Paper from International Geothermal Days USA 1999, Klamath Falls OR
organised by ISS, Skopje, Macedonia
(International Summer School on Direct Applications of Geothermal Energy)
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Introduction to Computer Models for Geothermal Heat Pumps

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ABSTRACT

Design of ground heat exchangers for heat pumps is increasingly done with the support of easy-to-use, fast computer programs. These programs vary widely in calculation approach and accuracy. This paper gives a short overview of the early development, and focuses mainly on programs based on the g-function-method. This method is a suitable compromise between rules-of-thumb and tables on one hand and time-consuming numerical simulation on the other hand. Other programs are also discussed briefly , and a study on the reliability of such programs is discussed.

KEYWORDS

Ground source heat pumps, borehole heat exchangers, design, calculation

Introduction

The correct sizing of ground heat exchangers, either horizontal or vertical, is crucial for the flawless operation of a ground source heat pump (GSHP). There are two main design situations for vertical loops (borehole heat exchangers, BHE):

- Maximum heating load for a short time on a cold winter day (and maximum cooling load in summertime), not exceeding an acceptable temperature drop (or increase) in the fluid.
- Long-term stability of the system; this is of particular importance in systems where the aggregate seasonal heating and cooling loads are unbalanced resulting in a large annual net heat extraction/rejection to the ground. In this case the natural heat transport in the ground is the only means of thermal recharge.

Practical use of heat transport calculation around pipes started with ALLEN (1920). The earliest approach to calculating thermal transport around a heat exchanger pipe in the ground was the Kelvin line source theory (INGERSOLL et al. 1948, INGERSOLL & PLASS 1948, INGERSOLL et al. 1950). PENROD (1954) described in 3 examples the use of this method for GSHP. A simplified version of the algorithm in INGERSOLL & PLASS (1948) was suggested by GUERNSEY et al. (1949). Converted to SI-units it reads:

$$\Delta T = \frac{0.1833\,Q}{\lambda}\left[\log_{10}\frac{\alpha\ t}{r^2} + 0.106\frac{r^2}{\alpha\ t} + 0.351\right]$$

The formula is valid only if $\frac{\alpha\ t}{r^2} > 1$. (Should the “>” be a “<” ???, I don’t have this reference.)

with: ΔT	Temperature change (at time t and radius r??)		(°C)
Q	heat flow per meter borehole length	(W/m)	
λ	Thermal conductivity of the ground	(W/m/K)	
α	Thermal diffusivity $\left[\alpha = \frac{\lambda}{\rho\, c}\right]$	(m^2/h)	
r	Distance from pipe center	(m)	
t	Time	(h)	

Design with these tedious calculations was seldom done in practice. The same happened with the numerical simulation approach in the 80s. Rules of thumb prevailed as the design method of choice. The first programs doing a reliable calculation and allowing easy use entered the stage at the end of the 80s, and came from Sweden. They are described in the following chapter.

Lund Programs

PC-programs for quick and reasonably sound dimensioning of ground heat systems with vertical earth heat exchangers have been presented by CLAESSON & ESKILSON (1988), CLAESSON et al. (1990), CLAESSON (1991) and HELLSTRÖM (1991). The algorithms have been derived from modeling and parameter studies with a numerical simulation model SBM (ESKILSON 1987; ESKILSON & CLAESSON 1988), evolving to an analytical solution of the heat flow with several functions for the borehole pattern and geometry (*g*-functions, see ESKILSON 1987). 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.

Several PC-programs have been established to cover different aspects of vertical earth heat exchangers. The most important programs are TFSTEP, DIM and INOUT. The programs are extremely fast and thus allow to try a variety of possible layouts. The simple spreadsheet input mask enabled experienced users to operate the programs easily for calculations with changing parameters. A major drawback in the use of the programs in the engineering practice was this input mask, which required good knowledge of values for input parameters and urged the user to do some calculation in advance. To make working with the Lund-programs easier, and to add other features, some more user-friendly programs have been developed on the same basis, e.g. GLHEPRO 2.0 (see www.igshpa.okstate.edu/Publications/catalog/1998/Sofware.html) and the program EED, which is described below.

EED

After first discussions in summer 1991, co-operative work on the programme began in June 1992, and was presented in 1994 (HELLSTRÖM & SANNER 1994), and the β-version distributed in summer 1995 (SANNER & HELLSTRÖM 1996). The new program EED combines features of TFSTEP and DIM. The calculation of brine temperatures is done 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 as in TFSTEP. The steps now are considered as 12 months, 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 are provided.

The program is written in Borland PASCAL. The user interface is an up-to-date menu technique with pull-down menus for input parameters, control of calculation and output. The borehole thermal resistance r_b is calculated in the program, using borehole geometry, grouting material and pipe material and geometry. The *g*-functions for borehole pattern can be browsed in a window, and the adequate function for the given layout is chosen directly. In TFSTEP and the early EED-versions, borehole distance was introduced through B/H-values, thus coupling it to borehole depth. This was a result of the geometrical nature of the *g*-functions. 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. The number of *g*-functions had to be increased considerably to allow this feature, and *g*-functions for smaller distances had to be added.

Calculations with EED were compared to numerical simulation, e.g. using the FD-code TRADIKON-3D (BREHM 1989), and a good agreement of predicted fluid temperatures was found (HELLSTRÖM et al. 1997). SZAUTER (1998) 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 thermal pattern shown in Fig. 1 was simulated. 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. The GSHP supplies heat to the chemical laboratory UEG, a building containing offices and labs. In summertime, cold brine from the BHE is used for direct cooling of the building (SANNER et al. 1996b). The plant is operational since spring 1992, monitoring started in July 1995. The monitoring revealed a considerable cooling demand even in winter, caused by some heat-generating installations like atom absorption spectometry (AAS).

Fig. 2 shows the monitored mean brine temperature from July 1995 - July 1996 in UEG, Wetzlar, 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. 2. 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. 3 do not match exactly due to the uncertainties, but EED gives a rather good prediction of the temperatures found in reality.

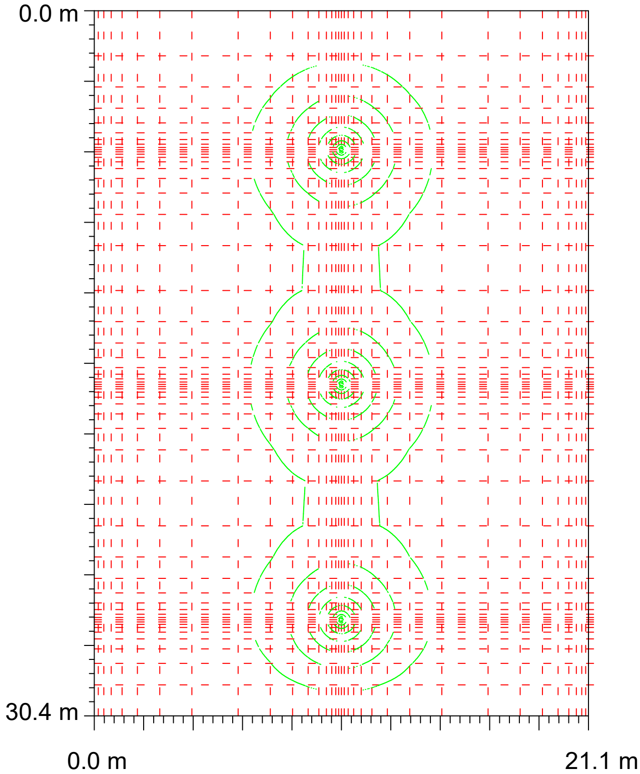

Figure 1: Temperature distribution (isotherm pattern) around 3 BHE, horizontal cross section in 50 m depth, after 8 month of winter operation (After SZAUTER 1998)

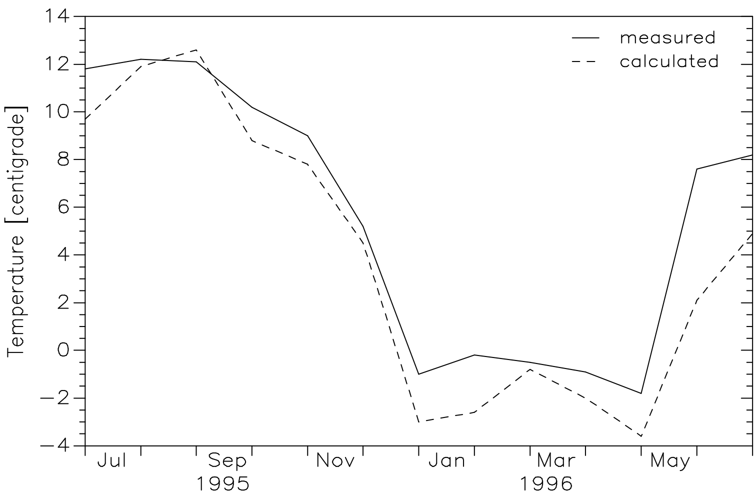

Fig. 2. Measured and calculated brine temperatures for UEG plant, Wetzlar (after HELLSTRÖM et al. 1997)

Non-Lund Programs - GchpCalc

KAVANAUGH (1984) developed a method that uses the cylindrical source solution and approximates the time varying nature of the heat extraction/addition to the ground using a steady state solution and effective thermal resistances. The basic method follows the approach of INGERSOLL et al. (1954) where cyclic pulses of heat from a line source are approximated. KAVANAUGH (1984) developed a solution for the cylindrical source and uses four cyclic load pulses (4 hour, daily, monthly, and annual). This method has been implemented in the software program GchpCalc and has been used widely within the United States for design of vertical ground-coupled systems (KAVANAUGH and RAFFERTY, 1997). In benchmarking comparisons (SHONDER and HUGHES, 1998; SHONDER et al., 1999) GchpCalc has proven to be amoung the most accurate programs (program C in both studies, see Figure 3 for results of one study). Like the "Lund" method, Kavanaugh's method allows for the thermal interaction of adjacent boreholes and the possibility for long term heat buildup/depletion within the ground. The method places no constraint on borehole separation distance and borehole depth. The thermal resistance of the piping, and especially any grout used in the borehole, has a major impact on the ability of the ground heat exchanger to transfer heat to the ground surrounding the borehole. The GchpCalc software allows the user to include these effects. The GchpCalc software also includes performance data for all major heat pump manufacturers in the United States.

The output from the GchpCalc software is the required borehole length in heating and a separate required length in cooling. Normally the longer of the two lengths is used for the design. However, if the required cooling length is significantly longer than the required heating length, not an infrequent occurrence in the United States, then a cooling tower may be designed to supplement the ground heat exchanger in the cooling mode and the shorter heating borehole length used in the design. A number of these so called "hybrid" systems have been constructed in the United States. PHETTEPLACE and SULLIVAN (1998) describe one such system and provide data gathered by monitoring its operation. For this system located in central Louisiana the heat rejected to the ground was 43 times greater than that extracted from the ground, even with the cooling tower operating approximately 30% of the time. PHETTEPLACE and SULLIVAN (1998) analyzed this system with the GchpCalc software and found that with the current borehole heat exchanger spacing of only 3 m the entering water temperature to the heat pumps could rise by as much as 8.3 °C after 10 years of operation. This assumes that there is no ground water flow to carry away the excess heat and thus it represents a worst case scenario. Increasing borehole heat exchanger spacing to 4.6 m would reduce the worse case temperature calculated by GchpCalc to 2.8°C and further increasing borehole heat exchanger spacing to 6.1 m would reduce the worse case 10 year temperature rise to only 1.1 °C.

The example above from PHETTEPLACE and SULLIVAN (1998) illustrates an important point: design models that account for thermal interaction of adjacent boreholes and long term heat buildup/depletion are essential when designing multiple borehole systems arranged in grid fashion. Ground water flow can reduce or eliminate the effects of long term heat buildup and borehole heat exchanger thermal interaction as well as enhance the performance of individual borehole heat exchangers. However, ground water flow information is seldom known and in addition none of the existing GSHP design programs account for this effect directly. The GchpCalc software provides the user with a borehole heat exchanger length calculated with no ground water flow assumed and a length calculated with high ground water flow assumed. The high ground water flow calculation assumes that no heat build up occurs beyond the annual cycle.

As noted above, the thermal resistance of grout or other backfill material used in the borehole has a major impact on the ability of the ground heat exchanger to transfer heat to the ground surrounding the borehole. Common grouts are often made with bentonite and have relatively low thermal conductivity, as well as the additional thermal disadvantage of impeding ground water flow (KAVANAUGH and RAFFERTY, 1997). Thus, their use should be minimized and where they must be used around major portions of the borehole heat exchanger, grouts with enhanced thermal conductivity should be used. ALLAN and KAVANAUGH (1999) predict that for a typical borehole heat exchanger (see reference for specifics of example) in a 100 mm borehole in soil with a thermal conductivity of 2.25 W/m•K that the necessary heat exchanger length would be increased by 22% by using a grout with a thermal conductivity of 0.84 W/m•K in place of a grout with a higher conductivity of 2.34 W/m•K. For larger boreholes, because the grout quantity is even higher, the effect is greater. ALLAN and KAVANAUGH (1999) predict that for the same borehole heat exchanger in a 150 mm borehole that the necessary heat exchanger length would be increased by 31% by using the same grout substitution. If the thermal conductivity of the surrounding soil is higher, the effect of the grout thermal conductivity will be even greater. For the same borehole heat exchangers and grout substitutions described above placed in soil with a thermal conductivity of 2.94 W/m•K, ALLAN and KAVANAUGH (1999) predict that in 100 mm bore the length is increased by 29% and in a 150 mm bore by 37%.

Other programs

Some other attempts have been made to develop easy-to-use design programs. Many have a focus on the heat pump design for residential houses, and treat the ground using empirical values, e.g.:

WDIM (see www.signsoft.de/germany/wdim/index.html)
CLGS (see www.igshpa.okstate.edu/Publications/catalog/1998/Sofware.html)

For saving computing time, analytical solutions have been tried (SMOLEN & SZAFLIK 1997). The line source concept is the basis for some computer codes, as GS2000 (Caneta Research, see www.geoexchange.org/dsgntool/grldes8.htm). An approach of combining numerical simulation of the direct surroundings of the BHE with other methods to determine the farfield is used by HUBER & SCHULER 1997 (see also www.igjzh.com/huber/bericht1/bericht1.htm).

Numerical simulation codes, mostly using the method of Finite Differences, have been developed in research organizations or specialized companies. Some examples are shown in Table 1. For most design purposes, these models are too difficult to use. To give a sound prediction they also require many input parameters of high accuracy, that normally are not available in the design phase. A survey within the Annex 8 of the IEA Energy Storage Programme recently investigated the suitability of some design tools (see www.sb.luth.se/vatten/projects/iea)

Table 1: Examples of numerical simulation models for ground heat transport

Name	Further information
COSUND / NUSOND	GILBY & HOPKIRK 1985, EUGSTER 1991
TRADIKON-3D	BREHM 1989, SANNER et al. 1996a
HST2D/3D	www.if-tech.nl/hsteng1.htm
SBM	ESKILSON 1987
TRNSYS with DST-module	HELLSTRÖM et al. 1996, PAHUD & HELLSTRÖM 1996

A report of the Geothermal Heat Pump Consortium (RP-003, Design Tools Benchmarking Study; see also: www.geoexchange.org/dsgntool/dsgn-dir.htm) lists the ground loop design software shown in Table 2.

Reliability of PC-programs for BHE design

The reliability of ground loop design programs is limited due to the simplifying assumptions necessary for fast calculation. In a study performed at Oak Ridge National Laboratory (SHONDER and HUGHES, 1998) several programs were tested against each other and against a simulation using TRNSYS with the BHE-module called DST (HELLSTRÖM et al. 1996). The versions of the design tools used in this study were those available in 1996.

Table 2: Software listed in the design tools benchmarking study of the Geothermal Heat Pump Consortium

Name	Source
GchpCalc	Energy Information Services, Tuscaloosa AL, USA
Lund programs	see above
GLHEPRO	IGSHPA, Stillwater OK., USA
CLGS	IGSHPA, Stillwater OK., USA
RIGHT-LOOP	Wright Associates, Lexington MA, USA
ECA	Elite Software Inc., Bryan TX., USA
WFEA	Water Furnace Int. Inc., Fort Wayne IN, USA
GS2000	Caneta Research Inc., Mississauga ON., Canada
GL-Source	Kansas Electric Utility, Topeka KS, USA
GEOCALC	HVACR Programs, Ferris State Univ., Big Rapids MI., USA

Fig. 3 shows the recommended heat exchanger lengths from the five design programs evaluated by SHONDER and HUGHES (1998) for various values of maximum entering water temperature in the heat pump cooling mode (Program C would not allow selection of entering water temperatures above ca. 37 °C). The wide variation in recommended loop length highlights the problem facing GSHP system designers. To take one example, if entering water temperature is to be limited to 35 °C, program A recommends a borehole depth of ca. 37 m and program D recommends 74 ft. In effect, the confidence interval is so large that it includes the entire bore depth. The study of SHONDER and HUGHES (1998) has recently been repeated and enhanced (SHONDER et al., 1999) with newer versions of the software packages used in the prior study and one additional software package. The conclusions from this most recent study are much more favorable, with the resulting borehole heat exchanger lengths varying by no more than approximately 7% at a cooling dominated site and 16% at a heating dominated site.

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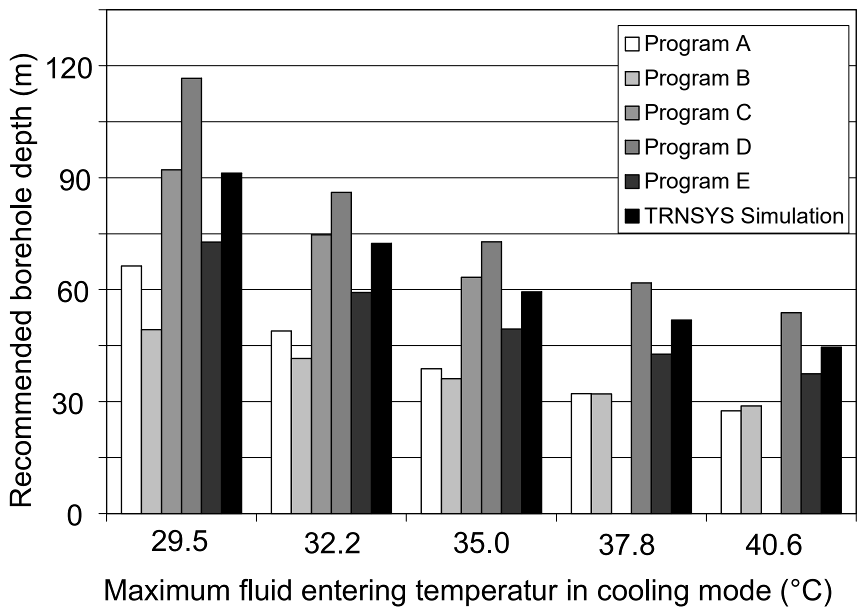

Figure 3: Results of comparison of BHE design programs (after SHONDER & HUGHES, 1998)

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