Paper from International Geothermal Days Germany 2001, Bad Urach
organised by ISS, Skopje, Macedonia
(International Summer School on Direct Applications of Geothermal Energy)
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PC-programs and modelling for borehole heat exchanger design

Göran Hellström[1] and Burkhard Sanner[2]

[1] Department of Mathematical Physics, Lund University of Technology
P.O.Box 118, S-22100 Lund, Sweden

[2] Institute of Applied Geosciences, Justus-Liebig-University
Diezstrasse 15, D-35390 Giessen, Germany

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.

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 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:

$$\Delta T = \frac{0.1833\,Q}{\lambda}\left[\log_{10}\frac{\alpha\ t}{r^2} + 0.106\frac{r^2}{\alpha\ t} + 0.351\right] \qquad [1]$$

The formula is valid only if $\frac{\alpha\ t}{r^2} > 1$.

with: ΔT	Temperature change at time t and radius r	(K)
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 (fig. 1) 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. the program EED, which is described below, and GLHEPRO (Spitler, 2000; see also http://www.mae.okstate.edu/Faculty/spitler/glhewin/glhepro.html)

Earth Energy Designer - 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 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.

```
Program TFSTEP : Fluid temperature Tf (°C) for a step-wisely varying
heat extraction (with maximum 12 steps with periodic repetition)
--------------------------------------------------------------------------
Name of g-function: 4 boreholes in a line, B/H = 0.1, THETA = 0
                                                      tn        qn (W/m)
Active borehole length, H      60.0        (m)
                                                  --------------------
Borehole radius, rb            0.08        (m)        0m           6.1
Thermal conductivity, lambda   2.21        (W/(mK))   1m           12.2
Volumetric heat capacity, C    1870000.0   (J/(m3K))  2m           21.4
Undist. ground temp, Tom       10.0        (°C)       3m           30.6
Borehole therm. resist., Rb    0.1         (K/(W/m))  4m           24.6
Period time, tp                1y                     5m           12.2
Print-out time, tprint         1m                     6m           3.0
                                                      7m           0.0
                                                      8m           0.0
                                                      9m           0.0
                                                      10m          0.0
                                                      11m          0.0
Distance between the boreholes,    B =     6.00  m
Average fluid temperature,        Tf =     7.836 °C
--------------------------------------------------------------------------
F1 Save  F2 Read       g-function: F3 List  F4 Read    Enter Run  Esc Quit
```

Fig. 1: Input- and output mask of program TFSTEP (s. text)

The user interface of version 1.0 used a menu technique with pull-down menus for input parameters, control of calculation and output, which was up-to-date under the DOS-environment. Input and control for Version 2.0 now is adapted to standard Windows practice (fig. 2). 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 patterns can be browsed in a window, and the adequate function for the given layout is chosen directly (fig. 3). 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.

Fig. 2: *Start screen of EED 2.0 (the photo shows the pipe connections of the 400-BHE-field at Richard Stockton College, New Jersey)*

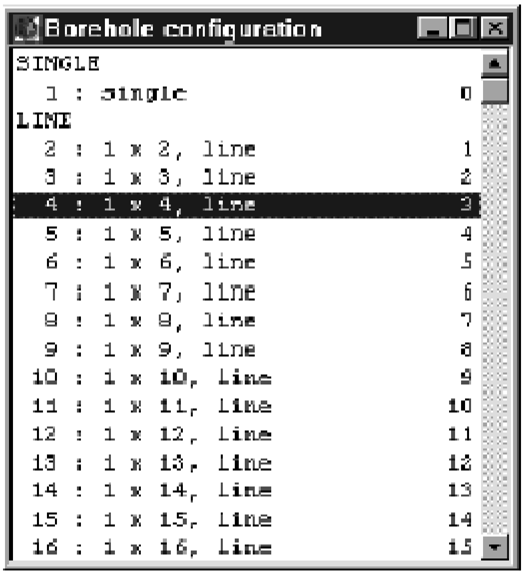

Fig. 3: *EED-Window for selection of borehole pattern (g-function); first row is total number of boreholes in pattern, last row is number of g-function*

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. 4 shows an example.

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 temperature development in the ground was simulated (fig. 5). 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.

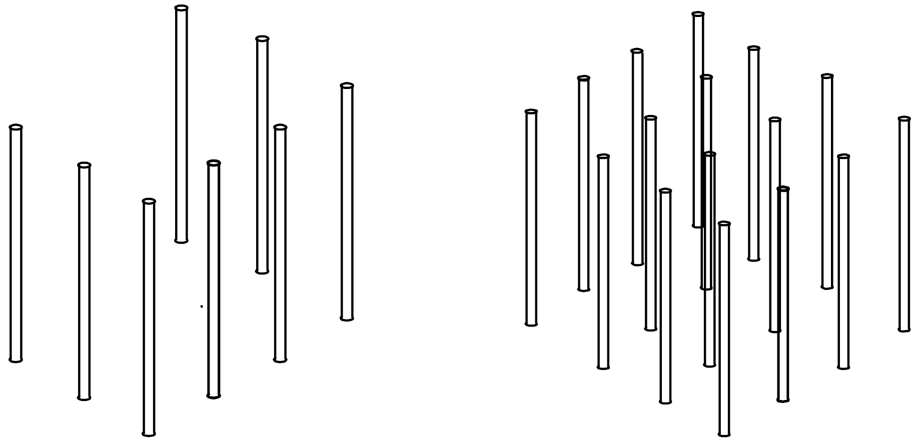

Fig. 4: *Examples of g-functions*
left: U-configuration, 3 x 4 boreholes, total 8 boreholes, g-function no.112
right: Filled rectangular config., 4 x 4 boreholes, total 16 boreholes, no. 262

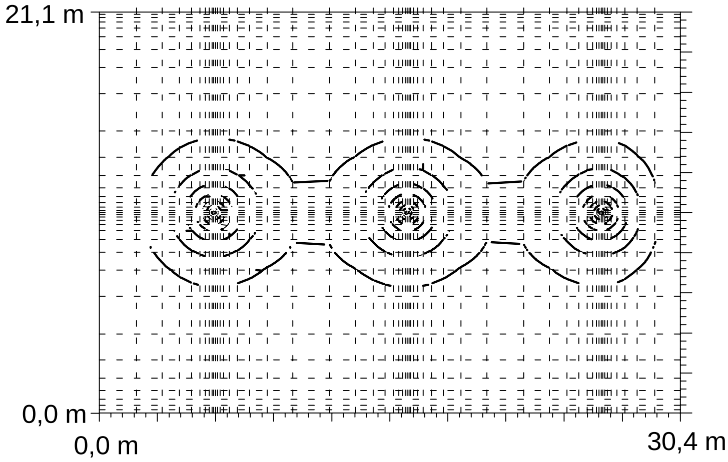

Fig. 5: *Temperature distribution (isotherms) around 3 BHE, horizontal cross-section in 50 m depth, after 8 month heating, with FD-grid (after Szauter, 1998)*

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 spectrometry (AAS).

Fig. 6 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. 6. 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. 6 do not match exactly due to the uncertainties, but EED gives a rather good prediction of the temperatures found in reality.

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 resistance. 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 & Rafferty, 1997). In benchmarking comparisons (Shonder & Hughes, 1998; Shonder et al., 1999) GchpCalc has proven to be among the most accurate programs (program C in both studies, see fig. 7 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.

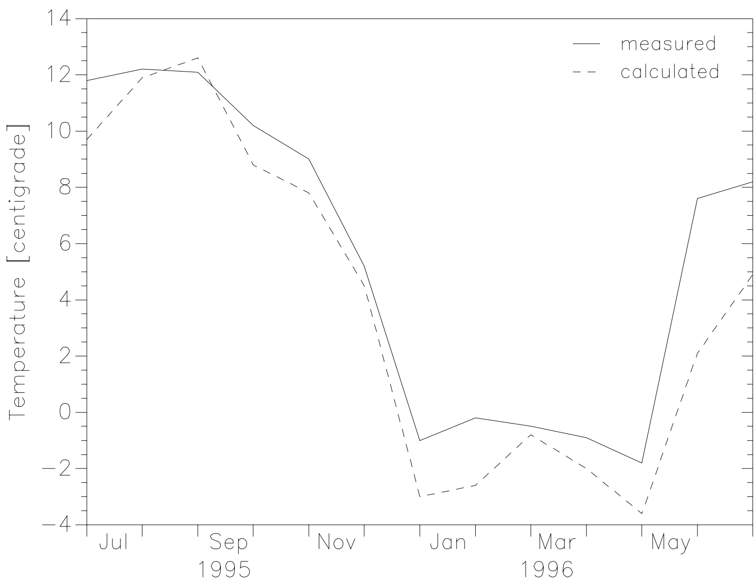

Fig. 5: Measured and calculated brine temperatures for UEG plant, Wetzlar (after Hellström et al., 1997)

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, 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. Phetteplace & Sullivan (1998) describe one such „hybrid" system and provide data gathered by monitoring its operation. They analysed the 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. 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. This example 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.

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 only; these programmes do not qualify for design of larger BHE fields.

For saving computing time, analytical solutions have been tried (Smolen & Szaflik, 1997). The line source or the cylinder source concept is the basis for some computer codes, as GS2000 (Caneta Research, see Morrison, 2000). 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).

Numerical simulation codes, mostly using the method of Finite Differences, have been developed in research organisations or specialised 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.

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	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 Tab. 2.

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

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 & Hughes, 1998) several programs used in North America 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.

Fig. 7 shows the recommended heat exchanger lengths from the five design programs evaluated by Shonder & 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. The study 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 study are more favourable, 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.

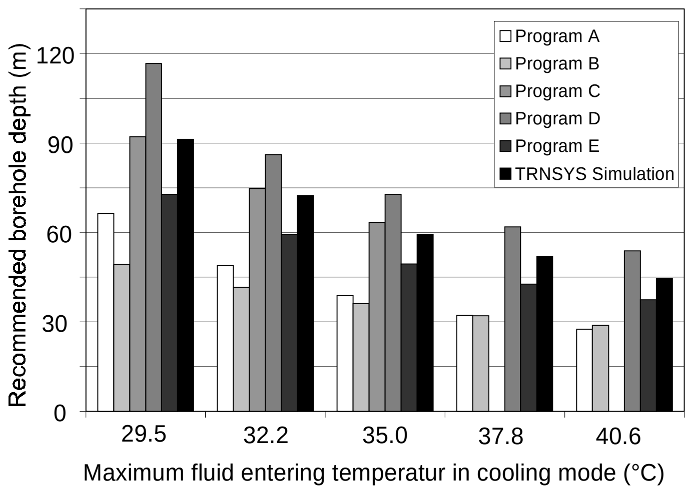

Fig. 7: *Results of comparison of BHE design programs (after Shonder & Hughes, 1998)*

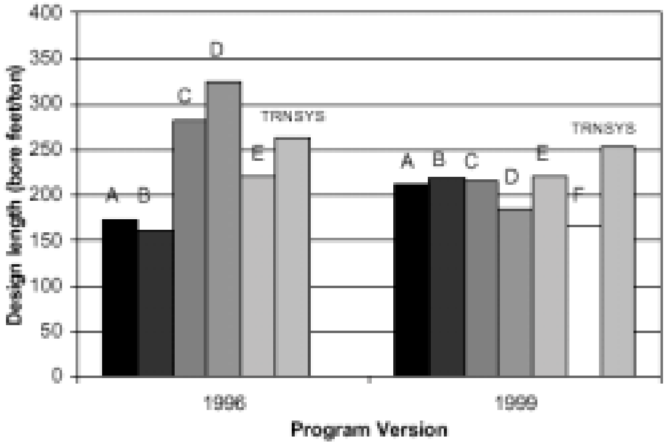

Fig. 8: *One-year design lengths for maximum entering fluid temperature of 35 °C for the cooling-dominated residential benchmark, 1996 and 1999 versions of design programs (from Shonder, 2000)*

The reliability of the US-programs is increasing further. In the latest benchmark test (fig. 8), Shonder (2000) writes: “A 1996 comparison for a cooling-dominated residential application using early versions of the software showed wide disagreement: the variation among the five programs tested was about 30% of the mean value of the five. By 1999, however, new versions of the programs had been produced, and this variation had been reduced to about 11% of the mean.“

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