DESIGN AND PERFORMANCE OF BOREHOLE HEAT EXCHANGER / HEAT PUMP SYSTEMS

by Ladislaus RYBACH

ABSTRACT

The ubiquitous shallow geothermal resources can feasibly be utilized by borehole heat exchanger (BHE) / heat pump (HP) systems. BHEs can be installed in nearly all kinds of geologic material. Design and installation must consider numerous influence factors. It is shown how the sizing needs to be done, at the example of Switzerland. Also the economic advantages of such systems are demonstrated. Finally, the basic questions of long-term operation are addressed, for a single BHE, by a combined experimental and theoretical (=numerical modelling) approach. It turns out that BHE/HP systems operate, if properly designed, fully reliable on the long term.

1. INTRODUCTION

Shallow geothermal resources (the heat content of rocks in the top few 100 meters of the earth's crust) represent a major and ubiquitous energy source. There are several technical means to tap this vast resource by extracting heat from the ground: a) horizontal coils, b) groundwater wells, and c) borehole heat exchangers (BHE). The installation of horizontal coils needs relatively large surface area and extensive earthworks (digging up actually the ground down to the level of coil layout), the prerequisite of extracting the heat of groundwater is the presence of a shallow water table.

For these reasons, the most widespread technology of shallow heat extraction is by BHEs. All systems need an electrical heat pump (HP) by which the low BHE output temperature (rarely above 10°C) can be lifted to the required level (35 – 50°C, depending upon the heating system like underfloor panels). The smaller the temperature difference of the lift needed, the higher the HP performance efficiency.

1.1 Installation

BHEs can be installed in nearly all kinds of geologic media (except in material with low thermal conductivity like dry gravel). 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.

BHEs are installed in backfilled boreholes of about 10 cm diameter. Drilling depths depend on design requirements on one hand (see later) and on drillability and drilling costs on the other. In the favorable Tertiary sediments of the Swiss Molasse basin drilling depths of 300 m (1000') are nowadays customary (Rybach et al. 2000).

Heat extraction is established by closed-circuit fluid circulation (a few m^3/hour of pure water or with an antifreeze additive in a single BHE) through the BHE and the evaporator side of the HP (see Fig. 1). The heat exchanger in the BHE consists mostly of a double U pipe made of polyethylene (2 – 4 cm diameter). Before backfilling, the pipe tightness is proved by a pressure test. The backfill material should secure good thermal contact between the heat exchanger and the surrounding ground. The material should have relatively high thermal conductivity, should be easily pumpable and should solidify in due time. Bentonite cement with some quartz sand and a superplasticizer additive (to ensure high thermal conductivity) has especially favorable properties (Allan and Philippacopoulos, 2000). Its low permeability prevents short-circuiting between different groundwater levels, a threat which is of concern of water protection authorities in many countries.

Depth and number of the BHEs depend on the utilization purpose (heating alone, combined heating/cooling, ± domestic hot water), the object size, and not least on the local conditions. The BHE/HP design must take into account all these factors.

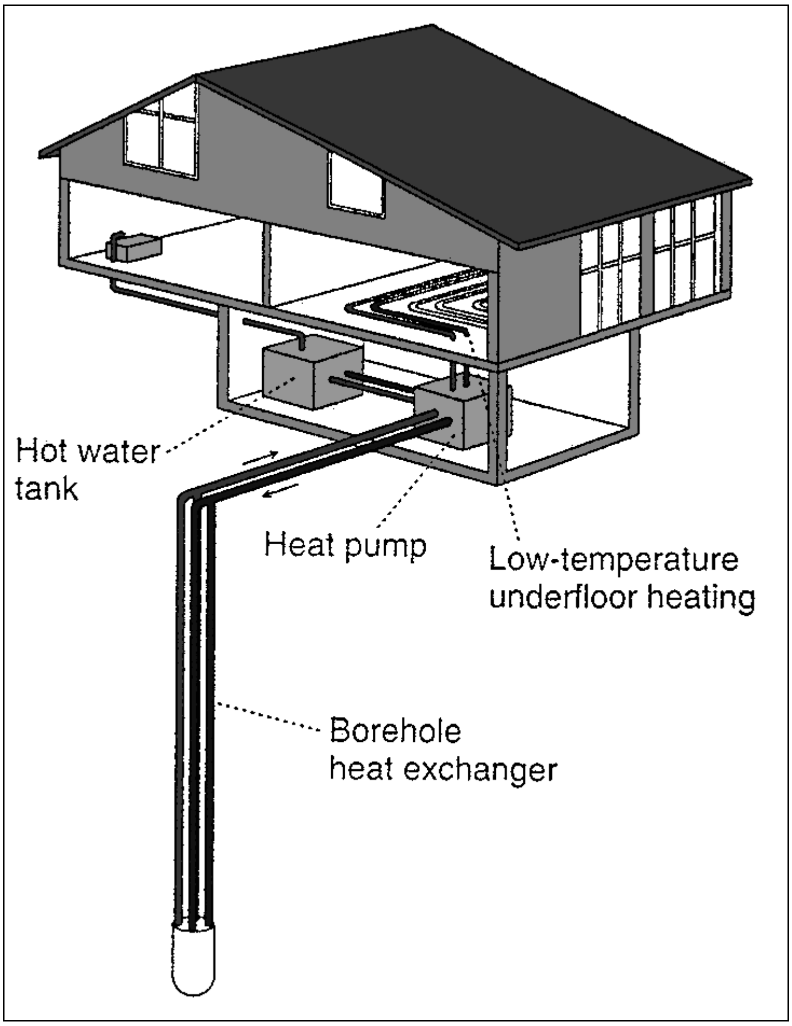


Figure 1: Typical application of a borehole heat exchanger (BHE) / heat pump (HP) system in a Central European home. Average BHE length: 100 m.

2. DESIGN (SIZING)

The design of BHE/HP systems aims at the appropriate sizing of the system components by taking into account a number of influence factors. In the following, some basic principles are outlined to illustrate the procedure.

The sizing must consider the demand characteristics of the object to be supplied (size, extension; heating alone, heating + domestic water, combined heating/cooling) as well as the local site conditions (climate, ground properties). Generally, simpler dimensioning procedure is sufficient for smaller objects. The limit is usually set at 30 kW capacity.

The first step is to evaluate the demand. This consists of several ingredients like the energy need in MWh per year and the capacity in kW. In many countries there are norms which describe how the necessary sizing input data are to be evaluated, using peak heat load, heat-degree-days etc. (e.g. for Switzerland the norms SIA 382/2 and 380/1, for Germany DIN 4701). The BHE construction characteristics (diameter, tube type and configuration, circulating fluid, backfill) must also be fixed beforehand. Also the user side characteristics (heat pump type, capacity, performance coefficient, evaporator ΔT) need to be fixed.

The local conditions are of great importance: ground temperatures (mainly determined by the site elevation for a given climatic zone), ground properties like the presence or absence of overburden, bedrock, groundwater are more or less dominant influence factors.

A key property is the thermal conductivity of the ground surrounding the BHE. The higher the rock thermal conductivity l (W/m,K), the higher the specific heat extraction rate (W/m) and the energy yield (kWh/m,a) per unit BHE length (see Table 1).

Table 1: Borehole heat exchanger performance (single BHE, depth ~ 150 m) in different rock types

Rock type	Thermal conductivity (W m^{-1} K^{-1})	Specific extraction rate (W per m)	Energy yield (kWh m^{-1} a^{-1})
Hard rock	**3.0**	**max. 70**	**100 - 120**
Unconsolidated rock, saturated	**2.0**	**45 - 50**	**90**
Unconsolidated rock, dry	**1.5**	**max. 25**	**50**

Fig. 2 displays the influence factors (demand, site, HP characteristics) and demonstrates the way of sizing for a small object (note the ranges of validity): first the top left diagram is entered with the demand characteristics power (kW) and total energy (MWh/a); from the point so defined a vertical line is drawn down until the site elevation (m.a.s.l.) is met. From there the line continues horizontally to the HP performance coefficient (COP); then the line goes vertically up until the local (average) ground thermal conductivity λ (W/m,K). Finally, a horizontal line exits to the necessary BHE length (for one or two BHEs). A HP COP of 4 means that 25 % electrical energy is needed for the system and 75 % heat is coming from the ground.

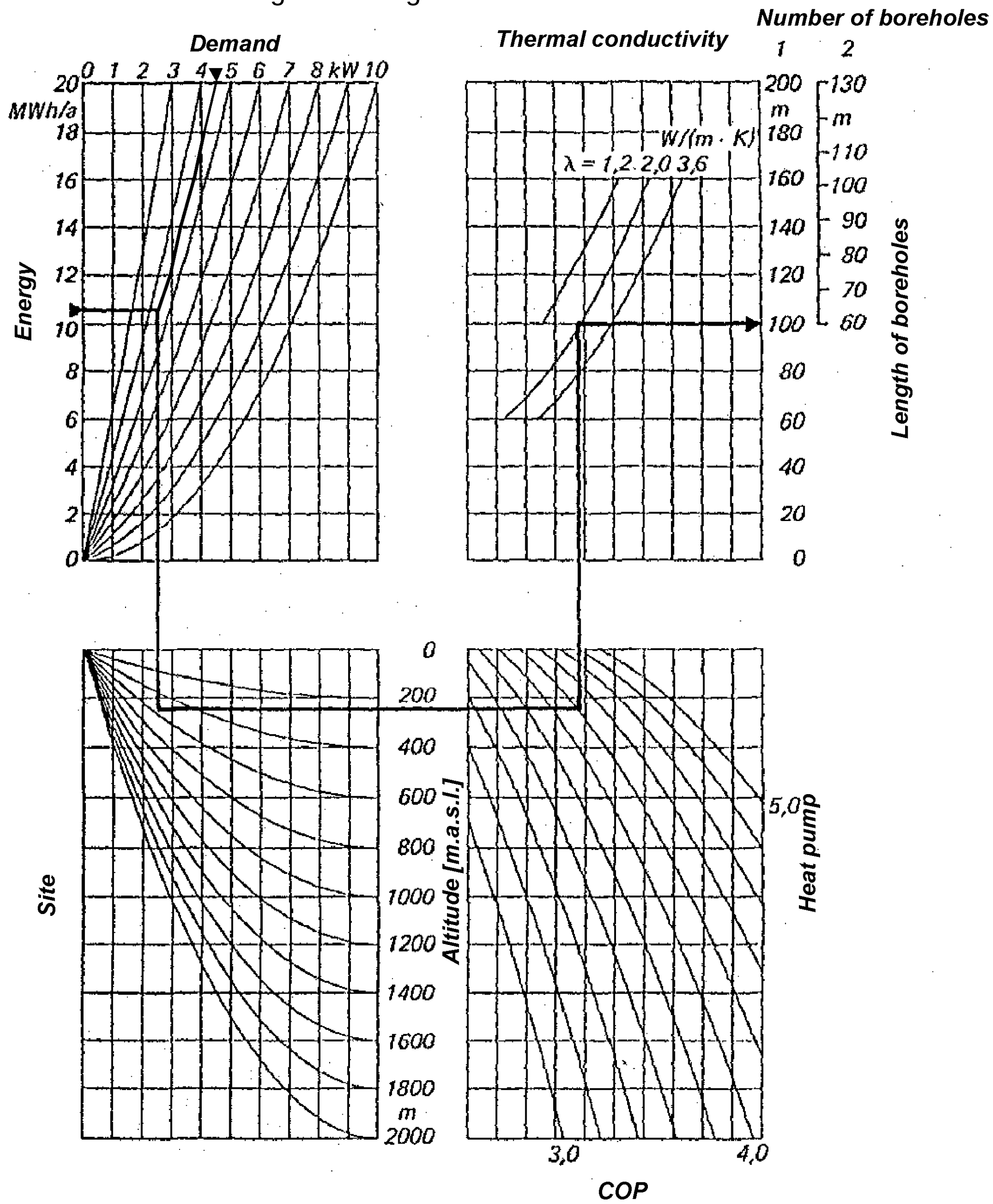


Figure 2: Sizing nomogram for small objects in Switzerland (from Stalder et al. 1995). For explanation see text.

Larger objects which need several BHEs require a more sophisticated sizing approach. Specific computer software is needed for this purpose. Of these sizing software packages the EED (Earth Energy Designer, see e.g. Sanner & Hellström 1996) is widely used. EED calculates the BHE fluid exit temperatures over many years of BHE operation, for predefined monthly heating/cooling loads and a given borehole depth/spacing ratio. The reliability of EED for regular BHE patterns (=rectangular equidistant grid) has been confirmed by measurements (Sanner and Gonka 1996).

The sizing software EED has, however, its limitations. Varying ground thermal properties cannot be considered, irregular BHE configurations which are often dictated by ground property boundaries cannot be handled. Also, the influence of moving groundwater cannot be taken into account. More flexible software like the package FRACTure (Kohl and Hopkirk 1995) has lately been used successfully to eliminate these shortcomings (Maraini 2000).

3. ECONOMICS

The installation and operation of a BHE/HP system needs installation and running costs. Its "economy" cannot be defined absolutely, only in relative terms. Therefore a comparison is presented here, for a typical single family house in Switzerland. The prices are characteristic for the year 2000; the introduction of a CO_2 tax (as well as oil and price variations) could strongly influence the comparison in the future. Electricity prices will change due to privatization and could decrease rather than increase. In any case, the installation for a BHE/HP system is more advantageous (and environmentally friendly!) than a conventional oil burner. The prices in Table 2 are in Swiss francs (1 CHF = 0.6 US $). It is clear from Table 2 that the operational and energy costs are more favorable for the BHE/HP solution. A similar comparison with an air-based HP system (which has, due to the lower source temperature during the critical heating period a lower COP and thus higher electricity demand) shows again favorable figures for the BHE/HP system.

Table 2: Cost comparison of BHE/HP installation and operation with a conventional oil burner heating system

	BHE/HP ***1 BHE 90m***	**Oil burner** ***tank 2x2000 l***
Basis: heating demand 6.5 kW		
Heating energy need per year kWh/a	**13,600**	**13,600**
System efficiency %	**95**	**80**
Seasonal Performance Factor	**3.5**	**-**
Effective energy used kWh/a	**4,900**	**17,000**
Fuel consumption liter/a	**-**	**1,703**
Space required m^3	**2.6**	**23**
CO_2 emmission tons/a	**-**	**3.8**
Installation costs (Swiss francs)		
Complete system incl. storage	**12,730.-**	**16,300.-**
BHE	**11,010.-**	**-**
Space in house (400.-/m^3)	**1,040.-**	**9,200.-**
Miscell. costs (trenches, chimney...)	**1,620.-**	**1,'600.-**
Total	**26,400.-**	**27,100.-**
Energy costs (per year, CHF)		
Electricity high tariff	**337.40**	**49.-**
Electricity low tariff	**224.95**	**22.-**
Basic payment/a	**102.-**	**8.-**
Fuel cost (Fr. 68.-/100 l)	**-**	**1'158.-**
Total	**664.35**	**1'237.-**
Running costs (per year, CHF)		
Maintenance	**150.-**	**370.-**
Chimney cleaning, smoke gas control	**-**	**180.-**
Total	*150.-*	*550.-*

4. LONG-TERM PERFORMANCE

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.

4.1 Study of long-term performance

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. For this basic study, a single BHE was treated.

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

The aim of the measurement campaign 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 3. 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).

In the autumn of 1996 (i.e. after 10 years of BHE operation) the measurement system was restarted. Due to the forced aging 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 3) 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 about 0.5 K, depending on the specific annual heating 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 and Eugster (1998). The excellent agreement between measured an calculated time histories at a number of specific points in the underground gives confidence to extrapolate future trends and situations by modelling.

For this, the 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 Gilby and Hopkirk (1985) and Eugster (1991). 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 using assumed load profiles (Eugster, 1991).

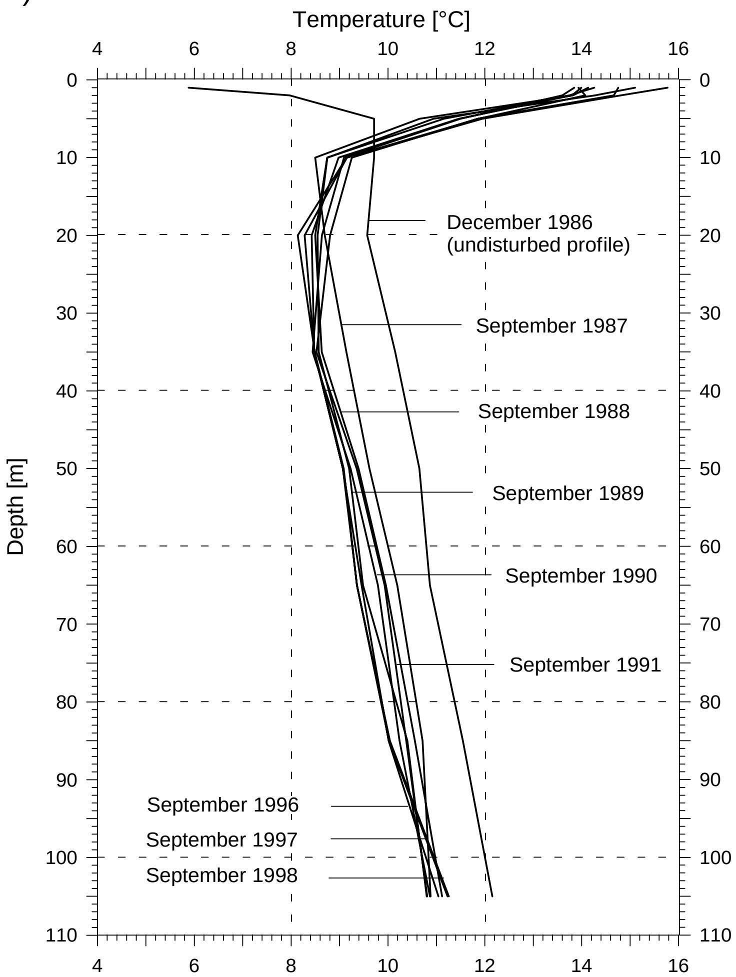


Figure 3: Ground temperature profiles at a distance of 1 m from the BHE in Elgg

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.

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. The model grid had 11'700 grid cells in a model volume of $2x10^6$ m^3 (for details see Rybach and Eugster, 2000).

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).

4.2 Thermal conditions around a BHE

The transient thermal conditions around a BHE in operation are very complex. Several processes are superimposed:

- a heavy cooling-down and a subsequent rewarming of the immediate vicinity of the BHE up to some 10 cm during a operational cycle (hourly cycle);

- the dissemination of this cooling and rewarming period up to several meter as a funnel-like temperature effect during a seasonal operation (yearly cycle);
- a large-scale, but only minimal cooling-down of the surrounding underground up to a distance of several 10's of meters during the full life cycle of the BHE (30-years-cycle);
- both the horizontal and vertical heat fluxes increase around the BHE. The massive cooling down of the BHE vicinity enlarges the heat flows from the atmosphere and from the underground.

These pure conductive processes are rather complicated and visualized in Figure 4. But in free nature, flowing groundwater and - in saturated formations - water vapor diffusion processes add their effects to this complex system.

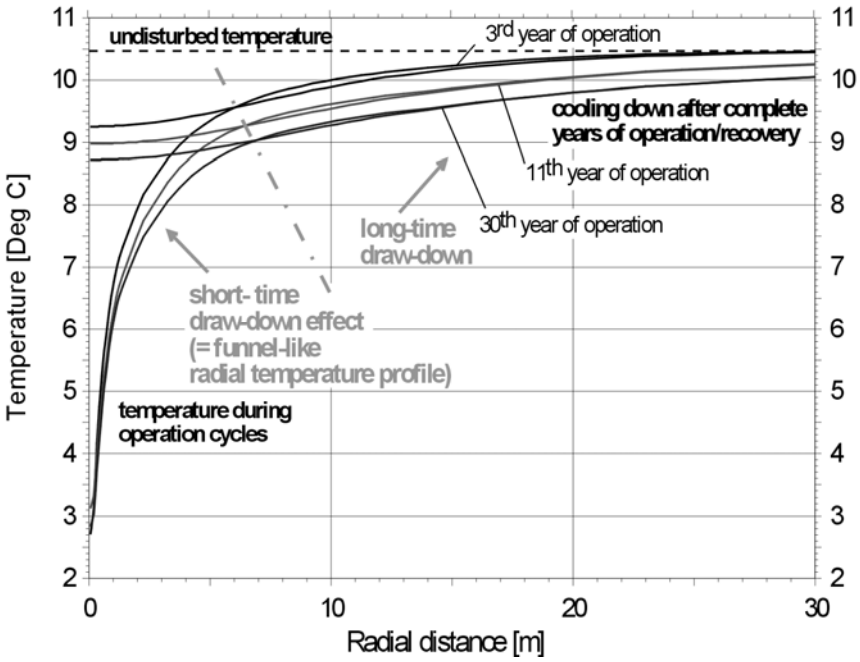


Figure 4: Funnel-like temperature distribution and long term cooling-down around a BHE. The short term and the long term influences are well documented.

The simulation runs show on one hand the expected decrease of the yearly temperature deficit and on the other hand an increasing volume around the BHE which is affected by the cooling (see Figure 5). 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 first few years of operation. Later, the yearly deficit decreases asymptotically to zero. During the recovery period after a virtual stop-of-operation , the ground temperature shows a similar behavior: during the first years, the temperature increase is strong and tends with increasing recovery time asymptotically to zero. 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 6 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. The installation in Elgg supplies on the average about 13 MWh per year. In fact, the BHE’s show stable and reliable performance which can be 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.

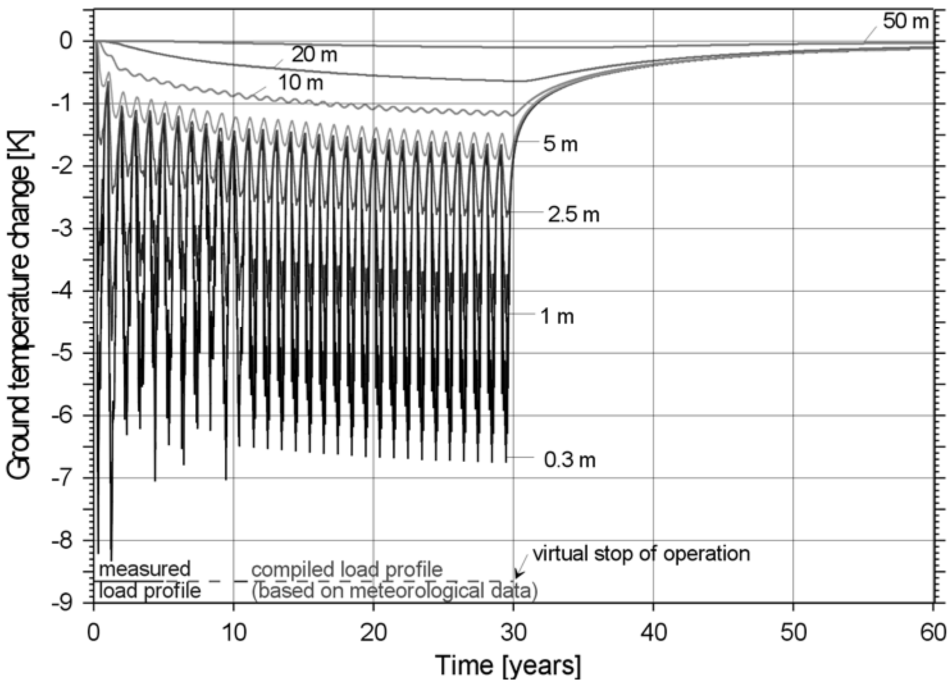
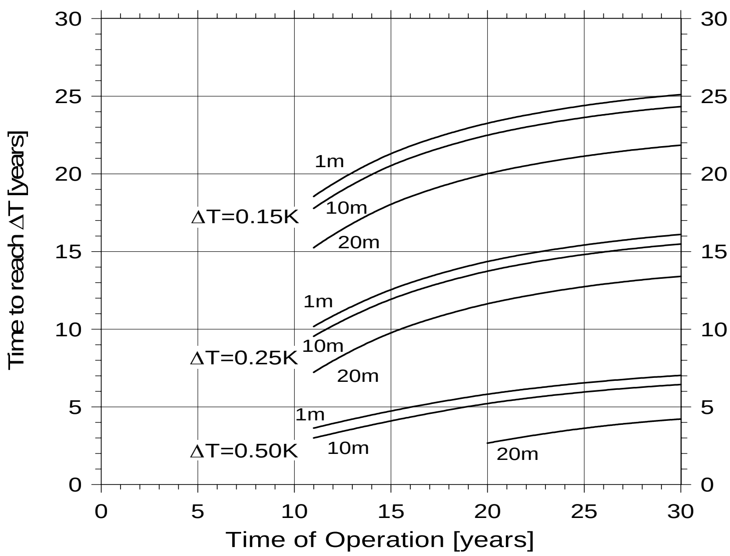


Figure 5: Measured and modelled ground temperature changes of the BHE at Elgg relative to the undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery



5.

Figure 6: Duration of recovery period to reach a minimal final 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.

6. 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. They can be installed in nearly all kings of geologic media. The design of BHE/HP systems must take into account a number of influence factors like demand, installation and site conditions. The economy of such systems is, at current oil prices, favorable.

BHE/HP 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 but constant level after the first few years. Thus sustainable operation can be 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 first 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.

The basic studies about long-term performance presented here apply to a single BHE. Similar studies are underway for BHE groups/patterns.

7. ACKNOWLEDGEMENTS

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