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How renewable are borehole heat exchanger systems?

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ABSTRACT

Extensive measurement campaigns have been performed at a commercially delivered BHE/HP installation in Elgg near Zurich. Object of the campaigns is a single, coaxial, 105 m long BHE, in use since its installation in a single family house. The BHE supplies a peak thermal power of about 70 W per m length. The measurement results were used to calibrate a 2D numerical code. Ground temperatures over the frst five years of measurement were fitted to within one or two tenths of a degree Celsius. Additionally the formation temperature was predicted for several further years using assumed load profiles. The immediate surroundings of the BHE cools down in the first years and does not fully recover during the system lifetime. The long-term performance stabilizes afterwards, albeit at a somewhat lower but constant level. Thus sustainable production can be achieved on the long **term.**

Heat extraction over decades causes heat depletiodtemperature decrease in a certain volume of the ground. After termination of BHE operation thermal recovery beings. Different simulation runs have been performed with different operation durations. The results show that the duration of ground thermal recovery for the analyzed simple case (single BHE) roughly equals the duration of heat extracting operation (e.g. for 30 years of BHE operation: ground recovery in about 30 years).

KEYWORDS

Shallow geothermal resources, long term performance, sustainability, numerical modelling

Introduction

Traditionally, geothermal direct use aims to utilise the heat content of formation fluids, if present. In any case, the heat content of the rock matrix is generally higher. This heat is the target of shallow resources utilisation.

Shallow geothermal resources (< 400 m depth by governmental definition in several countries) are omnipresent. Below 15 – 20 m depth everything is geothermal: the temperature field is governed by terrestrial heat flow and local ground thermal conductivity structure (± groundwater flow). The ubiquitous beat content of shallow resources can **be** made accessible **by** artificial circulation like the Borehole Heat Exchanger (BHE) system. Although working at much lower temperatures the BHE can in principle be considered as the "baby brother" of HDR (Hot Dry Rock). BHE's are ideal to make use of shallow geothermal resources, located right below our feet.

The most popular BHE heating system with one or more boreholes typically 50 - 200 m deep is a closed circuit, heat pump (HI')-coupled system, ideally suited to supply heat to smaller, decentral objects like single family or multi-family dwellings (for details see e.g. RYBACH et al. 1992). The heat exchangers (mostly double U-tube plastic pipes in backfilled boreholes) can be installed in nearly all kinds of geologic media (except in material with low thermal conductivity like dry gravel). The thermal load of the BHE depends mainly of the thermal conductivity of the surrounding ground (e.g. for a medium with 2.0 W/m,K: specific extraction rate 45-50 W/m, energy yield 90 kWh/m,year; RYBACH & EUGSTER 1998). These systems operate by conduction, i.e. there are no formation fluids produced. The **energy** supply for the heat exchanger comes from several sources: the vertical geothermal heat flux itself, the import of heat horizontally by conduction, advective transport with groundwater if present, and the compensating heat exchange between the ground surface and the atmosphere. The climatic conditions in Switzerland, being an alpine country, are such that practically no air conditioning is necessary; the BHE systems are mostly used for space heating/domestic water thus the HP's are operating -unlike the "Geothermal heat pumps" in the USA- in the heating mode only. Seasonal performance factors > 3.0 are common. The heating medium is water in low-temperature delivery systems lie floor heating.

To date, over 20'000 BHE systems are installed in Switzerland , with a total of about 4'000 km BHE length. At present, 1 m of BHE costs (drilling and installation included) ahout 40 US$. Annual energy production (after the HP) was 439 GWh in 1997, annual growth rate is 12 % (BRUNNER et al. 1999). The BHE/HP systems contribute the largest share to Switzerlands geothermal mix in 1997 (table 1).

Table** 1: **The Swiss geothermal mix in** 1997. **Total annual production:** 589 **GWh.

System	Annual production [GWh]	Production fraction [%]
Shallow horizontal coils	49.0	8.3
Borehole heat exchangers (BHE)	**439.0**	**74.5**
Groundwater wells	63.0	10.8
Foundation piles	5.3	0.9
Deep BHEís	0.7	0.1
Deep Aquifers	29.0	4.9
Tunnel waters	2.9	0.5

All this secures Switzerland a leading position in BHE applications worldwide and a prominent rank 4 in geothermal direct use: there is 1 BHE/HP installation every 2 km^2 of land area and 42.8 W installed geothermal capacity per capita (RYBACH 1998).

Nevertheless, even in view of these spectacular acheivements, some open questions remain. The oldest BHE installations are not older than about 15 - 20 years, thus experience and especially detailed studies on long-term performance (decades) are lacking. Therefore the question arises about the reliability of such systems on the long run. Along the same line come the questions: can such systems operate in a sustainable manner? Is the shallow geothermal resource renewable? (i.e. does the ground recover thermally after shut-down of the BHE heat extraction operation which is customarily designed to run over a few decades).

To answer these questions a combined theoretical/experimental approach has been followed to establish a solid, verified base for the confirmation of reliable long-term performance on one hand, and to clarify the terms of renewability on the other.

Concept of study

The verified base to confirm the reliability of BHE/HP systems on the long term has been elaborated by combining field measurements with numerical model simulations.

An extensive measurement campaign has been performed at a commercially delivered BHE installation in Elgg near Zurich. Object of the campaigns is a single, coaxial, 105 m long BHE, in use since its installation (1986) in a single family house. The single BHE stands isolated and supplies a peak thermal power of about 70 W per m length. The BHE is rather heavily loaded. The installation is by no means a particularly favorable example.

The aim of the measurement campaigns is the acquisition of ground temperature data in the surroundings of the BHE as well as of operational parameters of the entire system. For this purpose, 105 m long measuring probes were installed in boreholes at 0.5 and 1.0 m distance from the BHE, backfilled with a bentonite/cement mixture like the BHE itself. Both probes are equipped with temperature sensors at 1, 2, 5, 10, 20, 35, 50, 65, 85, and 105 m depth. The use of pre-aged Pt100 sensors, in combination with a high-resolution multimeter (DATRON 1061A), provides maximum long-term stability (± 0.1 K accuracy, ± 0.001 K precision) over the entire measurement period. In addition to the ground temperatures, the atmospheric temperature variations and all parameters relevant to the operation for the entire system (hydraulic system flowrates, circuit temperatures, power consumption of the HP etc.) have also been recorded in 30 minute intervals.

The first campaign extended over the years 1986-1991 and supplied a unique data base (details in EUGSTER 1991). The ground temperature results are displayed in figure 1. Atmospheric influences are clearly visible in the depth range 0 – 15 m; below 15 m the geothermal heat flux dominates. It is obvious that in the near field around the BHE the ground cools down in the first 2 - 3 years of operation. However, the temperature deficit decreases from year to year until a new stable thermal equilibrium is established between

BHE and ground, at temperatures which are some 1 - 2 K lower than originally. (This temperature deficit is characteristic of the measurement site with typical Tertiary "Molasse" formations).

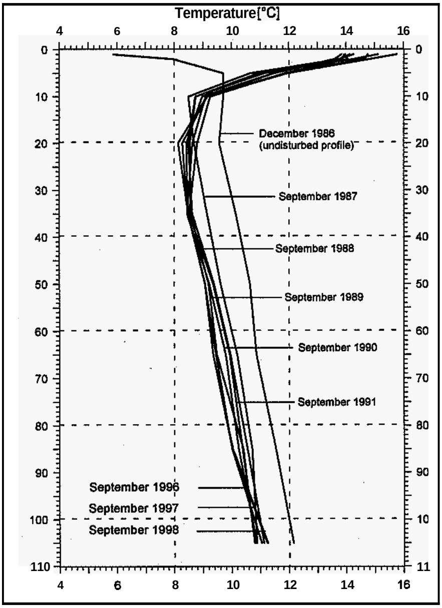

Figure 1: Ground temperature profiles at a distance of 1m from the BHE in Elgg. Curve "December 1986" marks the undisturbed profile at the start of the first heating season. The subsequent curves show the conditions after winter heat extraction and summer recovery, just before the start of the next heating season.

In the autumn of 1996 (i.e. after 10 years of BHE operation) the measurement system was restarted. Due to the forced ageing of the Pt100 sensors the high quality of temperature measurement has been maintained and the repeatability of the measurements is still better than ± 0.01 K. The new temperature profiles ("September 1996", "September 1997", "September 1998", figure 1) do not show any further significant shift towards lower temperatures, thus demonstrating that a quasi-steady equilibrium has been reached after the first few years. The small differences between the profiles of subsequent years after at least three years of operation are a result of the different yearly heating demands which, given unchanged living habits of the owners, are uniquely a product of the outside temperature. In the following years the ground temperatures fluctuate within a limited interval of ahout 0.5 K, depending on the specific annual beating demand. For a correctly designed BHE system in the absence of groundwater and with borehole depths of this order this corresponds to our theoretical expectations.

These measurements represent a unique data base which in turn was used to validate a numerical model. First, the temperature curve "September 1996" was predicted by simulation and in turn compared with the measured curve. The agreement was excellent; the deviations were within measurement error (± 0.1 K), see RYBACH & EUGSTER (1998).

The excellent agreement between measured an calculated time histories at a numher **of** specific points in the underground gives confidence to extrapolate future trends and situations by modelling.

Numerical modelling

The measurement results of the first measurement campaign (1986-1991) were used to calibrate a 2D numerical code (COSOND, in cylindrical coordinates). The code treats diffusive heat transfer in the ground, advection in the BHE, heat transfer between the BHE fluid and the wall materials, as well as heat transfer between atmosphere and ground. The program flow is controlled by a load profile which contains the atmospheric temperatures and the operational data of the heat pump. Details are given in EUGSTER (1991) and GILBY & HOPKIRK (1985). Ground temperatures over the first five years **of** measurement were fitted to within one or two tenths of a degree Celsius. Additionally the formation temperature was predicted for several further years (EUGSTER 1991) using assumed load profiles.

These computer simulations have now been recalculated using an adapted load profile based on the atmospheric temperatures of the years 1991-1997 actually measured in the meantime at a nearby meteorological station (Tänikon/TG) as well as on the homeowner's records about heat pump operation times. Furthermore the model grid was refined to take advantage of the better performance of the present generation of computers: 11'700 grid cells in a model volume of $2 \cdot 10^6$ m^3 instead of 1'300 cells in 165'000 m^3 used for the first modelling approach (details in EUGSTER 1998).

The operation of the Elgg BHE plant has been extrapolated for additional 19 years to a final period of 30 years (1986 - 2015). The load profiles for these extrapolation runs are based on the new Swiss Standard Climatic Database (METEONORM 1997). The simulation runs show on one hand the expected decrease of the yearly temperature deficit and on the other hand an increasing area around the BHE which is affected by the cooling. The cumulated temperature deficits after different years **of** operation are listed in table 2.

After shut-down of heat extraction, regeneration of the ground begins. During the production period of a BHE, the draw-down of the temperature around the BHE is strong during the fust few years of operation. Later, the yearly deficit decreases asymptotically to zero. During the recovery penod after a virtual stop-of-operation , the ground temperature shows a similar hehaviour: during the fust years, the temperature increase is strong and tends with increasing recovery time asymptotically to zero. These effects are shown in figure 2.

Table 2: Calculated cooling of the ground in different distances from the BHE and at a depth of 50 m afer discrete years of operation. In such a depth, the cooling is only caused by the BHE operation. Any atmospheric influences can be excluded.

Distance [m]	Calculated cooling of the ground [K] at a depth of 50 m after discrete years of operation			
	2 years	5 years	11 years	30 years
0.5	1.13	1.23	1.50	1.75
1.0	1.12	1.22	1.49	1.73
5.0	0.82	0.98	1.22	1.56
10.0	0.44	0.65	0.87	1.18
20.0	0.06	0.22	0.40	0.64
40.0	0.00	0.02	0.11	0.25
50.0	0.00	0.00	0.03	0.10

The time to reach a complete recovery depends on how long the BHE has been operational. Principally, the recovery period equals nearly the operation period. This is shown in figure **3** for different distances from the BHE and for different final temperature deficits.

In *summary,* the measurements and model simulations prove that sustainable heat extraction can be achieved with such systems. In fact, the BHE's show stable and reliable performance which can he considered renewable. Reliable long-term performance provides a solid base for problem-free application; correct dimensioning of BHE gives great scope of widespread **use** and optimisation.

Conclusions

Borehole heat exchanger (BHE)/heat pump (HP) systems prove to be a feasible way to tap shallow geothermal resources which, located directly below our feet, represent a unique, ubiquitous and therefore enormous geothermal potential. Such systems operate reliably also on the long term.

This has been proven by experimental and theoretical investigations: data of an extensive measurement campaign over several years were **used** to calibrate a numerical modelling code. The results of modelling with this code for a single BHE show that the long-term performance of the BHE/HP system stabilizes, relatively to initial conditions, at a somewhat lower hut constant level after the first few years. Thus sustainable operation can he achieved.

The ground around the BHE behaves in the following way: the long-term heat extraction causes heat depletion/temperature decrease. The temperature drop (which decreases with radial distance from the BHE) is significant after the fust years **of** operation but then it tends, in the subsequent years, asymptotically towards zero.

After shut-down of BHE operation thermal recovery begins, **strong** in the beginning and decreasing asymptotically afterwards. Model simulations with different operation/recovery periods show that recovery duration roughly equals that of operation: e.g. for **30** years **of** BHE operation the thermal recovery of the ground needs **30** years.

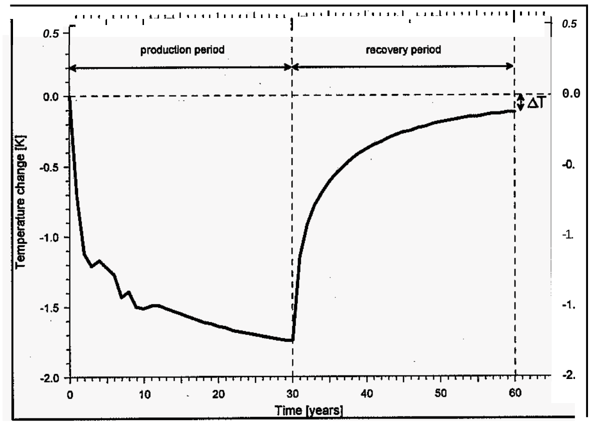

Figure 2: Calculated temperature change in a depth of 50 m and in a distance of 1m from the BHE over a production period and a recovery period of 30 years each.

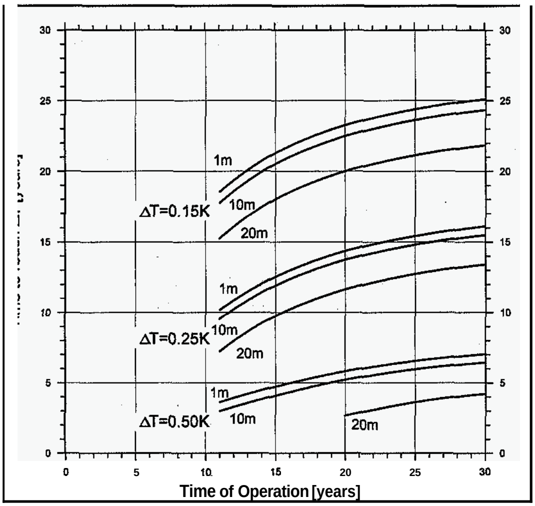

Figure 3: Duration of recovery period to reach a minimalfinal temperature deficit (ΔT) of 0.5, 0.25 and 0.15K for different distances from the BHE as a function of the time of operation.

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