Deep Borehole Heat Exchangers, Application to Ground Source Heat Pump Systems

Henrik Holmberg[1], José Acuña[2], Erling Næss[1], Otto K. Sønju[3]

1. Department of Energy and Process Engineering, Norwegian University of Science and Technology

2. Department of Energy Technology, KTH Royal Institute of Technology

3. Rock Energy AS

E-mail, henrik.holmberg@ntnu.no

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ABSTRACT

Deep borehole heat exchangers (BHE) can be used as a complementary heat source in ground source heat pump (GSHP) installations with a negatively balanced thermal load, i.e. when more thermal energy is extracted than recharged. GSHP systems can be made space effective and with a small or negligible visual footprint. Larger installations may, however, require certain amount of available drilling area for the boreholes. This area can be reduced by placing the boreholes closely together. This creates a system susceptible to the load balance. If the possibilities for thermal recharge are limited, the temperature in the boreholes will decline, which also degrades the performance of the system. To balance the thermal load, deep BHEs have to sustain the required temperature level without the need for thermal recharge. A numerical model is applied to simulate the performance of deep BHEs over time, and to determine the average specific thermal load and amount of energy extraction that can be sustained. The results are used to propose an alternative solution for a GSHP installation having a limited construction area and a negatively balanced thermal load. It is seen that the deep BHEs can support a high (increasingly with depth) thermal load, and that the required temperature level can be sustained over the life time of the system. Deep BHEs reduce the required borehole length, and are a viable option for GSHP installations in areas with scarcity of space and/or with negatively balanced loads.

1. INTRODUCTION

GSHP systems are made space effective by placing the boreholes in a compact pattern. Such systems favors thermal interaction between the boreholes and can be designed to store energy. Thus, if the yearly thermal load is positively balanced (more energy is being recharged than extracted) the temperature in the boreholes will increase over time, which favors the performance of the heat pump. On the contrary, if the thermal load is negatively balanced, the temperature in the boreholes will decline. Thermal recharge can often be provided with free cooling or by use of other thermal sources such as solar collectors, building exhaust air, outdoor air, amongst others.

This paper discusses cases where it is desired to use a GSHP system to provide heating in an energy system where both the recharge possibilities and construction area are limited, e.g. buildings with a heating dominated thermal load in urban areas. The study considers to what extent boreholes deeper than the conventional 200 – 300 m can be used to provide either a complementary or a standalone thermal source in such energy systems.

As discussed in Rybach and Hopkirk (1995), for a deep BHE there is the choice to produce either a higher thermal load at a lower temperature, or a lower thermal load at a higher temperature. With the depths (600- 1000 m) and undisturbed temperature gradient (0.02 K / m) analyzed in this paper it is most profitable to pursue the first option. Therefore, the aim is to provide thermal energy in the temperature range of conventional BHE installations. The temperatures the deep BHEs can provide are determined given a predefined average specific heat load, and operation time.

The BHE is modeled as a coaxial, pipe-in-pipe BHE where the central pipe is made of polypropylene. The annular space is separated from the borehole wall by a thin polyethylene membrane. This type of coaxial BHE has been presented in Acuña (2013). An illustration of the coaxial BHE is shown in Figure 1, where the fluid inlet is in the annular space.
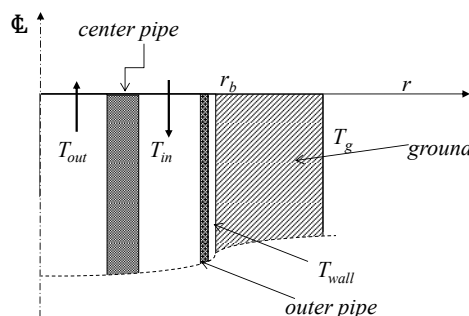

Figure 1: Coaxial BHE.

Holmberg et al.

It is assumed that water is to be used as the heat carrier, which limits the possible minimum temperature. During heat extraction, the water temperature will be lowest at the inlet of the BHE and this temperature limits the amount of energy that can be transferred in the BHE. By increasing the mass flow rate, it is possible to transfer more heat. Increasing the mass flow rate reduces the requirements for thermal insulation between the fluid in the annular space and the center pipe. Therefore, the center pipe can be made thinner and thus less expensive. This also allows for higher mass flow rates without causing excessively high-pressure drops.

The results presented in this paper are based on a numerical model that has been described and verified in an earlier paper (Holmberg et al. 2014). The model is used to determine the thermal performance of coaxial BHEs for three different depths and average specific heat loads. It is assumed that the BHEs will provide energy as a complementary source in a GSHP system. The layout for a GSHP system with a complementary deep BHE is shown in Figure 2. The deep BHE is working in parallel with conventional BHEs. The inlet temperature of the heat carrier to the conventional BHEs is coupled through the heat exchanger with the inlet temperature of the deep BHE. Due to the higher ground temperature level of the deep BHEs, they can sustain a higher specific heat load than shallow BHEs without needing thermal recharge.
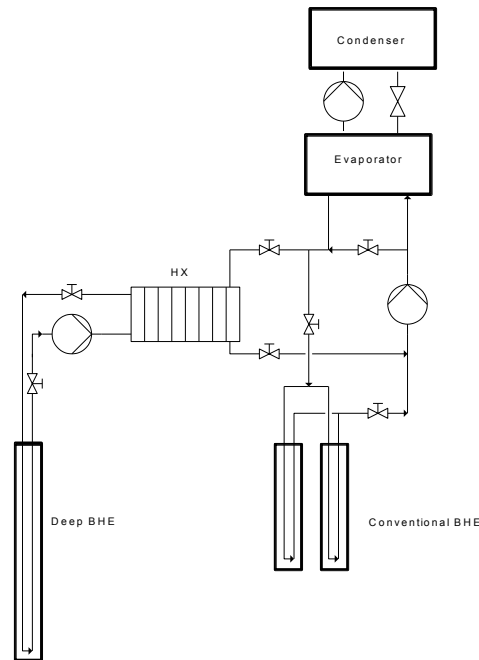

Figure 2: Layout for GSHP system with deep BHE.

2. MODELING

The coaxial BHE is simulated with a numerical model which uses an axisymmetric grid. The model uses a geometrical simplification where the analogy to electric networks is used to describe the thermal resistances within the borehole. A numerical grid is used to resolve the temperature profile in the bedrock surrounding the borehole in two dimensions, while the borehole, the collector and the heat carrier are simulated as one-dimensional features. The model is implemented in the Matlab® environment and it is compared with experimental data in the next section. Further details on the model and a more extensive comparison with experimental data can be found in (Holmberg et al. 2014).

It is assumed that the ground is homogenous and that the thermal properties of the ground are isotropic. The borehole diameter, the dimensions of the outer pipe, and the thermal properties of the center pipe and the outer pipe are assumed constant. The physical dimensions of the center pipe and the mass flow rate being used are determined from a parametric study and depend on the borehole depth. The values of the parameters held constant in the present study are shown in Table 1.

Table 1. Parameters that assumed constant.

Parameter	Value
Borehole diameter [mm]	140
Outer pipe [mm]	139 x 0.4
Ground thermal conductivity, k_g [W /m K]	3
Ground density, ρ_g [kg /m^3]	2600
Ground specific heat capacity, C_g [J/kg K]	840
Outer pipe, thermal conductivity, k_c [W /m K]	0.42
Center pipe, thermal conductivity k_{cp} [W /m K]	0.24
Heat carrier fluid	Water
Thermal gradient [K / m]	0.02

3. RESULT

3.1 Validation of numerical model

The results from the numerical model are validated with experimental data from Acuña (2013). The temperature measurements are from a distributed thermal response test (DTRT) with a coaxial pipe-in-pipe BHE operating with water in a 190 m deep borehole. Figure 3 show vertical temperature profiles that are measured in the early and late period of the DTRT. As seen the simulated values agree well with the experimental data.
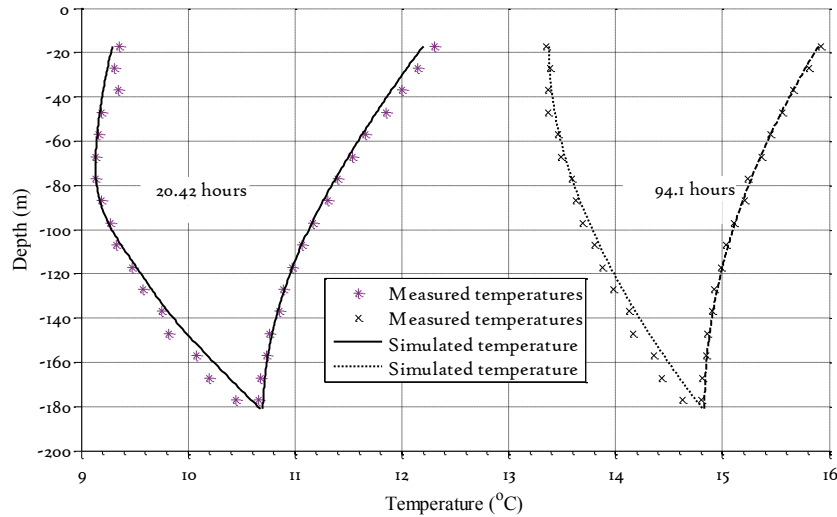

Figure 3: Vertical temperature profiles. Measured and simulated values are shown.

It should be noted that in the experimental setup, the BHE operates with the fluid inlet in the central pipe. For that specific setup, the flow direction does not affect the inlet and outlet temperatures. In the following sections the inlet is through the annular space since it is advantageous for heat extraction from deep BHEs.

3.2 Thermal performance for the deep BHE

The thermal performance of deep BHEs is studied using the numerical model. Three depths are simulated, namely 600, 800 and 1000 m. The parameters used are shown in Table 1 and Table 2. The dimensions of the center pipe was determined in a parametric study presented in Holmberg et al. (2014), where the influence of center pipe dimensions and the mass flow rate were studied for different borehole depths and heat loads. The simulations are performed assuming a continuous operation with an on/off interval of 24 hours and a seasonal recovery period of 4 months representing the warm season. The fluid temperatures for two cycles of the operation scheme are shown in Figure 4 for a 800 m BHE with an average specific heat load of 50 W /m.
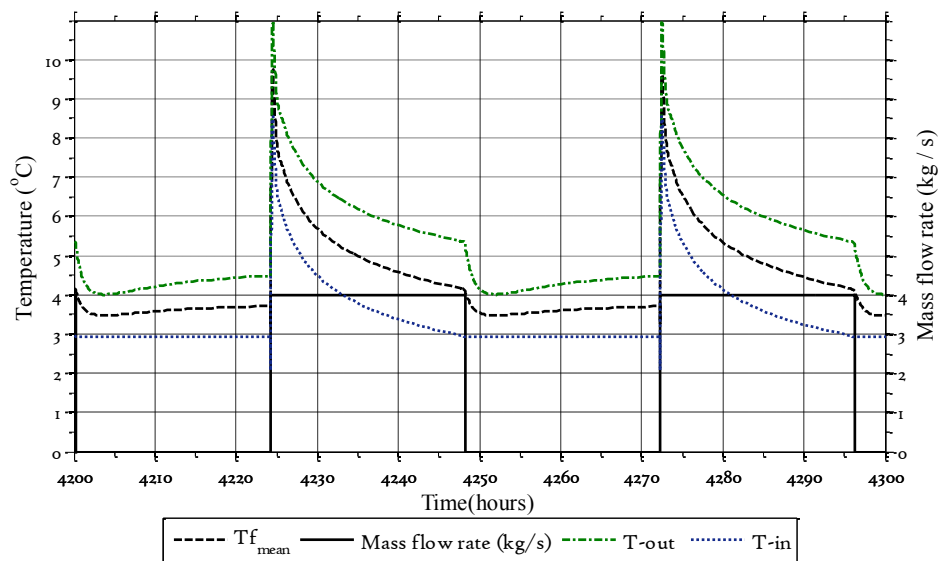

Figure 4: Inlet, outlet and mean fluid temperatures together with mass flow rate.

As shown in Figure 4 the fluid temperatures experiences a peak each time the mass flow is switched on followed by a monotonic decrease until the mass flow is switched off. The profiles shown are taken after nearly half a year of operation (4200 – 4300 h), the mass flow rate is 4 kg / s and the mean fluid temperature varies between 9.5 ºC and 4.2 ºC.

Table 2. Case specific parameters

Parameter	Value	Value	Value
Active length BHE [m]	600	800	1000
Collector (center pipe) [mm]	75 x 4.3	90 x 5.1	90 x 3.5
Mass flow rate [kg / s]	3.5	4.0	5
Thermal load [W /m]	40	50	60
Pressure drop[1] [bar]	1.0	1.0	1.7
Pump power required[2] [kW]	0.47	0.53	1. 33

[1]It is assumed that the annular space is confined within a smooth-walled outer pipe. [2]Assuming η_{pump}=0.75.

The mean fluid temperatures (Tf_{mean}) are shown in Figure 5 for the cases described in Table 2. As seen, the minimum temperature decreases by approximately 1.5 K during 20 years operation. The values in Figure 5 are calculated by averaging each load cycle, i.e. the mean value of Tf_{mean} shown in Figure 4 is determined for each period when the mass flow is on.

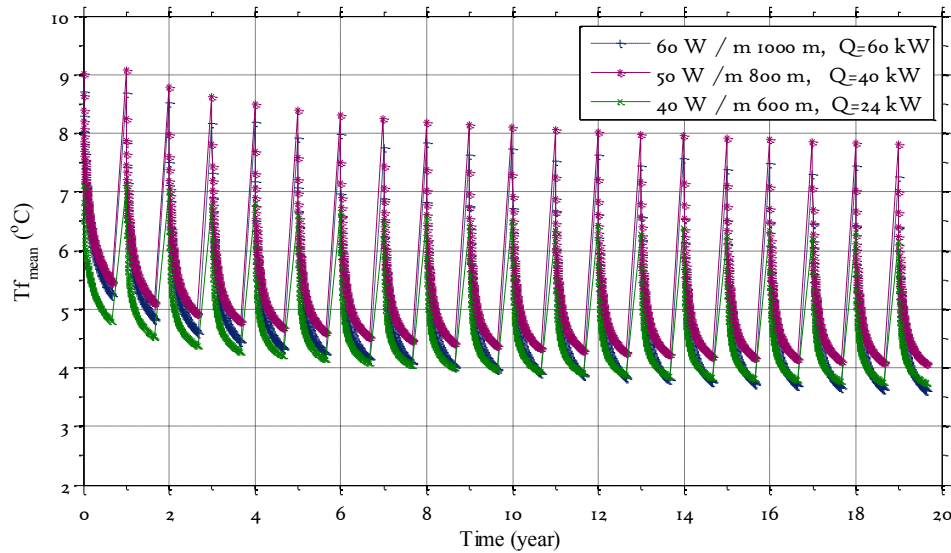**Figure 5: Mean fluid temperature (Tf_{mean}) for 1000 m, 800 m and 600 m deep BHEs, with an average specific heat load of 60, 50 and 40 W/m, respectively. The BHE operates with an on/ off interval of 24 hours and a seasonal recovery period of 4 months.**

As seen from the figure, the decline in minimum mean temperature is relatively small. In these cases the total accumulated operation time is 4 months / year. Given this operation time, the 1000 m BHE can sustain 60 kW_{th} and can deliver 175 MWh_{th} / year, the 800 m BHE can sustain 40 kW_{th} and can deliver 117 MWh_{th} / year, and the 600 m BHE can sustain 24 kW_{th} and can deliver 70 MWh_{th} / year. The share of high value energy (electricity) required for fluid circulation is highest for the 1000 m BHE and amounts to 2.2% relative to the produced thermal energy. This could, however, be reduced using a somewhat larger borehole diameter.

The specific heat flux is proportional to the temperature difference between the BHE wall and the undisturbed temperature profile and increases with depth. Therefore, most energy is being extracted in the lower part of the borehole. In Figure 6, the change in the temperature of the borehole wall during the first 5 years of operation is shown along with its initial (undisturbed) profile for a 800 m BHE. It is seen that the temperature change is largest in the lower part of the borehole, indicating that most energy has been extracted in the deeper region.

The figure shows both the temperatures during heat extraction, (which takes place during the first 2/ 3 of the year) and recovery (last 1/ 3 of the year). As seen, the temperature of the upper part of the borehole wall is initially warmer than the undisturbed temperature, indicating that heat is being transported from the borehole. As more energy is being extracted, the temperature drops and in the extraction profile at 5000 h the temperature of the borehole wall is lower than the undisturbed temperature profile also in the upper part. The profiles for 6000 h and 8000 h show how the temperature recovers and approaches that of the initial undisturbed profile. The last profile shows the temperature profile at the end of the thermal extraction period during the fifth year.

The specific thermal load is calculated based on the conductive temperature profile and is shown in Figure 7 for the same cases as in Figure 6. The first temperature profile (100 h) show a negative specific thermal load in the upper 100 meters of the borehole while the energy extraction is higher in the lower part as compared to the later profiles. For 5000 hours, the thermal load is positive in the entire borehole.

As the operation time increases, the distribution of the specific thermal load becomes slightly more evenly distributed. Most of the energy is, however, extracted from the lower part of the borehole. The distribution of the thermal load at the end of the thermal extraction period during the fifth year is shown in Figure 8.
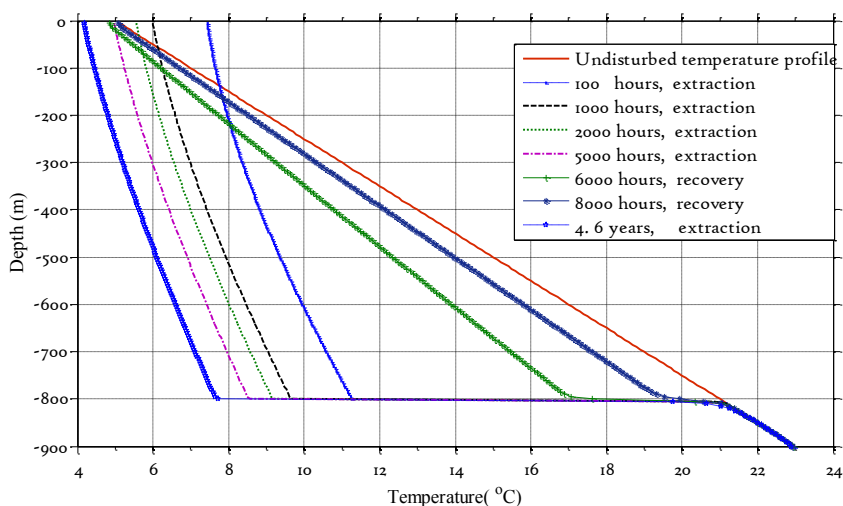
Figure 6: Vertical profiles showing the borehole wall temperature during the first 5 years of operation.
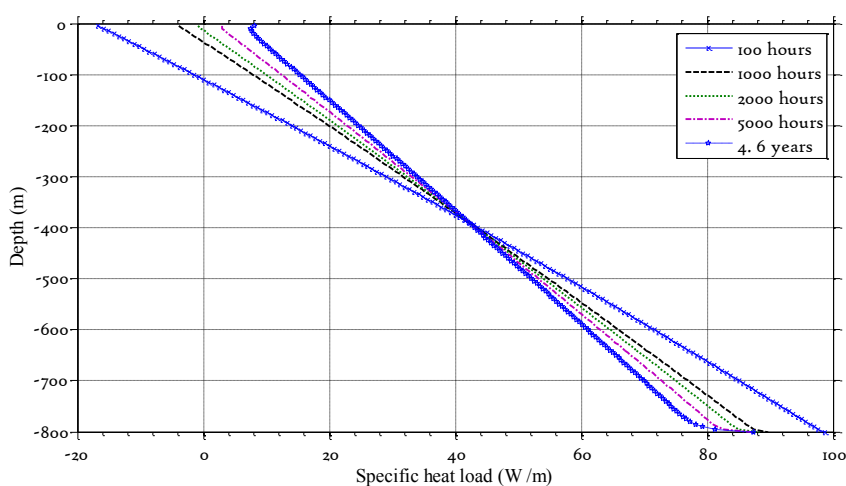

Figure 7: Vertical distribution of thermal load in 800 m deep coaxial BHE, total thermal load is 40 KW.
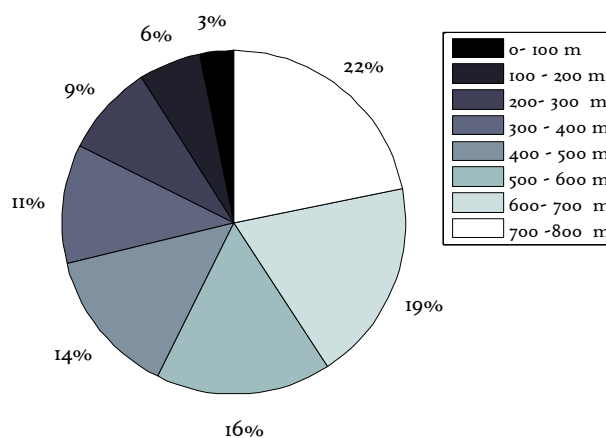

Figure 8: The distribution of the thermal load in the borehole after 4. 6 years of operation.

It is noticeable that 71 % of the thermal energy is extracted from the lower half of the borehole, while less than 10 % is being extracted from the upper 200 meters. Although there is a slight change in the distribution as the borehole is further cooled down, the distribution in Figure 8 is characteristic for the this type of deep BHEs.

The distribution of the specific heat is important when considering thermal influence from neighboring boreholes. With a higher heat flux, a larger thermal volume is required. Deep BHEs can, therefore, be placed relatively close on the surface and then deviate a few degrees from vertical to create sufficient distance between the lower parts of the boreholes. The required distance between the wells can be determined based the distribution of the specific heat flux. Figure 9 shows the thermal influence based on an infinite series of boreholes placed on a line. The figure is based on a simulation using Comsol Mulitphysics (2014); the parameters in Table 1 are used in the simulation together with values representing the vertical distribution of the specific heat load in Figure 7.
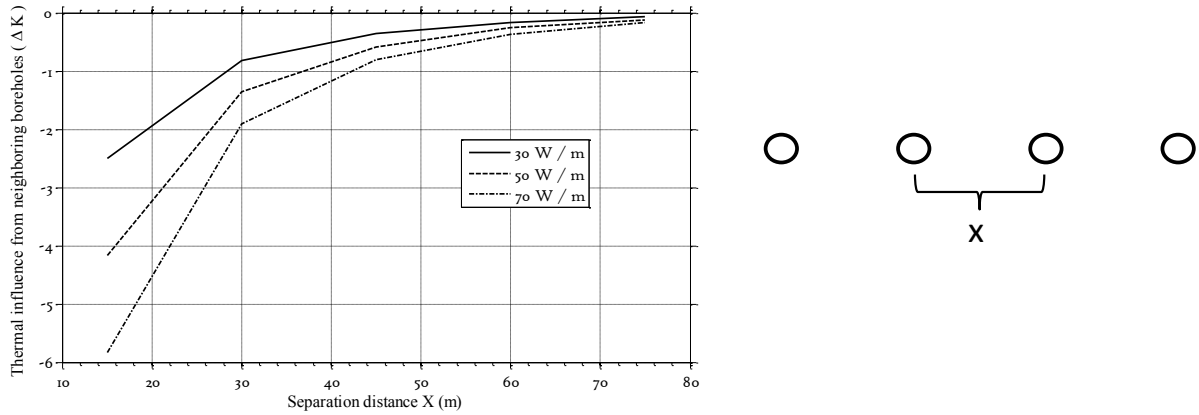

Figure 9: Thermal influence after 20 years of operation. X is the separation distance for a series of boreholes placed on a line as seen on the right side.

The additional temperature decrease due to the thermal influence from neighboring borehole is expressed by Δ K in the figure. The values are taken after 20 years of operation. It is seen in Figure 9 that the influence of the specific heat load is largest for short separation distances, and that a larger separation distance is required for higher specific heat loads. E.g. assuming two BHEs with a separation distance of 20 meters and a deviation from vertical of a few degrees creates a sufficient distance between the boreholes to avoid thermal influence in the lower part of the boreholes.

3.3 GSHP system with complementary deep BHEs

A GSHP installation is to be built. The specified thermal effect is 180 kW$_{th}$, the yearly heating load is 600 MWh and the cooling load is 200 MWh. With an average heat pump coefficient of performance (COP) of 3, the heating load (energy that is extracted from the BHEs) is twice the cooling load (amount of energy rejected to the BHEs). The site is large enough to fit twenty, 200 m deep boreholes with 6 m spacing (Figure 10, left). It is, however, expected that the temperature level will decrease in the BHEs due to the unbalanced thermal load. Simulations using the design software EED (2010) do indeed show a temperature decline on the order of 6-7 K during 20 years with a minimum Tf$_{mean}$ of -4.8 ºC.
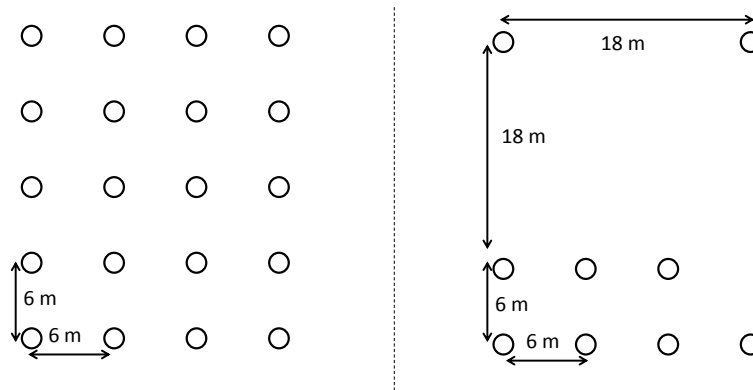

Figure 10: borehole pattern for 20 BHEs (left) and for pattern with complementary deep BHEs (right).

As an alternative, it is proposed to drill fewer boreholes and to complement these with some deep coaxial BHEs. As mentioned above a 800 m deep BHE could produce 40 kW$_{th}$ and deliver 117 MWh / year of water in the temperature range needed by the heat pump. Therefore, the unbalanced heating load can be covered by two 800 m deep BHEs, which can deliver 2/3 of the required thermal effect. These would have to be drilled with a deviation of a few degrees away from each other to ensure that thermal interaction is limited in the lower part of the boreholes. Additionally, seven, 200 m BHEs can cover the rest of the thermal effect requirement (Figure 10, right), these are now thermally balanced and the minimum Tf$_{mean}$ is -1.75 ºC after 20 years. For the two 800 m deep BHEs the minimum Tf$_{mean}$ is 4 ºC as shown in Figure 5. The total drilling length for this alternative solution is 3000 m, as compared to 4000 m for the twenty 200 m boreholes. The required power for fluid circulation in the deep BHEs is approximately 1.7 % of the power required for the heat pump.

4. CONCLUSIONS

It is seen that deep BHEs can sustain a higher average specific heat load than conventional BHEs; this is due to the higher temperature level in the borehole. The analysis performed favors high mass flow rates since it makes it possible both to keep the thermal extraction rate high and the installation cost low as the need for thermal insulation is reduced. The distribution of the thermal load is proportional to the thermal gradient, which in the simulated cases is linear. Most energy is extracted in the lower part of the borehole, making deep BHEs insensitive to thermal influence from neighboring BHEs (shallow or deep) in the upper part. Deviated deep BHEs can be closely spaced and provide a significant amount of thermal energy. Since the thermal influence in the upper part is small, deep BHEs can also be placed in the vicinity of conventional borehole fields. The required energy for circulation of the heat carrier fluid in the cases shown is on the order of 1-2 % of the produced thermal energy and can be reduced using a larger borehole diameter. Deep BHEs are, therefore, a viable option for GSHP installations in areas with scarcity of space and negatively balanced loads.

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