

THERMAL PERFORMANCE OF BOREHOLE HEAT EXCHANGERS

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ABSTRACT

An important issue in the design of systems using borehole heat exchangers is to find cost-effective methods to construct the borehole heat exchanger so that heat can be injected or extracted from the ground without excessive temperature differences between the heat carrier fluid and the surrounding ground. This paper presents an overview of experiences and current activities in this field.

1. INTRODUCTION

The interest in using the ground as a source or storage device for thermal energy has grown considerably in the last few years. Ground-coupled heat pumps for domestic heating are now a standard option endorsed by national energy agencies to reduce primary energy consumption. For single-family houses and other small-scale applications the objective is basically to use the natural ground temperature as a heat source during the heating mode and as a recipient of heat during the cooling mode. The ensuing change of ground temperature around the boreholes should be kept small in order to avoid reduced performance of the system. A maximum thermal interaction with the surrounding ground is desired, since the intention is to *dissipate* the thermal energy in the ground. A new application of this type of system is the all-year or summer cooling without heat pump of telecommunication equipment in Sweden (Hellström and Gehlin, 1997). The ground is also used for *storage* of thermal energy (Underground Thermal Energy Storage) in which case the thermal interaction with the ground surrounding the storage volume ground is undesirable. Applications involve seasonal storage of solar heat, surplus cogeneration heat, winter cold, etc. Some of the most profitable applications use seasonal storage of both heat and cold. Large-scale applications of ground-coupled heat pumps with closely spaced boreholes in the US are in principle UTES applications.

A common interest in both dissipative and storage type applications is to develop cost-effective designs of the borehole heat exchanger where excessive temperature differences between the heat carrier fluid and the store can be avoided. This paper will specifically address the thermal performance.

2. FLUID-TO-GROUND THERMAL RESISTANCE

The heat transfer between the heat carrier fluid and the surrounding ground depends on the arrangement of the flow channels, the convective heat transfer in the ducts, and the thermal properties of the materials involved in the thermal process. The thermal resistances associated with these different parts may be assembled to form a fluid-to-ground thermal resistance. The two major parts of this resistance are the thermal resistance between the heat carrier fluid and the borehole wall, which is commonly called the *borehole thermal resistance*, and the thermal resistance of the surrounding ground from the borehole wall to the some suitable average temperature level. This temperature level is often chosen to be the natural undisturbed ground temperature in systems of the dissipative type, whereas the local average ground temperature is more appropriate in storage applications. The influence of the borehole thermal resistance may in conventional designs become relatively large. Especially crucial are applications with high demands on heat injection rates and high temperatures such as solar heating systems and other low temperature applications with high demands on achieving high heat transfer rates at small temperature differences.

2.1 Ground Thermal Resistance

The ground thermal resistance involves the surrounding ground from the borehole wall to some suitable average temperature level. This temperature level is often chosen to be the natural undisturbed ground temperature T_0 in systems of the dissipative type, whereas the local average ground temperature T_m is more appropriate in storage applications.

2.1.1 Dissipative Type Applications

For dissipative type applications, the thermal process in the ground has a genuine transient behavior that has to be accounted for. It is convenient to consider the thermal response due to a step-change in specific heat injection rate q (W/m) given per unit length of the borehole and to associate the temperature evolution with a time-dependent ground thermal resistance R_g , so that $T_b - T_0 = q \otimes R_g$. Thereby the unit of the ground thermal resistance R_g becomes K/(W/m).

In the absence of regional groundwater flow, the heat conduction in the radial direction from the borehole dominates. Vertical effects, in particular the influence of the boundary conditions at the ground surface, can often be neglected for the initial 5-10 years (depending on the borehole depth). The thermal interaction between boreholes in multiple-well applications may be rather small during the first year(s) if large borehole spacings are used, but it will gradually develop and reduce the efficiency of the borehole heat exchanger. The behavior of thermally interacting boreholes was analyzed by Eskilson (1987) and are accounted for in design software such as GLHEPRO (Manickam et al, 1997) and EED (Hellström and Sanner, 1997) for ground-coupled heat pumps.

The influence of regional groundwater flow has so far not been analyzed in great detail. An analytical solution for steady-state conditions during heat injection from a single borehole into a medium with a constant horizontal flow rate has been derived by (Claesson and Eskilson, 1988). Assuming that the groundwater affects the whole borehole length, the ground thermal resistance (for the longterm behavior) is reduced by 10 % at a darcy flow of 1 m/year. Numerical simulations by Poppei et al (1996) show significant regeneration of thermal energy at this flow rate.

2.1.2 Storage Type Applications

A certain ground region can be assigned to each ground heat exchanger due to symmetry. The temperature in this ground region is called the local average temperature T_m . The thermal resistance R_g between the temperature T_b in the borehole wall and the local average temperature T_m is defined by $T_b - T_m = q \odot R_g$. For heat injection and extraction pulses with a duration of about a week or more, the thermal interaction between adjacent boreholes is fully developed. Short-term variations, where the thermal interaction often can be neglected, are superimposed on this process. Explicit, relatively simple, formulas for the ground thermal resistance have been derived for several types of borehole heat exchangers (Hellström, 1991).

The ground thermal resistance depends on the borehole spacing, which usually is intended to be uniform throughout the storage volume. In reality, the deviations from the intended drilling directions will result in an irregular distribution of the boreholes in the store. Analytical studies show that the influence of an irregular borehole spacing should be small if the storage volume is about the same (Hellström, 1991). The influence has also been investigated in numerical simulation studies of two Swedish field experiments. The first study concerns a large-scale heat store in Luleå where 120 (10×12) vertical boreholes were drilled in crystalline rock to a depth of 65 m (Nordell, 1990). The boreholes are placed in a quadratic pattern with a spacing of 4 m. The mean deviation in the horizontal plane at a depth of 65 m was 5.7 m. A simulation was performed where *all* boreholes deviated 5.7 m in random directions at a depth of 65 m. The amount of injected energy was reduced by about 2 % compared with vertical boreholes. In Luleå it is probably less than 1 % since the deviation is more or less in the same direction. The second case concerns a heat store with 25 (5×5) boreholes in Stockholm (Olsson, 1989). The design specifies a borehole spacing of 2 m at the ground surface and diverging to 5 m at the bottom of the store at 80 m. Borehole measurements revealed that the store's center of gravity at a depth of 80 m moved about 9 m in the horizontal plane. The average deviation with respect to the new center of gravity was 4.4 %. The effective storage volume became slightly smaller than planned. Simulations showed that both the injected energy and the extracted energy for the realized store were about 3 % lower than for the design case. This is to a large extent a result of the reduced storage volume.

Ground water movement through the storage region may significantly increase the losses of thermal energy. There may be both regional flow, caused by hydraulic gradients at the site of the store, and natural convection induced by the increased temperatures in the storage region. A numerical study by van Meurs (1985) concerning a porous medium with homogeneous hydraulic

properties indicates that a heat store requires a protecting hydraulic screen if the ground water flow exceeds 0.05 m/day (≈ 20 m/year). The geothermal well field at Richard Stockton State College of New Jersey penetrates through several aquifers with high groundwater flow. The effect of this groundwater flow is currently being investigated (Pal et al., 1997). Ground water flow in crystalline rock takes place through fissures and fractured zones within the rock mass. The magnitude of the ground water flow becomes very site-specific and a general statement about the influence on the thermal behavior of the heat store is difficult to make.

The heating of a water-saturated ground material will induce natural convection due to the temperature-dependent density of water. Buoyancy flow will cause warmer water with lower density to flow upwards. For a ground heat store in a porous medium the natural convection currents will be most pronounced at the vertical boundaries of the store. The magnitude of the buoyancy flow depends primarily on the temperature levels of the store and the surrounding ground, the horizontal and vertical permeability of the ground material, and the vertical extension of the store (Hellström et al., 1988). Numerical studies (van Meurs, 1985; Lund, 1985) show that, under normal applications, the thermal performance of the store will be affected if the intrinsic permeability of the ground exceeds 10^{-12} m^2 . However, the presence of impermeable horizontal layers, will reduce the natural convection.

2.2 Borehole Thermal Resistance

The thermal resistance R_b (K/(W/m)) between the heat carrier fluid in the borehole and the borehole wall is defined by $T_f - T_b = q \cdot R_b$. The temperatures of the fluid and the borehole wall are denoted T_f and T_b respectively.

2.2.1 Heat Transfer Between Flow Channels

The fluid temperatures along the flow channels will vary in accordance with the heat balance between the axial convective heat transport and the transverse heat transfer to the surrounding ground. The temperature difference that arise between the upward and the downward channels may become large at low flow rates. The ensuing heat exchange between the channels of opposing flow may lead to a reduced efficiency of the ground heat exchanger. Formulas for an effective borehole thermal resistance that includes the effects of the fluid temperature variation and the internal heat exchange have been derived for the cases of uniform heat flux and uniform temperature along the borehole (Hellström, 1991). For conventional U-pipe borehole heat exchangers, these effects are usually important when the flow is laminar or when the borehole depth exceeds 200 m.

3. BOREHOLE WITH ANNULAR DUCT

The most simple arrangement of the flow channels in a borehole heat exchanger is to insert a single plastic tube to the bottom of the borehole. The annular region between the plastic tube and the borehole wall provides the channel for the returning flow. This type of open borehole heat exchanger is very favorable from a heat transfer point-of-view because the heat transfer fluid can

be in direct contact with the borehole wall. It was used in the high-temperature borehole heat store in Luleå (see section 2.1.2). No measures were taken to keep the inner pipe the center of the borehole, so the pipe will most likely have an eccentric position. Heat carrier fluid temperatures ranged between 20 C and 82 C. The borehole thermal resistance during periods with turbulent flow conditions ($Re \approx 9000$) was verified to be very low (≈ 0.01 K/(W/m)). During the extraction periods, the fluid flow rate was lowered and approached laminar conditions. In combination with the eccentric position of the inner pipe, these conditions reduced the amount of extracted energy by 30-35 % (Nordell, 1990). No geohydrological and geochemical problems, such as mineral depositions in the heat exchangers, were observed.

However, a closed system is often required due to geochemical concerns or required because of unstable borehole walls. A closed annular duct can be realized by lining the borehole with an impermeable material. Inserting and cementing stiff PVC-liners in boreholes are rather difficult and expensive compared to U-pipes, so this method has only been used a few times in relatively shallow boreholes (both in crystalline rock, limestone and clay). In Stocksundstorp, Sweden, an experiment is performed to investigate the benefits of using a flexible rubber liner, which after insertion will be pushed against the borehole wall. Preliminary tests have experienced severe leakage problems.

In Central Europe, several "dry wells" intended for geothermal exploration have been converted to very deep heat extraction boreholes. The maximum depth is close to 3,000 m. An annular duct with an insulated inner pipe is used in order to make use of the increasing temperatures with depth and to avoid heat exchange between the two channels over this great length.

4. BOREHOLE WITH U-PIPE

The usual method to achieve the heat exchange in a borehole is to insert one or more U-shaped loops of polyethylene tubing into the borehole. Single U-pipes are used in Northern Europe and North America, whereas double U-pipes are common in Central Europe. In Northern Europe, the boreholes are usually filled with groundwater to a few meters below the ground surface. In the US and in Central Europe it is common practice, and sometimes required, to backfill the boreholes with some material such as bentonite, concrete, quartz sand, etc. Special mixtures, so-called thermally enhanced grouts, have been developed to provide for better heat transfer than pure bentonite (Remund and Lund, 1993).

4.1 Grouted Boreholes

In the absence of natural convection, moisture flow and freezing, the borehole thermal resistance can be analyzed as a process involving steady-state heat conduction in the region between the fluid in the pipes and a suitably chosen cylinder around the borehole. A so-called multipole method to compute the steady-state conductive heat flows to and between pipes in a borehole cylinder has been developed by Bennet et al. (1986). The pipes may be placed at arbitrary locations. The exact analytical model gives a precise estimate of the borehole thermal resistance

and the thermal resistances between the pipes. Explicit formulas with high accuracy for the single U-pipe have been derived from the first-order multipole expansions (Hellström, 1991).

Figure 1 shows the temperature field around a single U-pipe during injection of 50 W per meter borehole. The temperature inside the pipes is 13.6 C when the ground temperature is kept at 0 C at a radius of 0.3 meter from the center of the borehole. The borehole thermal resistance becomes 0.100 K/(W/m). The corresponding case for a double U-pipe (pipe diameter 0.032 m) is shown in Figure 2. The pipe temperature is now 11.4 C and the borehole thermal resistance is 0.056 K/(W/m).

The most important parameters influencing the borehole thermal resistance are the thermal conductivity of filling material, the number of pipes, pipe position and the pipe thermal conductivity. Figure 3 shows the borehole thermal resistance for a single U-pipe as a function of filling material thermal conductivity for three different positions. The range of thermal conductivity for different filling material are: stagnant water (0.6), bentonite (0.8-1.0), thermally enhanced grouts with quartz (1.0-1.5), pure water-saturated quartz sand (1.5-2.0), ice (2.3) and bentonite with graphite (3.0). Pure quartz sand has been successfully poured down into 60 m deep boreholes in Switzerland (Pahud 1993). Bentonite with graphite has been considered as sealing material for nuclear waste repositories in Sweden. In the US, Paul (1996) have completed a study that points to significant advantages of thermally enhanced grouts on design, costs and heat pump performance in ground-coupled heat pump systems.

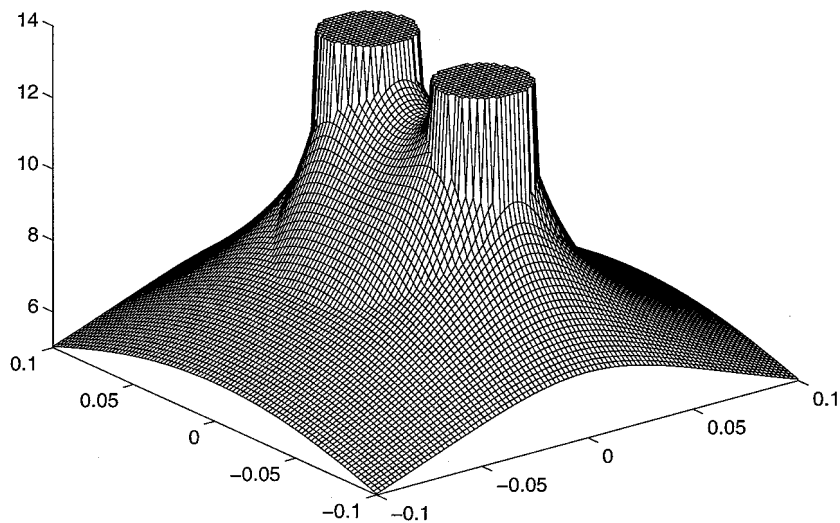


Figure 1. The temperature field (vertical axis) in a horizontal plane around a single vertical U-pipe (pipe diameter 0.040 m, borehole diameter 0.115 m, grout thermal conductivity 1 W/(m,K), ground thermal conductivity 2 W/(m,K)) during injection of 50 W per meter borehole.

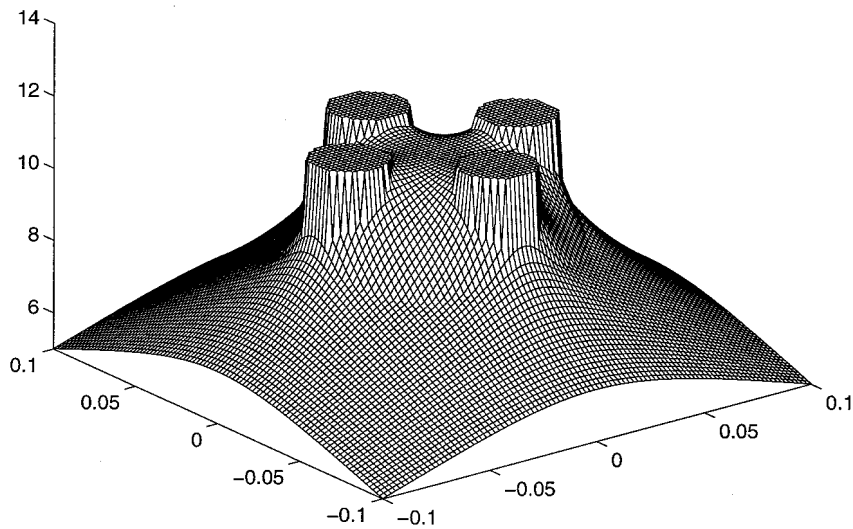


Figure 2. The temperature field (vertical axis) in a horizontal plane around a double vertical U-pipe (pipe diameter 0.032 m, other conditions as in Fig. 1) during injection of 50 W per meter borehole.

The thermal resistance of the pipe material and the convective heat transfer inside the pipe have to be kept low. The contribution to the total borehole thermal resistance is quite large for single U-pipes of polyethylene, but usually decreases with number pipes in the borehole. Copper tubes have been used in applications involving direct expansion heat pumps, but there are concerns about the long-term durability. Efforts are being made to reduce the thermal resistance of polyethylene tubing by adding substances that will give higher thermal conductivity or permit a thinner wall. A few cases have been reported where freezing groundwater in the borehole has squeezed the U-pipe and severely restricted the flow of the heat carrier fluid. In unsaturated media there may also be problems with moisture transport causing a dry zone with poor heat transfer around the pipes.

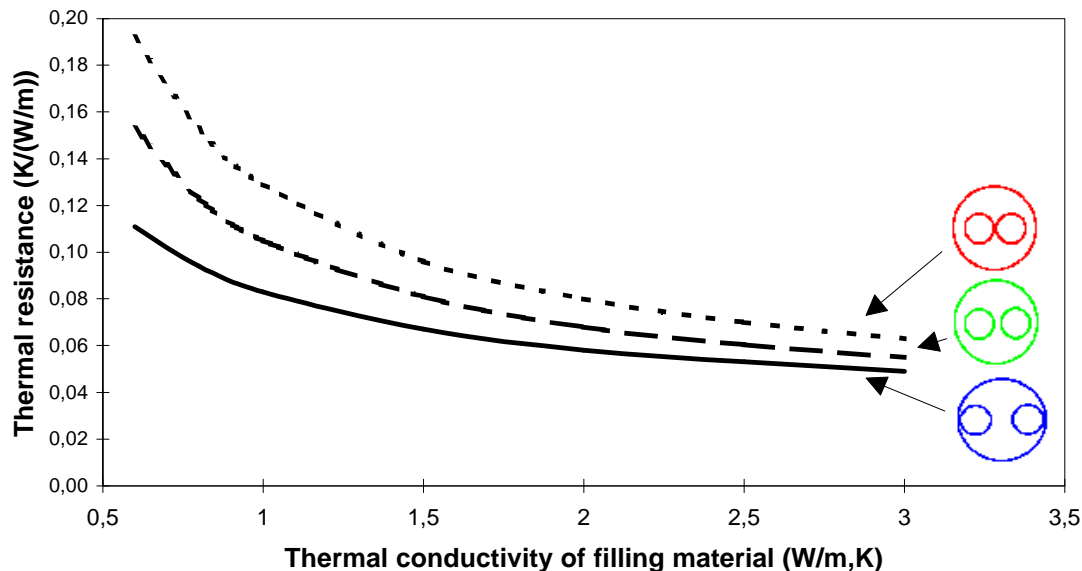


Figure 3. The borehole thermal resistance (K/(W/m)) for a single U-pipe as a function of filling material thermal conductivity (W/m,K) for three different positions of the U-pipe shanks.

In a large single-family house in Zürich, Switzerland, a new type of borehole heat exchanger has been installed (Kapp, 1997). Two boreholes (diameter 0.16 m) have been drilled to 100 m depth. The heat carrier fluid flows to the bottom of a borehole through a coaxial insulated pipe (diameter 0.060 m) and returns to the surface through eight smaller pipes (polyethylene, diameter 0.020 m) equally spaced along the borehole wall. The space between the coaxial and the peripheral pipes is filled with bentonite. Preliminary measurements show better heat transfer than conventional designs. Estimates based on the MPC model indicate a borehole thermal resistance of 0.03 K/(W/m), which is lower than for a single U-pipe (0.11 K/(W/m)) or a double U-pipe (0.06 K/(W/m)) under similar circumstances. The extra costs of multiple U-pipes and thermally enhanced grout have to be compared with savings in borehole length or improved system performance.

4.2 Groundwater-Filled Boreholes

In the case of a water-filled borehole, the heat transfer will induce natural convection. A laboratory experiment is currently performed at Lund University to investigate the influence of different pipe materials (polyethylene and copper), pipe geometry at high fluid temperature levels (15-45 C) and large specific heat transfer rates (50-100 W/m) (Kjellsson and Hellström, 1997). The laboratory test equipment consists of an outer steel cylinder with a vertical extension of 3 m and a diameter of 0.4 m. The envelope of the cylinder is maintained at a given temperature by a cryostat-controlled circulating fluid. The borehole wall is represented by an inner, concentric

plastic pipe with an inner diameter of 0.117 m. The annular ground region between the borehole and the steel cylinder is filled with of a mixture of fine sand and water. The measurements for the case of a single U-pipe (diameter 0.040 m and 0.032 m) and double U-pipe (diameter 0.032 m) of polyethylene, and a single U-pipe of copper (diameter 0.025 m).

This experiment shows that natural convection has a small effect at low temperatures and low heat injection rates, which agrees with field experiences from heat extraction boreholes. Yet, the influence was large at high temperatures and large heat injection rates; the convective heat transfer was at most about 3-5 times higher than the estimated heat transfer for pure conductive heat transfer through stagnant borehole water. The results imply that the borehole thermal resistance for U-pipe installations may become relatively low at high temperature applications.

The groundwater movement in a borehole can become quite intricate depending on extent of the possible flow paths between interconnecting natural cracks and the borehole. Heat transfer to the borehole water changes the hydrostatic equilibrium and may induce siphon type circulation through the borehole. In a dissipative system, small-scale and large-scale natural convection and regional flow may contribute to improve the performance, whereas in a storage type of system they may improve the heat transfer from the borehole to the store but also increase the thermal energy losses.

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REFERENCES

Bennet, J., Claesson, J., and Hellström, G, (1987). Multipole Method to Compute the Conductive Heat Transfer to and between Pipes in a Composite Cylinder. Notes on Heat Transfer 3-1987, Department of Building Physics, Lund Institute of Technology, Box 118, S-221 00 Lund, Sweden.

Claesson, J., and Eskilson, P., (1988). Conductive Heat Extraction by a Deep Borehole, Thermal Analyses and Dimensioning Rules, Energy, Vol. 13, No. 6, pp. 509-527.

Eskilson, P., (1987). Thermal Analyses of Heat Extraction Boreholes. Ph.D. Thesis. Department of Mathematical Physics, Lund Institute of Technology, Box~118, S-221~00 Lund, Sweden.

Hellström, G., (1991). Ground Heat Storage, Thermal Analyses of Duct Storage Systems, Part I: Theory (thesis). Mathematical Physics, Lund.

Hellström., G., and Gehlin, S., (1997). Direct Cooling of Telephone Switching Stations Using a Borehole Heat Exchanger, Proc. of 7th Int. Conf. on Thermal Energy Storage, Megastock'97, June 18-21, 1997, Sapporo, Japan, pp.509-514.

Hellström, G., Tsang, C.F., and Claesson, J., (1988). Buoyancy Flow at a Two-Fluid Interface in a Porous Medium: Analytical Studies, Water Resources Research, Vol. 24, No.4, pp. 493-506.

Hellström, G., and Sanner, B., (1997). EED - Earth Energy Designer, version 1.0, User's Manual, Prof. Dr. Knoblich & Partner GmbH, Virchowstrasse 4, D-35578 Wetzlar, Germany.

Kapp, C., (1997). Neuartige Erdwärmesonden mit deutlich besserem Wärmeübergang - erste Erfahrungen aus der Praxis. 3. Symposium "Erdgekoppelte Wärmepumpen - Systeme zum Heizen und Kühlen, November 20-22, 1997, Schloss Rauschholzhausen, Justus-Liebig-Universität, Giessen, Germany.

Kjellsson, E., and Hellström, G., (1997). Laboratory Study of the Heat Transfer in a Water-Filled Borehole with a Single U-pipe, Proc. of 7th Int. Conf. on Thermal Energy Storage, Megastock'97, June 18-21, 1997, Sapporo, Japan, pp.509-514.

Lund, P., (1985). Effect of Ground Water Flow on the Performance of Long-Term Pipe Heat Storage in the Ground, Report TKK-F-A586 (1985), Helsinki University of Technology, Finland.

Manickam, A., Dharapuram, M., Delahoussaye, R.D., and Spitler, J.D., (1997). GLHEPRO for Windows, The Professional Ground Loop Heat Exchanger Design Software, Version 2.02., International Ground Source Heat Pump Association, Stillwater, Oklahoma, USA.

van Meurs, G.A.M, (1986). Seasonal Heat Storage in Soil, thesis, Dept. of Applied Physics, University of Technology Delft, P.O.Box 5046, 2600 GA Delft, Netherlands.

Nordell, B., (1990). A Borehole Heat Store in Rock at the University of Luleå. The Lulevärme project 1982-1988. Document D12:1990, Swedish Council for Building Research, Stockholm.

Olsson, U., (1989). Simulering av bergvärmelager i kvarteret Höstvetet. (Simulation of a bedrock heat store. The Höstvetet project. In Swedish). Royal Institute of Technology, Stockholm, Sweden.

Pahud, D., (1993). Etude du Centre Industriel et Artisanal, Marcinhès à Meyrin (GE), Rapport final, septembre 1993, Groupe de Physique Appliquée de l'Université de Genève, Genève.

Pal, S., Epstein, C., Stiles, L., Taylor, H., Mowbray, C., and Pena, L., (1997). Simulation of Large Geothermal Field, Proc. of 7th Int. Conf. on Thermal Energy Storage, Megastock'97, June 18-21, 1997, Sapporo, Japan, pp. 121-126.

Paul, N.D., (1996). The Effect of Grout Thermal Conductivity on Vertical Geothermal Heat Exchanger Design and Performance, M.Sc. thesis, South Dakota University.

Poppei, J., Kabus, F., Fischer, D., Lenz, G., and Hoffmann, F., (1996). Erarbeitung eines Konzeptes zur Ermittlung von Auslegungskriterien für Erdwärmesonden in Mecklenburg-

Vorpommern unter Berücksichtigung lokaler geologischer und hydrogeologischer Verhältnisse, Geothermie Neubrandenburg GmbH, Lindenstrasse 39, D-17033 Neubrandenburg, Germany.

Remund, C.P., and Lund, J.T., (1993). Thermal Enhancement of Bentonite Grouts for Vertical GSHP Systems, AES-Vol., 29, Heat pump and Refrigeration Systems, Design, Analysis, and Applications, ASME.