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Sustainability of Production from Borehole Heat Exchanger Fields

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ABSTRACT

Sustainability and renewability aspects of a borehole heat exchanger (BHE) group are treated by numerical model simulations. The software FRACTure (Kohl and Hopkirk, 1995) is used as the modeling tool which implies transient, coupled heat and mass transfer, rock mechanics and rock/water interaction in 3D. The tool is equipped with a semiautomatic mesh generator. The long-term thermal behavior (heat extraction / recovery) of an array of six 100 m deep BHEs has been simulated over 100 years. The distance between the BHEs is 7.5 m. The model simulations are based on load profiles with monthly differing heating demands, with a total of 1800 h/a heat pump runtime.

The results (ground temperatures and BHE delivery temperatures) have been compared to a single BHE of the same length. Single and multiple BHEs show the same cooling and recovery characteristics: the cooling is strong at the beginning and slows asymptotically down later. The recovery is also strong in the beginning and with time it levels off. The BHE array spacing is a critical parameter; the minimum distance shall not fall short of 8 m to provide sustainable production. In a BHE array the recovery time is longer than for a single BHE. The lower temperatures of the produced fluid can be compensated for by additional drilling meters. Numerical values are given for the latter. Sustainable production from a BHE field can be achieved by proper design.

1. INTRODUCTION

In Central and Northern Europe, borehole heat exchangers (BHE) are the most common heat sources for geothermal heat pumps (GHP; Sanner et al., 2003). After a starting phase a dozen years ago, with installations comprising predominantly single BHEs (for single family dwellings), the market nowadays is characterized by an increasing demand for BHE fields to supply a variety of larger buildings like multi-family houses, schools, factories, administration complexes etc. The number of BHEs in such arrays depends on the object size and varies from a few to some hundreds BHEs (Lund et al., 2003). For a relatively new technology, the market must be based on customer confidence. This requires reliable long-term operational experience with BHE-coupled GHPs. The long-term stability of the BHE heat source for GHP guarantees sustainable production.

In their 2002 Stanford Workshop paper Rybach and Eugster (2002) addressed the sustainability and renewability aspects of GHPs. In particular, the long-term performance of a single BHE system was analyzed by numerical modeling. The main result was that sustainable production can be achieved and that the ground around the BHE cools and recovers in an asymptotic manner. The cooling is highest at the beginning and slows down later asymptotically. Recovery is also strong in the beginning and with time it levels off (Figure 1).

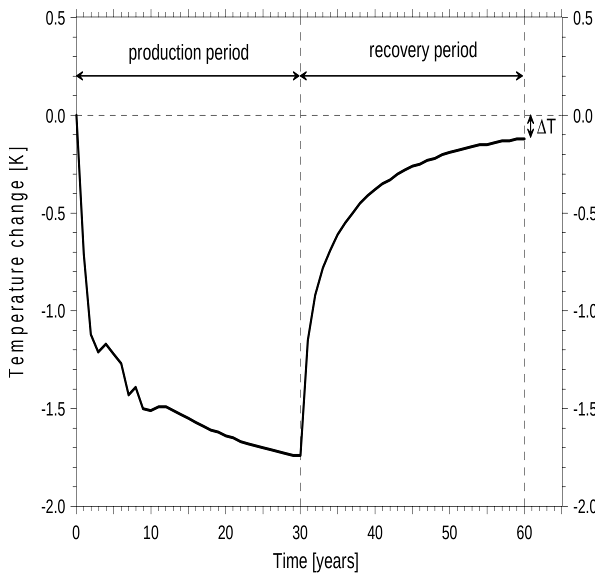

Figure 1: Ground temperature change at 50 m depth and at 1 m distance from a 100 m deep BHE; measured during the first 10 years of operation and calculated afterwards. After 30 years the recovery is almost total (ΔT = -0.1 °C)

Furthermore, it was declared in Rybach and Eugster (2002) that similar studies on a group of BHEs have been initiated. Now we report the results of model simulations on a BHE array. Due to various constraints (e.g. property size) the BHE spacing is often limited. Multiple BHEs provide less heat per BHE than a single BHE, due to mutual influences. First an individual BHE of the array will be treated and subsequently so will be the whole array (6 BHEs, each 100 m long). Special attention will be given to the BHE spacing. In particular, the operation of the single BHE will be simulated for 30 years, followed by a recovery period of 70 years; emphasis will be on the change in subsurface temperature. The same will be calculated for the array with a constant spacing of 7.5 m. Finally, it will be shown by what boring lengths the array should be lengthened in order to achieve the same production temperatures as a single BHE.

2. MODEL SETUP

For the numerical model simulations, the Finite Element (FE) software FRACTure (Kohl and Hopkirk, 1995) is used which allows treating coupled heat and mass transfer, rock mechanics and rock/water interaction in 3D. The tool is equipped with a semiautomatic mesh generator. In this section, we will introduce the FE mesh and the model conditions which will be used to investigate the sustainability of BHE fields.

2.1 FE Mesh of BHE Arrays

A FE mesh has been set up for six, 100 m deep, BHEs. Figure 2 shows the model geometry for the case of 7.5 m borehole spacing. Each BHE is equipped by four 40 mm polyethylene pipes (“double U-pipe type”) grouted at the periphery of the borehole (Figure 2, bottom). Water with 20 % ethylenglycol is taken as circulation fluid. The design of the FE mesh applies varying numbers of horizontal layers according to the depth extent of the BHE system. The nodal spacing is fine in the center around the borehole where the largest temperature gradients are expected (Figure 2, top). In the vertical direction the FE mesh is discretized generally in 20 m steps with refinements near the surface at the top (1 m) and at the bottom of the borehole (< 0.1 m) to reduce numerical instabilities. Boundary conditions are set at the surface (here: ground surface temperature with seasonal variation) and at the basis of the model (here: constant heat flow) resulting in a temperature gradient along the BHE. Laterally, Neumann type boundaries are assumed. To avoid boundary effects, the bottom and side boundaries must be at some distance from the BHE field. A total model volume of 2000 x 2000 x 1000 m has therefore been chosen, which is absolutely sufficient (Kurmann, 2003). Analogous FE meshes have been designed additionally for BHE spacings of 3 m, 5 m and 15 m. Table 1 lists BHE geometry data, material parameters, and boundary conditions.

By defining individual load time functions in FRACTure, we can control the transient behavior of selected parameters or boundary conditions, as variation in flow rate or in ground surface temperature. Therefore, an individual BHE can be run as well as the whole BHE field using the same FE mesh. A more detailed description of the BHE modeling using FRACTure is given in Kohl et al. (2002).

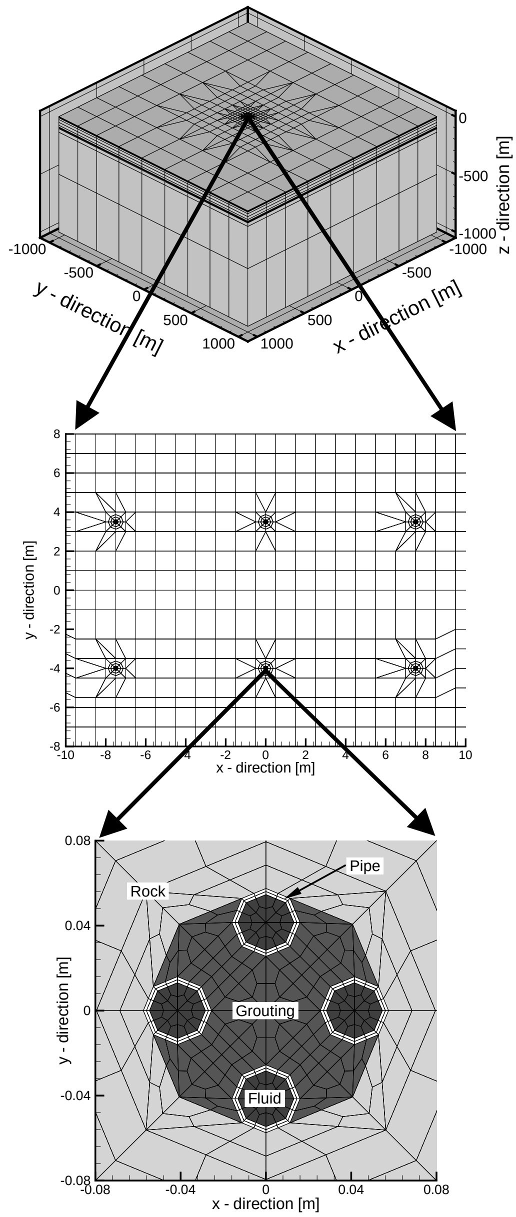

Figure 2: Model geometry: complete model volume 2 x 2 x 1 km (top), plane view of BHE field model (middle), borehole interior (bottom). The spacing in the BHE field is 7.5 m.

2.2 Site Condition

The model BHE field is assumed to be placed at the site of the Swiss Meteorological Service, Zurich/Switzerland. The site represents average conditions for the Alpine Foreland, the most densely populated area in Switzerland. The elevation is 556 m.a.s.l. and the mean annual temperature is 11.1 °C with annual variations between + 9.0 K and –9.5 K. The geologic profile in the top 100 m comprises Quarternary moraine (0 – 14 m) covering an alternating sequence of Tertiary „Molasse“ marls (73 %), marly sandstones (14 %) and clean sandstones (13 %). The average thermal conductivity is 2.44 W m-1 K-1. All model conditions are listed in Table 1.

Table 1: Heat exchanger geometry, material parameters, and boundary conditions in the BHE field

Borehole heat exchanger geometry	Double U-tube vertical length = 100 m Pipe diameters = 26.2 (inner), 32 mm (outer) Borehole diameter = 115 mm		
Material parameters	Material	Thermal conductivity [$Wm^{-1}K^{-1}$]	Heat capacity [$Jm^{-3}K^{-1}$]
	Rock (average at site)	2.44	$2.51 \cdot 10^6$
	Polyethylene pipe	0.42	$1.62 \cdot 10^6$
	Backfill (standard bentonite/ cement grouting)	0.80	$2.00 \cdot 10^6$
	BHE fluid (water with 20 % ethylenglycol)	0.51	$4.05 \cdot 10^6$
Boundary conditions	Flow velocity inside one tube circuit=	$0.38\ ms^{-1}$ (constant)	
	Temperature difference between outlet and inlet fluid=	3 K	
	Basal heat flow =	$90\ mWm^{-2}$ (constant)	
	Ground surface temperature: average=	11.1 °C, +9 K; –9.5 K	

2.3 Load Profiles

For the given geological setting, the thermal power of the single BHE is assumed corresponding to the Guideline VDI 4640 to be 5 kW (= 50 W per meter of BHE specific capacity). Considering a temperature difference between the outlet and inlet fluid temperature of ΔT= 3 K, (general customary design figure), the flow velocity inside one tube circuit is 0.38 ms^{-1} (=turbulent flow). All model runs are loaded with this power. We assume only heat supply (=”heating mode”). However, BHE fields are often used for cooling purposes, whereby the subsurface is reloaded during summer period and the temperature drop is clearly lower.

For the model simulations, a total runtime of 1'800 hours per year was applied, subdivided into various runtimes per months. This corresponds to the average annual operation time in the Swiss Alpine Foreland. The proportions have been set according to the climatic data of the site. Table 2 lists the runtime distribution over the annual cycles.

Table 2: Runtime subdivision over the annual cycle (Average over 20 years).

Month	Runtime per month (h)	Percentage[%]
September	48.6	2.7
October	120.6	6.7
November	239.4	13.3
December	288.0	16.0
January	311.4	17.3
February	264.6	14.7
March	216.0	12.0
April	144.0	8.0
May	72.0	4.0
June	48.6	2.7
July	23.4	1.3
August	23.4	1.3
Total	1800.0	100.0

The simulated production temperature and the cooling of the subsurface resulting from the BHE operation depends on the load profile applied. To illustrate this influence two differently loaded models are investigated.

- Case 1: constant operation at the beginning of the month, followed by a recovery phase during the rest of the month.

- Case 2: daily operation cycles.

The two test cases require different CPU-time: from 6 hours up to 3 days for the simulation of one year of operation on a 2 GHz PC. In Figure 3, for August after the first year of operation, the ground temperature evolution at 50 m depth in a distance of 0.1 m from the BHE is compared for the two test cases. The cooling of the subsurface is much stronger for Case 1 than for Case 2 with the load distributed over the month. The continuous load Case 1 with subsequent recovery overestimates the ground temperature at the end of August by about 0.2 K relative to the more realistic load of case 2, see Figure 3.

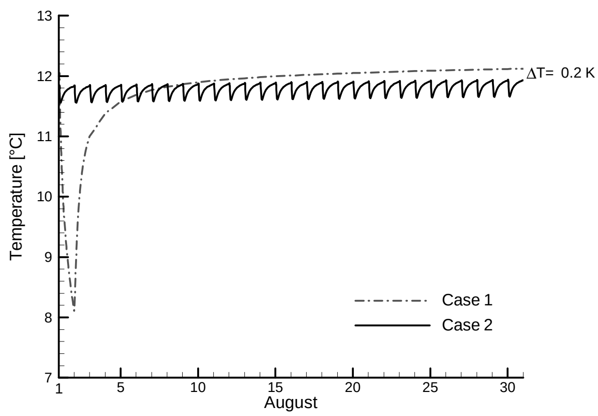

Figure 3: Ground temperature at 50 m depth and in 0.1 m distance from the BHE during August of the first year of operation for the two different load profiles. ΔT is the difference between the two different load regimes on 31st August.

In February the differences between the continuous and individual load profiles (not shown here) are rather large. In spite of the slightly overestimated ground temperatures, Case 1 is used for the simulations due to the shorter calculation time. For the following comparison of subsurface cooling, the reference point has therefore been taken on 31st of August. This also corresponds to the procedure of Rybach and Eugster (2002). The temperature field before the new heating period is relevant for the next heating period. It is a function of the energy that has been extracted from the subsurface and the recovery period during the summer season, and therefore, defines the amount of energy that is available for the coming heating season.

Figure 4 compares the simulated outlet fluid temperature in August for both test cases. The minimum fluid temperature in Case 1 is strongly lower than for the daily loaded profile in Case 2 and is therefore much too conservative. More detailed investigations show that the relative temperature change from one year to the following is nearly identical in both cases. Therefore for the evaluation of fluid production temperature the load Case 1 can also be applied when the temperatures are compared relatively to each other. In the following the minimum temperature is always compared.

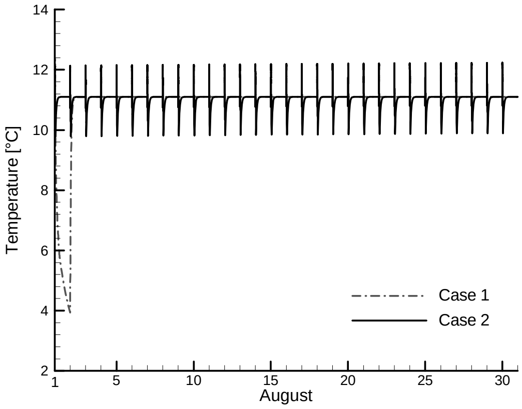

Figure 4: Production fluid temperatures in August. The outlet temperature in Case 1 (=constant operation) is much too conservative. The minimum temperature in Case 1 is always lower than the minimum temperature in Case 2.

3. BHE SPACING AND SUSTAINABILITY

3.1 Effect of Spacing

A practitioner's rule of thumb says that spacing should not be less than 8 m. Kälin and Hopkirk (1991) investigated the mutual influence for two neighboring BHEs. They report that with a spacing of 15 m there is no noticeable influence. On the other hand, with a spacing <5 m the influence is so strong that the system operation can break down (permafrost at the BHE!). The situation is better for a BHE field in flowing groundwater. These results correspond well to the findings of Pahud et al. (2002). Moreover, they showed that lower ground thermal conductivity introduces a larger long-term influence, resulting in higher mutual influences than for high thermal conductivities.

To get a more precise hold on the mutual effect of neighboring BHEs, the modeling has been performed by varying the spacing in the 6-BHE array between 3 and 15 m. Figure 5 compares the relative difference in minimum outlet temperature between the single BHE and the borehole fields over the first three years of operation. Analogous to Kälin and Hopkirk (1991), no significant effect results for BHE spacing of 15 m, but strong influences are visible for spacing shorter than 5 m (up to ~5 K difference). For the 7.5 m-spaced array, the mutual influence is still clearly noticeable. This indicates that a BHE in an array must be drilled deeper to achieve the same efficiency as a single BHE. It must be emphasized that production temperatures below –5 °C can cause mechanical damage of the BHE backfill and thus destroy the thermal contact between the heat exchanger pipes and the surrounding ground.

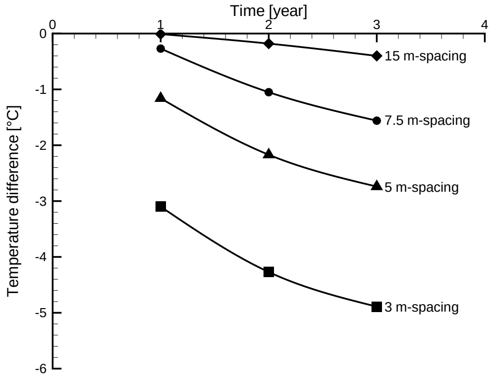

Figure 5: Temperature difference of the outlet fluid temperature of BHE fields relative to the single BHE.

3.2 Comparison Single BHE / BHE Field

In this section, the sustainability of the single BHE and the 7.5 m-spaced BHE field is investigated. Both BHE arrangements are simulated for an operation of 30 years, followed by 70 years of recovery. Thereby, the central BHE of the field with the highest mutual influence is compared to a single BHE. Figure 6 shows the ground temperatures for both model runs. The temperature changes exhibit the same asymptotic behavior as described in Rybach and Eugster (2002): The cooling is strong at the beginning and levels off at later times. The subsurface temperature field stabilizes at a lower temperature level and no thermal collapse occurs. The same behavior results for the recovery period. Due to the mutual influence of BHEs in a field the ground cooling is significantly more pronounced than around a single BHE with no neighbors. The recovery of the BHE field takes 70 years, whereas for the single BHE, the deviation to the initial temperature field is <0.1 K after 24 years.

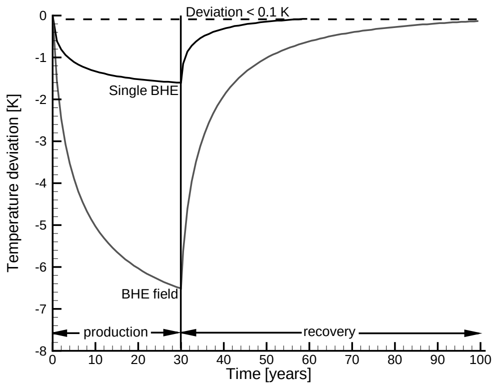

Figure 6: Ground temperature changes in 50 m depth at 0.1 m distance from the BHE(s), over a 30 year production and a 70 year recovery period. The temperatures are plotted at the end of August, for the single BHE and for the BHE field with 7.5 m spacing relative to the initial temperature of 12.7 °C. The curve for the BHE field represents the temperature evolution of the central BHE with the highest mutual influence.

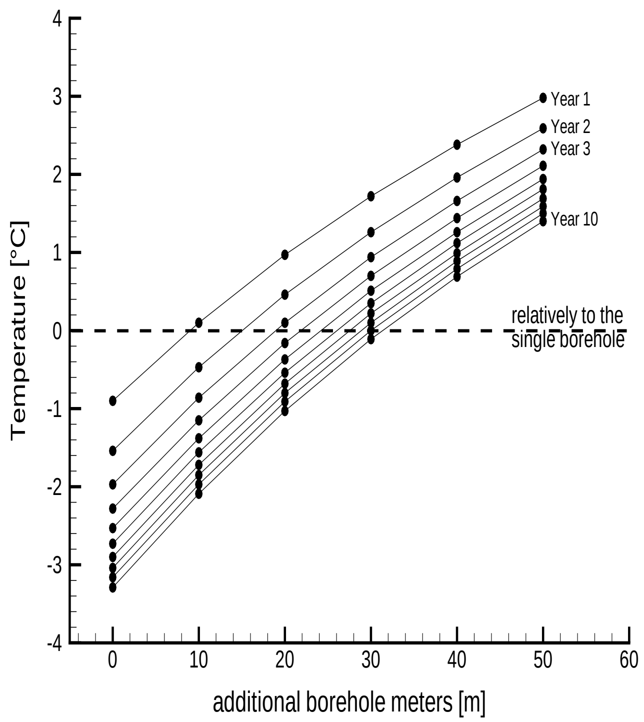

Figure 7: Difference between single BHE and BHE field fluid production temperatures during the first 10 years of operation, in function of additional drilling meters. To achieve the same fluid temperature as the single BHE, additional drilling meters of > 30 % are needed for a field with 6 BHEs of 100 m length and 7.5 m spacing.

3.3 Comparison Single BHE / BHE Field

The thermal production power of the array with 6 BHEs is taken to be six times that of a single BHE, i.e. in our case 6 x 5 kW. But the mutual influence of the neighboring BHEs leads to lower ground temperatures and correspondingly lower fluid outlet temperatures.

The lower temperatures can be compensated for the 7.5 m spacing by longer BHEs. Figure 7 shows the deviation of the minimum fluid temperature in the center BHE for various additional BHE lengths up to 50 m, relative to the single BHE, during the first 10 years of operation. Drilling the BHE field deeper by ~30 % yields the same fluid temperature than the single BHE after 10 years of operation. It can be recognized from Figure 7 that the temperature decrease slows down with time and the difference in fluid outlet temperature between year 9 and 10 is less than 0.1 K. Therefore, no significant changes must be expected during further operation.

4. CONCLUSION

It could be verified that the long-term thermal performance of BHE fields shows the same general behavior as a single BHE. Heat extraction from BHEs increasingly cools the surrounding ground during operation, and the subsurface ground temperature recovers during stoppage due to strong temperature gradients created by the BHE heat sink. Cooling and recovery follow an asymptotic manner. The cooling is highest at the beginning and slows asymptotically down later; recovery is also strong in the beginning and with time it levels off. The recovery duration for a single BHE is roughly equals that of operation: After 30 years of operation, the thermal recovery of the ground needs ~30 years (see also Rybach and Eugster, 2002). For BHE fields, the recovery time is longer, approaching ~70 years. The model simulations for single and multiple BHE systems prove that sustainable heat extraction can be achieved and that subsurface temperature recovers from the BHE operation. In fact, the BHEs show stable and reliable performance which can be considered renewable.

The spacing in a BHE field is a critical factor: the mutual influence of neighboring BHEs leads to lower ground temperatures and fluid production temperatures than for a single BHE under the same load. The minimum spacing should not fall short of ~7 m even in ground with high thermal conductivity (>3 W m 1K 1) in order to provide sustainable production. Additional drilling meters provide feasible help: drilling the BHE 7.5 m-spaced field deeper by ~30 %. It yields the same fluid temperature as for the single BHE. This report illustrates that sustainable production from a BHE field can be achieved by proper design.

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