes the temperature variations is larger, around 6 °C for 150 m. This is because the area that releases the heat is smaller and the boreholes reach a smaller volume of the ground that can take up the heat. For the recharging case the temperature variation is much larger, 10 °C as shown in figure 6. This is because the recharging case takes out heat from the boreholes during the winter which decreases the temperature more than just letting them rest during the winter.

Figure 7 shows the fluid mean temperature for the unloading case with the ground temperature gradient from table 3 and 212 m long boreholes, compared with the from the 212 m case in Figure 5 (without ground temperature gradient). The result shows that the temperatures are slightly higher with the gradient. This is natural since the average ground temperature is higher than 6.6 °C with the temperature gradient.

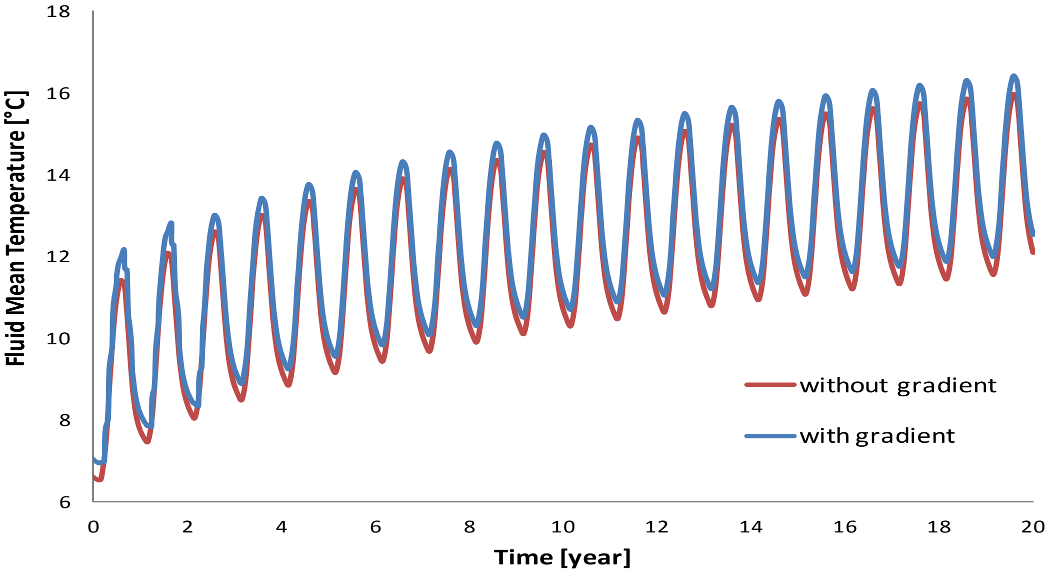

Figure 7. Temperature profiles of the fluid mean temperature for the unloading case with a ground temperature gradient and a 212 m deep borehole

3.3 Simulation model

The simulation model used in this work is a numerical heat transfer model in the software Comsol.

In the model a heat load is applied homogeneously over all the borehole surfaces. This is a simple but perhaps not optimal solution. The drawback is that it does not take the temperature of the fluid inside the borehole into account, meaning that heat is transferred to the ground even though the ground has a temperature above 18°C, which is the maximum fluid temperature in this project.

In a real case, more heat would be transferred to the ground at greater depths where the temperature is lower and the upper parts of the boreholes would not transfer any heat to the ground. A simulation method alternating the temperature of the borehole wall is more difficult. The temperature is actually the unknown variable and it is not known beforehand. One solution to this problem could be to distribute the load along the borehole depending on its vertical temperature profile so that less heat is released at the top of the borehole where the temperature is high and more is released further down the borehole where the ground is colder. Developing the simulation model further is not within the scope of this project but will be done as a future study.

As explained before, the tight placement of the boreholes at the top gives rise to an uneven temperature distribution in the ground. This temperature distribution gives rise to heat transfer from the warm parts of the ground to the colder parts further down. In Figure 8 this distribution is shown with arrows that show the direction of the heat transfer in the ground, representing the Unloading case after 20 years.

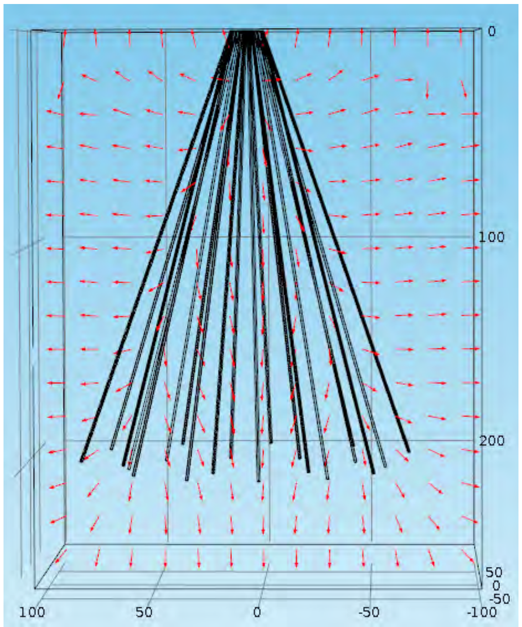

Figure 8. Plot with heat flow arrows indicating the direction of the heat flow.

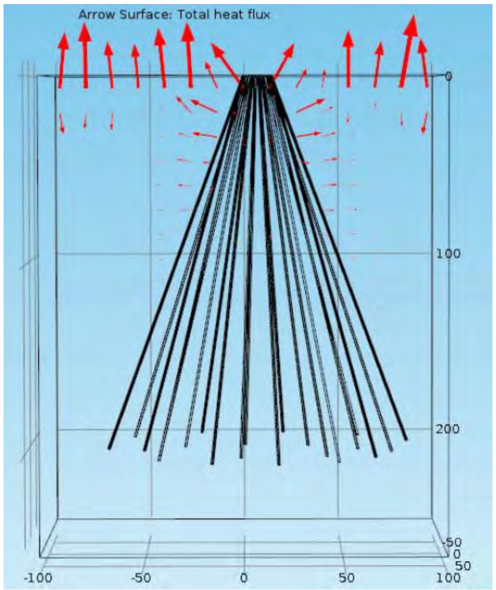

Figure 9. Plot with heat flow arrows indicating the direction and magnitude of the heat flow.

Figure 8 clearly indicates that heat is transferred from the upper area to the lower areas in the ground. Since other software do not really take this phenomenon into account for inclined boreholes it can have an effect on the results when sizing these kind of systems. Figure 8 is taken at a time during the winter when the outdoor temperature is low, some heat flow arrows point upwards, illustrating that part of the heat is released to the ambient.

Figure 8 shows all arrows having the same size and not taking the magnitude of heat transfer into account. In Figure 9 the size of the arrows shows the magnitude of the heat transfer upwards.

3.4 Software Comparison

The software that is more popularly used when sizing borehole energy systems is, in Europe, Earth Energy Designer (EED). This software has a large but limited amount of borehole geometries that it can handle, all of them being for vertical borehole configurations.

A comparison has been done with the results from the EED software by trying to approximate a vertical borehole geometry from the EED database to the inclined borehole field simulated in this study. This fictional geometry consists of 20 straight boreholes in a 6 x 6 open square configuration with a spacing of 15 m. This geometry is similar to a cross section located at the middle point of the tilted boreholes when seen from above. In the EED simulation, the same load, borehole length and other conditions as in the Unloading case were used. The resulting fluid temperatures are shown in Figure 10 together with results from the corresponding Comsol calculations from figure 5.

A comparison was also made between the two software for a case having a ground temperature gradient. Here, a heat flux of 0.05 W/m^2 and a ground surface temperature of 6.28 °C (which is the lowest value in table 3) were used to get a similar ground temperature as in the Comsol calculation. The comparison with the EED results and the results from Figure 7 is shown in Figure 11.

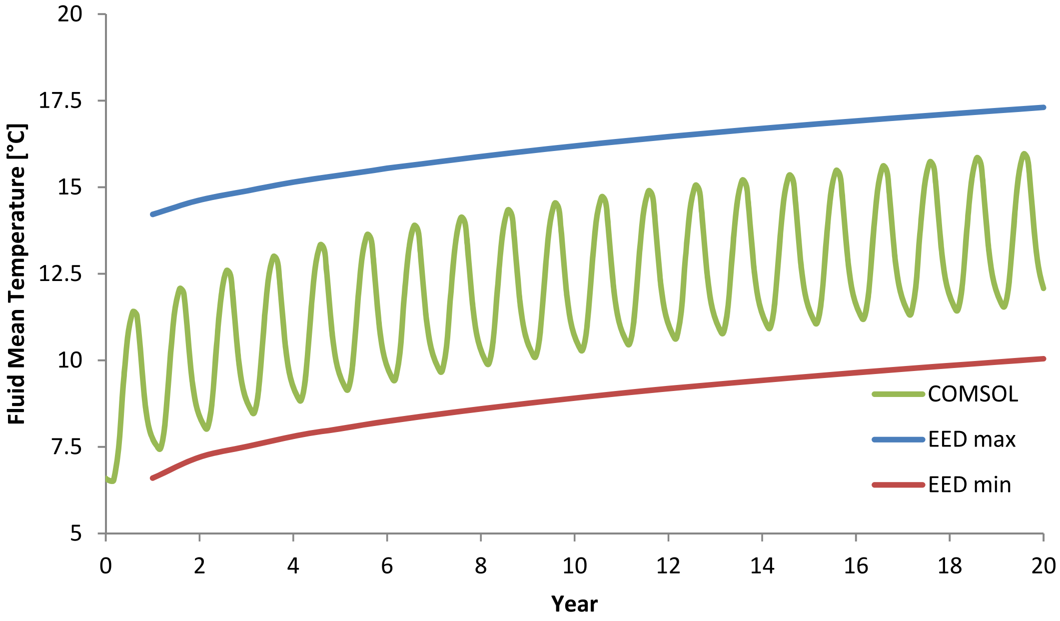

Figure 10. Yearly maximum and minimum temperatures from the EED calculation compared with the Comsol calculations

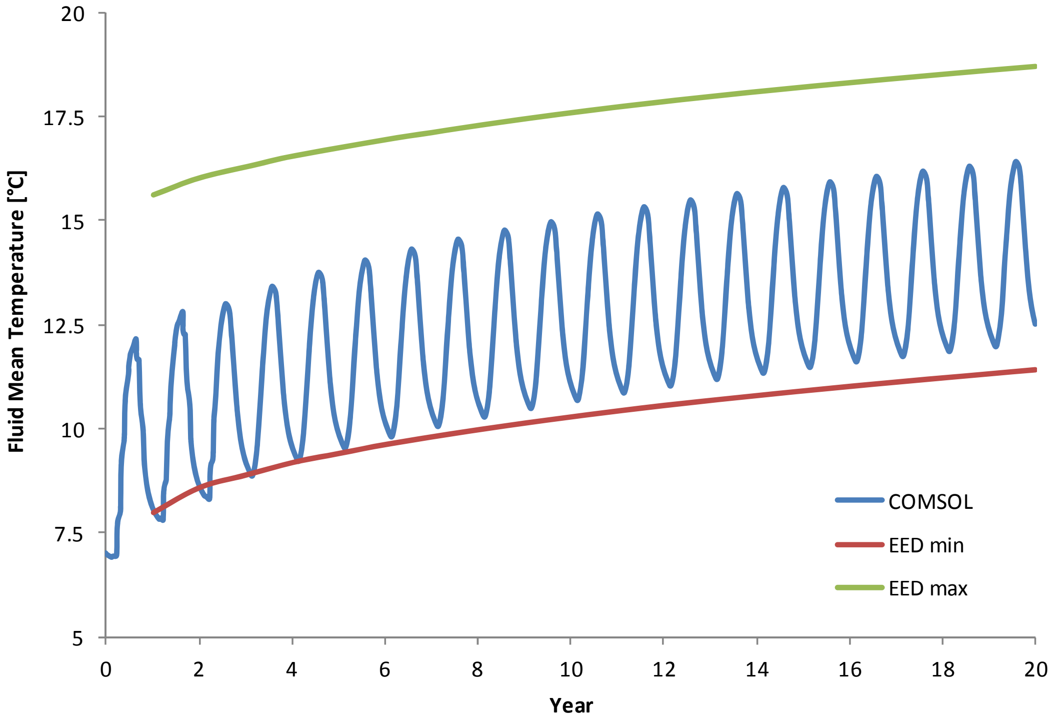

Figure 11. Yearly maximum and minimum temperatures from the EED calculation compared with the Comsol calculations with ground temperature gradient

When comparing the results from the different software in Figure 10 and 11 it is observed that EED gives slightly higher temperatures than the Comsol simulations done in this project, indicating that different calculation approaches can result in small errors when sizing the inclined system. The temperatures are slightly higher in the first years.

The conformity between the two software becomes better without the temperature gradient (Figure 10) than with the temperature gradient (Figure 11), having to do with the depth that EED uses for carrying the superposition analysis when the geothermal heat flux and the thermal conductivity are considered.

Adjusting the borehole spacing in EED and studying the Comsol problem with the temperature boundary conditions will perhaps result in better fitting between the two software simulations.

4. Conclusions

A satisfactory design of a cooling system based on an inclined borehole field has been performed.

A model for the design of the borehole field using Comsol was possible since this software allowed including inclined boreholes and taking three dimensional heat conduction effects around the boreholes into account. The model can also be adjusted to represent almost any borehole geometry, even deviations from the drilling of the boreholes. It is possible to assign different loads on different boreholes and also analyze each of them separately.

The results show that inclined boreholes used for cooling purposes may give a higher temperature at the top of the ground, giving rise to a heat flow from the top of the boreholes to the lower parts. Simulations using Comsol and other software as EED may not give exactly the same result even if similar boundary conditions are used.

5. References

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