INTERNATIONAL SUMMER SCHOOL
on Direct Application of Geothermal Energy
POLISH GEOTHERMAL ASSOCIATION
International Geothermal Days
POLAND 2004
EUROPEAN BRANCH
Under the auspice of Division of Earth Sciences

2.6.
GEOTHERMAL HEAT PUMPS TECHNOLOGIES AND DEVELOPMENT

Burkhard Sanner
Lahnau, Germany
http://www.sanner-geo.de

Abstract

Geothermal Heat Pumps, or Ground Source Heat Pumps (GSHP), are systems combining a heat pump with a ground heat exchanger (closed loop systems), or fed by ground water from a well (open loop systems). They use the earth as a heat source when operating in heating mode, with a fluid (usually water or a water-antifreeze-mixture) as the media transferring the heat from the earth to the evaporator of the heat pump, utilising that way geothermal energy. In cooling mode, they use the earth as a heat sink.

With BHE geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet any demands. More than 25 years of R&D focusing on BHE in Europe resulted in a well-established concept of sustainability for this technology, as well as sound design and installation criteria. Recent developments are the Thermal Response Test, which allows in situ-determination of ground thermal properties for design purposes, and thermally enhanced grouting materials to reduce borehole thermal resistance.

Despite the use of geothermal heat pumps for over 50 years now (first in USA), market penetration of this technology, is still at its infancy, with fossil fuels dominating the market of heating of buildings and air-to-air heat pumps dominating the market of cooling of buildings. In some countries, namely Germany, Switzerland, Austria, Sweden, Denmark, Norway, France and USA, already larger numbers of geothermal heat pumps are operational. In these countries meanwhile installation guidelines, quality control and contractor certification becomes a major issue.

1. INTRODUCTION

First, two abbreviations have to be mentioned, which are used frequently throughout this text:

- GSHP — Ground Source Heat Pump
- BHE — Borehole Heat Exchanger (in USA, the term Vertical Loop is common)

Most European countries do not boast abundant hydro-geothermal resources that could be tapped for direct use (some exceptions are e.g. Iceland, Hungary, France). The utilization of low-enthalpy aquifers that enable the supply of a larger number of customers by district heating is limited so far to regions with specific geological settings.

However, the underground in the first approx. 100-200 m is well suited for supply and storage of thermal energy. The climatic temperature change over the seasons is reduced to a steady temperature at 10-20 m depth (fig. 1), and with further depth temperatures are increasing according to the geothermal gradient (average 3 °C for each 100 m of depth).

In this situation the utilization of the ubiquitous shallow geothermal resources by GSHP systems is an obvious option. Correspondingly, a rapidly growing field of applications is emerging and developing in various European countries. A rapid market penetration of such systems is resulting; the number of commercial companies actively working in this field is ever increasing and their products have reached the "yellow pages" stage.

The climatic conditions in Central and Northern Europe, where most of the market development took place, are such that by far the most demand is for space heating; air conditioning is rarely required. Therefore, unlike the "geothermal heat pumps" in the USA, the heat pumps usually operate mainly in the heating mode. With the inclusion of larger commercial applications, requiring cooling, and the ongoing proliferation of the technology into Southern Europe, the double use for heating and cooling will become of more importance in the future.

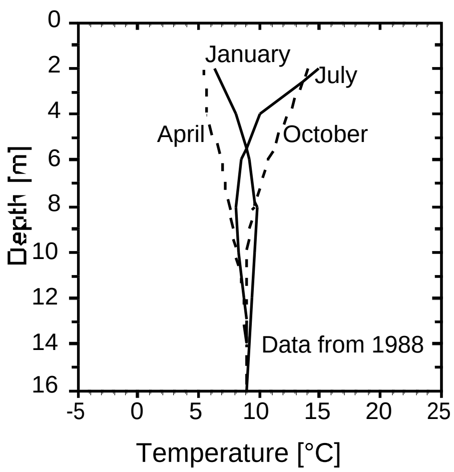

Fig 1: Underground temperatures from a borehole south of Wetzlar, Germany, not influenced by the heat pump operation

2. GSHP TECHNOLOGY STATUS

Ground Source Heat Pumps (GSHP), or Geothermal Heat Pumps, are systems combining a heat pump with a system to exchange heat with the ground. The first GSHP has been operated in Indianapolis, USA, in 1945, with horizontal heat exchanger pipes. A brief history of GSHP is given in [1]. As early as in 1947, most of the different groundcoupling methods have been described, and most of them demonstrated (see fig. 2). The systems can be divided basically into those with a ground heat exchanger (closed loop systems), or those fed by ground water from a well (open loop systems). The means to tap the ground as a shallow heat source comprise:

- groundwater wells ("open" systems)
- borehole heat exchangers (BHE)
- horizontal heat exchanger pipes (incl. compact systems with trenches, spirals etc.)
- "geostructures" (foundation piles equipped with heat exchangers)

The ground system links the heat pump to the underground and allows for extraction of heat from the ground or injection of heat into the ground. To choose the right system for a specific installation, several factors have to be considered: Geology and hydrogeology of the underground (sufficient permeability is a must for open systems), area and utilisation on the surface (horizontal closed systems require a certain area), existence of potential heat sources like mines, and the heating and cooling characteristics of the building(s). In the design phase, more accurate data for the key parameters for the chosen technology are necessary, to size the ground system in such a way that optimum performance is achieved with minimum cost.

Main technical part of open systems are groundwater wells, to extract or inject water from/to water bearing layers in the underground („aquifers"). In most cases, two wells are required („doublette", fig. 3), one to extract the groundwater, and one to re-inject it into the same aquifer it was produced from. With open systems, a powerful heat source can be exploited at comparably low cost. On the other hand, groundwater wells require some maintenance, and open systems in general are confined to sites with suitable aquifers. The main requirements are:

- Sufficient permeability, to allow production of the desired amount of groundwater with little drawdown.
- Good groundwater chemistry, e.g. low iron content, to avoid problems with scaling, clogging and corrosion.

Open systems tend to be used for larger installations.

The closed system easiest to install is the horizontal ground heat exchanger (synonym: ground heat collector, horizontal loop). Due to restrictions in the area available, in Western and Central Europe the individual pipes are laid in a relatively dense pattern, connected either in series or in parallel (fig. 4).

To save surface area with ground heat collectors, some special ground heat exchangers have been developed (fig. 5): Spiral forms, mainly in the form of the so-called „slinky" collectors, and trench collectors. Exploiting a smaller area at the same volume, these collectors are best suited for heat pump systems for heating and cooling, where natural temperature recharge of the ground is not vital.

The main thermal recharge for all horizontal systems in heating-only mode is provided for mainly by the solar radiation to the earth´s surface. It is important not to cover the surface above the ground heat collector.

Because the temperature below the „neutral zone" (ca. 10-20 m) remains constant over the year, and because of the need to install sufficient heat exchange capacity under a confined surface area, vertical ground heat exchangers (borehole heat exchangers, fig. 6) are widely favoured. In a standard borehole heat exchanger, plastic pipes (polyethylene or polypropylene) are installed in boreholes, and the remaining room in the hole is filled (grouted) with a pumpable material.

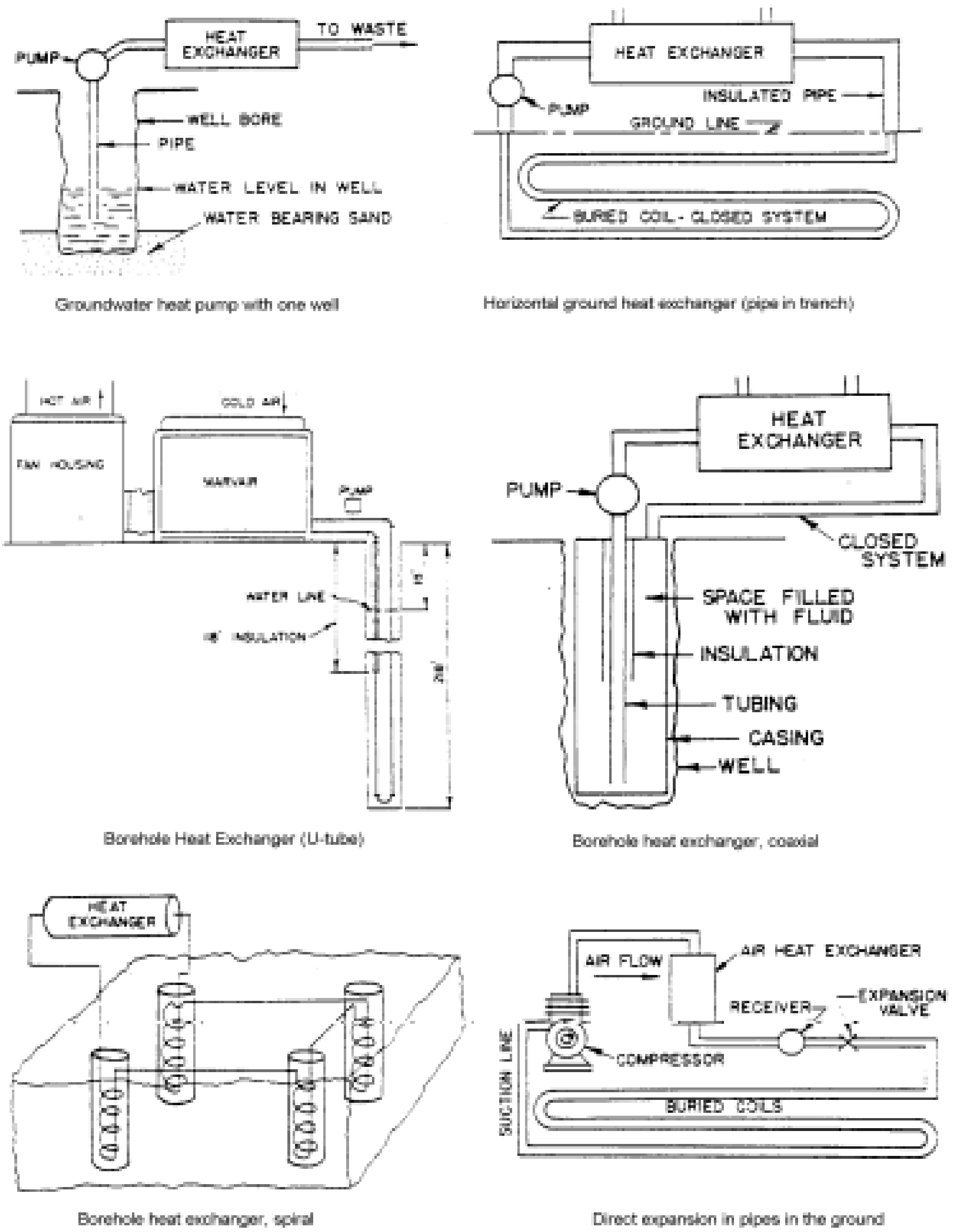

Fig. 2: Different types of ground heat exchangers as described in 1947, after [2]

Several types of borehole heat exchangers have been used or tested; the two possible basic concepts are (fig. 7):

- U-pipes, consisting of a pair of straight pipes, connected by a 180°-turn at the bottom. One, two or even three of such U-pipes are installed in one hole.

The advantage of the U-pipe is low cost of the pipe material, resulting in double-U-pipes being the most frequently used borehole heat exchangers in Europe.

- Coaxial (concentric) pipes, either in a very simple way with two straight pipes of different diameter, or in complex configurations.

The borehole filling and the heat exchanger walls account for a drop in temperature, which can be summarised as borehole thermal resistance.

Thermally enhanced grouting (filling) materials have been developed to reduce this losses.

A special case of vertical closed systems are „energy piles“, i.e. foundation piles equipped with heat exchanger pipes (fig. 8 and 9). All kind of piles can be used (pre-fabricated or cast on site), and diameters may vary from 40 cm to well over 1 m.

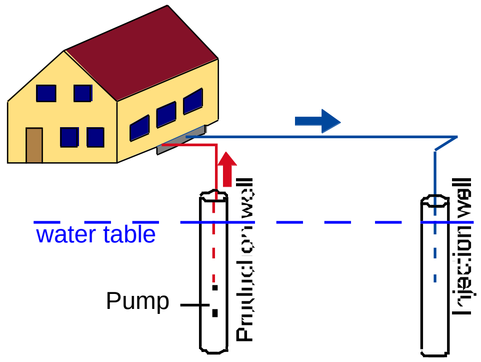

Fig. 3: Groundwater heat pump (doublette)

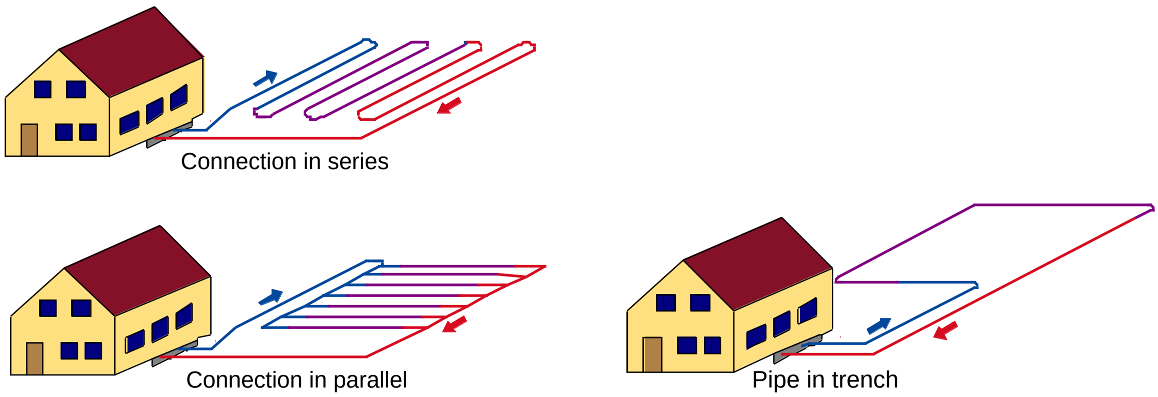

Fig. 4: Horizontal ground heat exchanger types

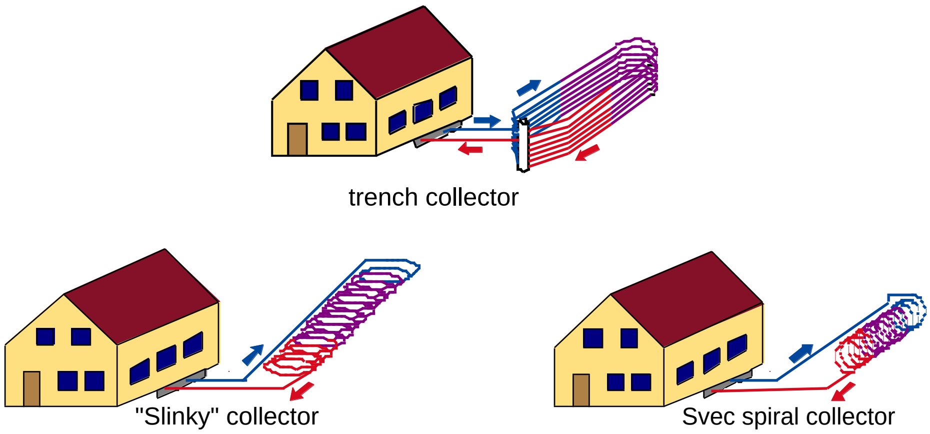

Fig. 5: Horizontal ground heat exchanger types for smaller areas

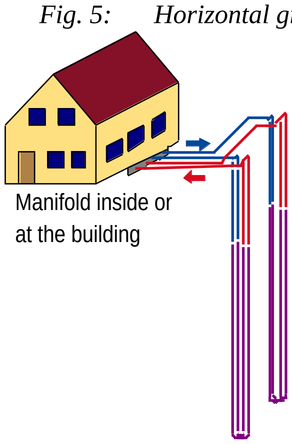

Fig. 6: Borehole heat exchangers (double-U-pipe)

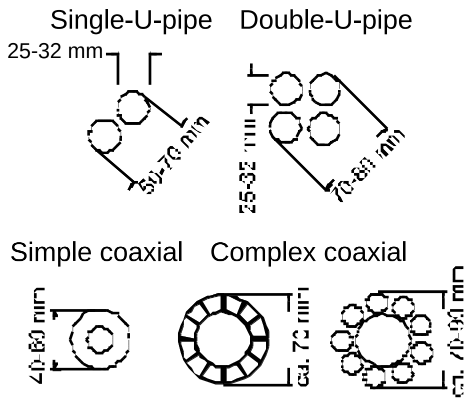

Fig. 7: Cross-sections of different types of borehole heat exchangers

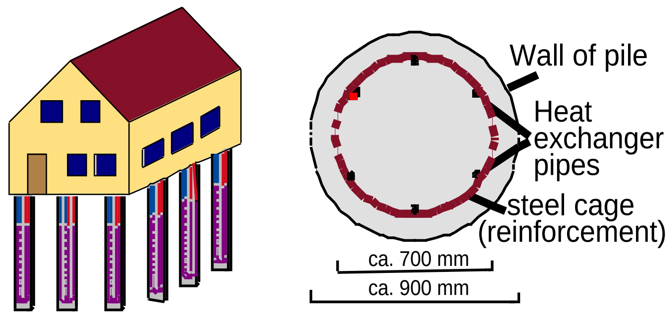

Fig. 8: Energy piles and cross-section of a pile with 3 loops

The technology most widely applied today is the borehole heat exchanger (BHE). From all of the different approaches shown in fig. 7, the U-tube design has the best cost-performance-ratio, and has outnumbered all other designs by far. In Central Europe, the double-U-tube is popular, while in Northern Europe and North America the single-U-tube prevails. It can be said in general, that double-U-tubes allow for a thermal efficiency 15-25 % higher than single-U-tubes. Thus in regions with low drilling cost, but higher pipe cost, the single-U-tube is preferred, and in regions with high drilling cost and cheap pipes, the double-U-tube becomes more economic.

Experimental and theoretical investigations (field measurement campaigns and numerical model simulations) have been conducted over several years to elaborate a solid base for the design and for performance evaluation of BHE systems (see [3], [4], [5]). While in the 80´s theoretical thermal analysis of BHE-systems prevailed in Sweden [6], [7] monitoring and simulation was done in Switzerland [8], [9], and measurements of ground heat transport were made on a test site in Germany [10].

3. PLANNING AND OPTIMIZATION OF BHE-SYSTEMS

When using (BHE), the required length for a given power output is highly dependent upon soil characteristics including temperature, moisture content, particle size and shape, and heat transfer coefficients. Correct sizing of the BHE continues to be a cause for continued design concern, and special attention should be placed on minimising interference between neighbouring BHE. Key points are building load, borehole spacing, borehole fill material and site characterisation. Due to the high capital costs involved, over-sizing carries a much higher penalty than in conventional applications.

Two important technical developments of recent years should be mentioned in this respect:

- Thermal Response Test to determine the thermal parameters of the underground in situ
- Grouting material with enhanced thermal conductivity

For a thermal response test [11], basically a defined heat load is put into the BHE and the resulting temperature changes of the circulating fluid are measured (fig. 9). Since mid 1999, this technology now also is in use in Central Europe for the design of larger plants with BHE, allowing sizing of the boreholes based upon reliable underground data. Thermal response test first was developed in Sweden and USA in 1995 [12], [13] and now is used in many countries world-wide, including Turkey. Together with reliable design software [14], [15], BHE can be made a sound and safe technology even for larger applications.

Thermally enhanced grouting material is available in Europe in different mixtures and with several brand names. The advantage of its use is a significant reduction in the borehole thermal resistance (fig. 10), which governs the temperature losses between the undisturbed ground and the fluid inside the BHE pipes. The table in fig. 10 gives some values for typical BHE; the effect could meanwhile also be demonstrated in situ, using the Thermal Response Test on BHE with different grouting materials. The difficulty in developing a good grouting material is that different properties have to be combined in one material: good sealing of the borehole annulus, good thermal conductivity, and good pumpability (i.e. low wear on pumps). Material choices for this properties partly contradict each other, but suitable solutions meanwhile have been found in Germany.

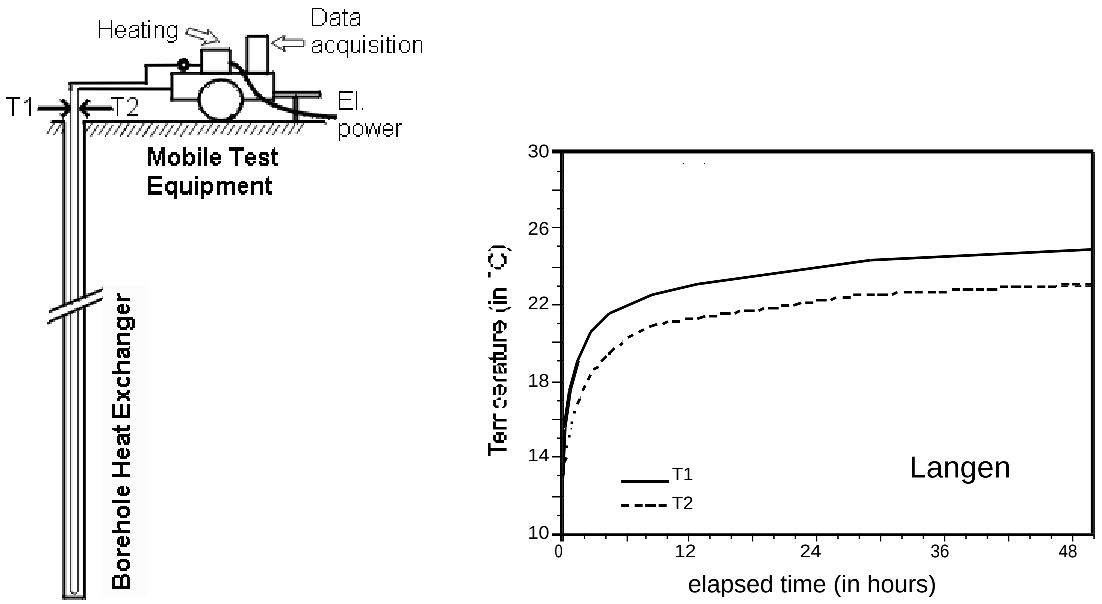

Fig. 9: left: Schematic of a Thermal Response Test
right: Example of measured data from a Thermal Response Test, from [11]

Practical use of heat transport calculation around pipes started in 1920 [17]. The earliest approach to calculating thermal transport around a heat exchanger pipe in the ground was the Kelvin line source theory in [18], [19]. PC-programs for quick and reasonably sound dimensioning of ground heat systems with borehole heat exchangers have been presented by [20], [21], [22] and [23].

The algorithms have been derived from modeling and parameter studies with a numerical simulation model SBM ([24], [25]), evolving to an analytical solution of the heat flow with several functions for the borehole pattern and geometry (*g*-functions, see [24]). Those *g*-functions depend on the spacing between the boreholes at the ground surface and the borehole depth. In the case of graded boreholes there is also a dependence on the tilt angle. The *g*-function values obtained from the numerical simulations have been stored in a data file, which is accessed for rapid retrieval of data by the PC-programs.

After first discussions in summer 1991, co-operative work on a new programme called "Earth Energy Designer" (EED) began in June 1992, and was presented in 1994 [26], and the β-version distributed in summer 1995 [27]. The program EED allows for calculation of heat exchanger fluid temperatures for monthly heat/cool loads. Databases provide the key ground parameters (thermal conductivity, specific heat) as well as properties of pipe materials and heat carrier fluids. The calculation is done using 12 separate extraction steps. The steps are considered as 12 month, and the monthly average heat extraction/injection are the input data. In addition, an extra pulse for maximum heat extraction/injection over several hours can be considered at the end of each month. The user can choose between different methods of establishing a monthly load profile. A printed output report and output files containing data for graphical processing were provided in version 1.0 under MS-DOS; version 2.0, running under MS-Windows 95 and higher, offers direct graphical output.

The borehole thermal resistance rb is calculated in the program, using borehole geometry, grouting material and pipe material and geometry. It is also possible to give input data for rb, suing e.g. measured date from Thermal Response Test. The *g*-functions for borehole patterns can be browsed in a window, and the adequate function for the given layout is chosen directly. In the recent version, the borehole distance is typed in directly, and the program interpolates between suitable *g*-functions, keeping the borehole distance constant with changing borehole depth.

Type of BHE	λ grout	r_b
single-U, PE	0.8 W/m/K	0.196 K/(W/m)
	1.6 W/m/K	0.112 K/(W/m)
double-U, PE	0.8 W/m/K	0.134 K/(W/m)
	1.6 W/m/K	0.075 K/(W/m)

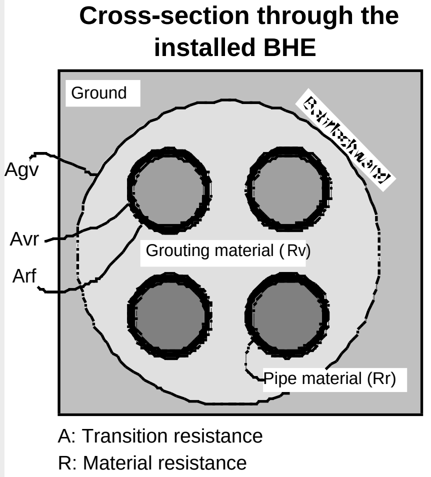

Fig. 10: left: Table with data for r_b for different grouting materials
right: schematic of the concept of borehole thermal resistance r_b

The current version of EED can be found under http://www.buildingphysics.com (go to „Software“), where also a demo version and the user manual can be downloaded. A total of 308 different borehole patterns is available, including boreholes in a straight line, in the form of L- or U-shaped lines, and as open or filled rectangles. Fig. 11 shows an example:

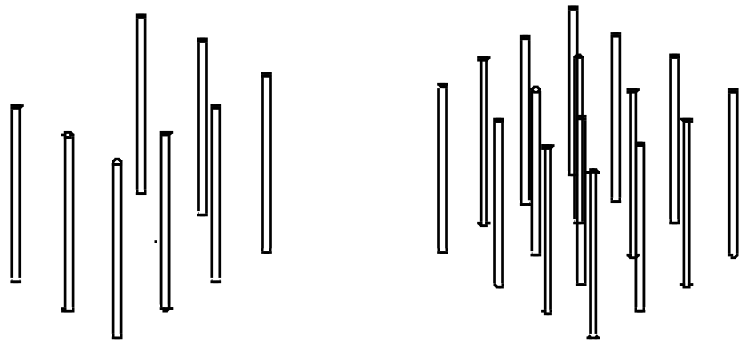

Fig. 11: Examples of g-functions
left: U-configuration, 3 x 4 boreholes, total 8 boreholes, g-function no.112
right: Filled rectangular config., 4 x 4 boreholes, total 16 boreholes, no. 262

Calculations with EED were compared to numerical simulation, e.g. using the FD-code TRADIKON-3D [28], and a good agreement of predicted fluid temperatures was found [29]. [30] described the design of a field of BHE in a new development area. For 3 houses in a row with one BHE each and 10 m distance between BHE, the temperature development in the ground was simulated (fig. 12). A comparison was made to EED, where only an average value for fluid temperatures in all 3 BHE is given:

- In the two external BHE, simulated temperatures were up to 0.4 K higher than EED-values
- In the inner BHE, simulated temperature was up to 0.5 K lower than EED-values

Overall, EED showed a rather good agreement with the mean of the simulated temperatures.

An existing ground source heat pump (GSHP) plant with direct cooling was monitored from July 1995 on (UEG, Wetzlar, see paper on case studies in this volume). Fig. 13 shows the monitored mean brine temperature from July 1995 - July 1996 and the brine temperature calculated with EED. Monthly heat and cold demand was taken from measured data for EED calculation. Since the plant was operational over 3 years before monitoring started, temperature values for the fourth year were chosen for the graph in fig. 13. The exact load values for the three preceding years are not known, adding some possible error to the comparison. Also the exact distribution of simultaneous heat and cold generation in some months is unknown. However, the curves in fig. 13 do not match exactly due to the uncertainties, but EED gives a rather good prediction of the temperatures found in reality.

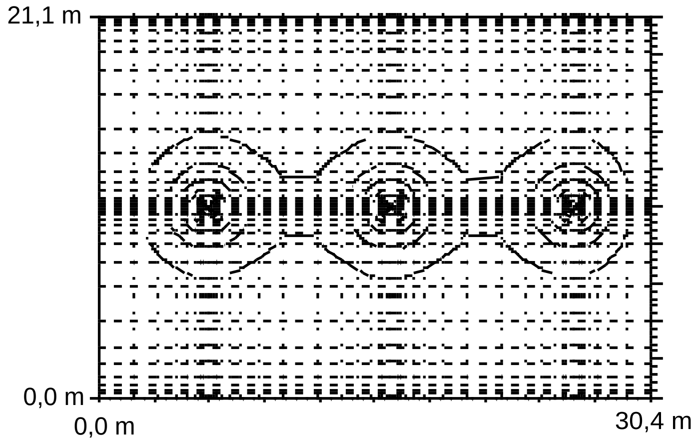

Fig. 12: Temperature distribution (isotherms) around 3 BHE, horizontal cross-section in 50 m depth, after 8 month heating, with FD-grid (after [30])

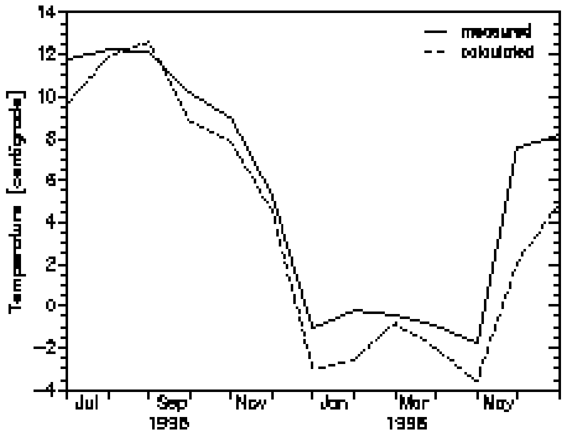

Fig. 13: Measured and calculated brine temperatures for UEG plant, Wetzlar, after [29]

7. CONCLUSIONS

GSHP are no longer exotic. Their number has increased steadily over the years, and the technology is well understood. Optimization and further development will be required to keep GSHP efficiency in line with the advancements of competing heating and cooling systems. The main goals currently are

- cost reduction without decrease of efficiency and longevity
- quality certification not only for the heat pump, but for the ground coupling system also
- further increase in efficiency and design accuracy
- proliferation of GSHP into regions with no or low market penetration (e.g. Eastern Europe and the Mediterranean)

Looking back at a development over some 60 years since the first plants, some 25 years since the first BHE in Europe, and some 20 years of personal experience with GSHP by the author, the concept of shallow geothermal energy still has but started to explore its real potential.

References

[1] SANNER, B. (2001): Some history of shallow geothermal energy use. - in: POPOVSKI, K. & SANNER, B. (eds.), International Geothermal Days Germany 2001 Bad Urach, Supplement pp. 3-12, GtV, Geeste

[2] KEMLER, E.N. (1947): Methods of Earth Heat Recovery for the Heat Pump. - Heating and Ventilating, Sept. 1947, S. 69-72, New York

[3] KNOBLICH, K., SANNER, B. & KLUGESCHEID, M. (1993): Energetische, hydrologische und geologische Untersuchungen zum Entzug von Wärme aus dem Erdreich. - Giessener Geologische Schriften 49, 192 p., Giessen

[4] RYBACH, L., HOPKIRK, R. (1995): Shallow and deep borehole heat exchangers - achievements and prospects. Proc. World Geothermal Congress 1995, 2133-2139

[5] RYBACH, L., EUGSTER, W.J. (1997): Borehole heat exchangers to tap shallow geothermal resources: The Swiss success story. In: S.F. Simmons, O.E. Morgan & M.G. Dunstall

(eds.): Proc. 19th New Zealand Geothermal Workshop. Auckland, 63-69

[6] CLAESSON, J., ESKILSON, P. (1988): Conductive Heat Extraction to a deep Borehole, Thermal Analysis and Dimensioning Rules. Energy 13/6, 509-527

[7] ESKILSON, P., CLAESSON, J. (1988): Simulation Model for thermally interacting heat extraction boreholes. Numerical Heat Transfer 13, 149-165

[8] GILBY, D.J., HOPKIRK, R.J. (1985): The coaxial vertical heat probe with solar recharge, numerical simulation and performance evaluation. Proc. 2nd WS on SAHPGCS Vienna, 443-456

[9] HOPKIRK, R.J., EUGSTER, W.J., RYBACH, L. (1988): Vertical earth heat probes: mesurements and prospects in Switzerland. Proc. 4th int. Conf. Energy Storage JIGASTOCK 88, 367-371

[10] SANNER, B. (1986): Schwalbach Ground-Coupled Heat Pump (GCHP) Research Station. - Newsletter IEA Heat Pump Centre 4/4, pp. 8-10, Karlsruhe

[11] SANNER, B., REUSS, M., MANDS, E. & MÜLLER, J. (2000): Thermal Response Test - Experiences in Germany. - Proc. TERRA-STOCK 2000, pp. 177-182, Stuttgart

[12] EKLÖF, C. & GEHLIN, S. (1996): TED - a mobile equipment for thermal response test. - 62 p., Master´s thesis 1996:198E, Luleå University of Technology

[13] AUSTIN, W. (1998): Development of an in-situ system for measuring ground thermal properties. - 164 p., MSc-thesis, OSU, Stillwater OK

[14] HELLSTRÖM, G. & SANNER, B. (1994): Software for dimensioning of deep boreholes for heat extraction. - Proc. CALORSTOCK 94, pp. 195-202, Espoo/Helsinki

[15] HELLSTRÖM, G., SANNER, B., KLUGESCHEID, M., GONKA, T. & MÅRTENSSON, S. (1997): Experiences with the borehole heat exchanger software EED. - Proc. MEGASTOCK 97, pp. 247-252, Sapporo

[16] VDI (2001): Thermische Nutzung des Untergrundes / Thermal Use of the Underground. – Guideline, German Association of Engineers VDI, part 2, Beuth Verlag, Berlin

[17] ALLEN, J.R. (1920): Theory of Heat Loss from Pipe Buried in the Ground. - Journal ASHVE 26, 455-469 and 588-596

[18] INGERSOLL, L.R. & PLASS, H.J. (1948): Theory of the ground pipe source for the heat pump. - ASHVE Trans. 54, 339-348

[19] INGERSOLL, L. R., ADLER, F.T., PLASS, H.J. & INGERSOLL, A.C. (1950): Theory of earth heat exchangers for the heat pump. - ASHVE Trans. 56, 167-188

[20] CLAESSON, J. & ESKILSON, P. (1988): PC Design Model for Heat Extraction Boreholes. - Proc. 4th Int. Conf. Energy Storage JIGASTOCK 88, 135-137

[21] CLAESSON, J., ESKILSON, P. & HELLSTRÖM, G. (1990): PC Design Model for Heat Extraction Boreholes. - Proc. 3rd WS on SAHPGCS Göteborg, CITη 1990:3, 99-102

[22] CLAESSON, J. (1991): PC Design Model for Thermally Interacting Deep Ground Heat Exchangers. - IEA Heat Pump Centre report HPC-WR-8, 95-104

[23] HELLSTRÖM, G. (1991): PC-Modelle zur Erdsondenauslegung. - IZW Bericht 3/91, 229-238

[24] ESKILSON, P. (1987): Thermal Analysis of Heat Extraction Boreholes. - 264 p., PhD-thesis Lund-MPh-87/13, Lund University of Technology

[25] ESKILSON, P. & CLAESSON, J. (1988): Simulation Model for thermally interacting heat extraction boreholes. - Numerical Heat Transfer 13, 149-165

[26] HELLSTRÖM, G. & SANNER, B. (1994): Software for dimensioning of deep boreholes for heat extraction. - Proc. 6th Int. Conf. Energy Storage CALORSTOCK 94, 195-202

[27] SANNER, B., HELLSTRÖM, G. (1996): "Earth Energy Designer", eine Software zur Berechnung von Erdwärmesondenanlagen. - Proc. 4. Geothermische Fachtagung Konstanz, GtV, 326-333

[28] BREHM, D.R. (1989): Entwicklung, Validierung und Anwendung eines dreidimen-sionalen, strömungsgekoppelten finite Differenzen Wärmetransportmodells. - Giessener Geologische Schriften 43, 120 p.

[29] HELLSTRÖM, G., SANNER, B., KLUGESCHEID, M., GONKA, T. & MÅRTENSSON, S. (1997): Experiences with the borehole heat exchanger software EED. - Proc. 7th Int. Conf. Energy Storage MEGASTOCK 97, 247-252

[30] SZAUTER, S. (1998): Untersuchungen der gegenseitigen Beeinflussung von EW-Sonden durch Grundwasserfluß bei dichter Bebauung. - 92 p., Dipl. thesis, Giessen University