

DOCTORAL THESIS

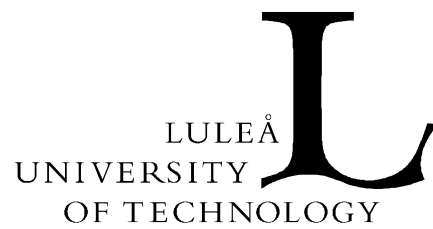
Thermal Response Test

Method Development and Evaluation



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Cover picture: TED during measurement in Karlstad, Sweden
Photo: Signhild Gehlin

The Road goes ever on and on
Down from the door where it began
Now far ahead the Road has gone
And I must follow, if I can
Pursuing it with eager feet
Until it joins some larger way
Where many paths and errands meet
And whither then? I cannot say

The Road goes ever on and on
Out from the door where it began
Now far ahead the Road has gone
Let others follow it who can!
Let them a journey new begin
But I at last with weary feet
Will turn towards the lighted inn
My evening-rest and sleep to meet

J.R.R Tolkien

*To Nina, with whom it all began
To Johan, my beloved brother
To Peter, who never stopped believing in me
To Elna, for being my kindred spirit*

SUMMARY

Thermal response tests with mobile measurement devices were first introduced in Sweden and USA in 1995. Since then the method has developed and spread to several other countries in North America and Europe. A variety of analytical and numerical data analysis models have been developed. Various applications of the line source theory is the most commonly used model for evaluation of the response test data because of its simplicity and speed, and is dominant in Europe. The use of the cylinder source model and numerical models coupled with parameter-estimation techniques are common in USA. Thermal response tests have so far been used primarily for in situ determination of design data for BHE (borehole heat exchanger) systems, but also for evaluation of grout material, heat exchanger types and groundwater effects.

The Swedish response test apparatus TED has been used at a number of tests since 1996. The main purpose has been to determine in situ values of effective ground thermal conductivity, including the effect of groundwater flow and natural convection in the boreholes. The tests indicate that convective heat transfer may play an important role for the thermal behaviour of groundwater-filled BHE, which is the typical BHE design in Sweden. The magnitude of the induced natural convection depends on the heat transfer rate and the temperature level. The influence is small on grouted boreholes.

To shed light on the influence of groundwater flow on thermal response testing, simulation models for estimating the heat transfer effect of groundwater flowing near a borehole heat exchanger were developed. The groundwater flow was represented as 1) a flow through an equivalent porous medium (continuum), 2) a flow through an impermeable medium with a porous zone, and 3) a flow through an impermeable medium with a thin vertical fracture. The three cases result in significantly different temperature field patterns around the borehole and all three cause lower borehole temperatures. The fracture flow model results in higher effective thermal conductivity than the continuum and porous zone models within a certain flow rate interval. This illustrates the efficiency of the high flow velocity in the fracture and the large temperature gradient between the borehole and the fracture flow. The effect of the flow in the fracture or porous zone decreases with the distance from the borehole, but even at distances of half a meter or more the porous zone or fracture may result in significantly enhanced heat transfer. Even a relatively narrow fracture close to a borehole may result in greater effective thermal conductivity, although estimations for the same flow rate made with a continuum approach may indicate otherwise.

A thermal response test is likely to induce a thermosiphon flow due to the temperature difference between borehole and surroundings, resulting in enhanced effective thermal conductivity estimation. The enhancement of the effective thermal conductivity of the BHE depends on injected power rate and flow resistance in fractures. The fracture flow resistance may be quantified in terms of hydraulic conductivity. A thermosiphon flow enhancing the convective heat transfer from a heated groundwater filled borehole in hard rock takes place when fractures exist in the BHE.

The findings from the groundwater flow simulations and thermosiphon simulation are encouraging for further studies, both as simulations and in field experiments. The author suggests further studies of the possibility to develop models for estimating and investigating the influence of groundwater from drilling data and hydraulic testing. A future aim should be to gain enough knowledge of fracture flow and thermosiphon effects that hydraulic well test and drilling data may be used in BTES (borehole thermal energy storage) design.



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I am grateful to Prof. Olof Andersson, Operating Agent of IEA IA ECES Annex 13, for inviting me to join his work group, and to Prof. Jeffrey D. Spitler at Oklahoma State University, for a fruitful cooperation in the work with the Thermal Response Test State-of-the-Art Report. General Secretary Bengt-Göran Jarefors, at the Swedish Association of HVAC Engineers (Swedvac), has also been most supportive during the late part of my work.

There are many more people, in Sweden and abroad, who have helped me along the way. Among them Martin Edman at IdéArktica who built TED, and my friend Catarina Eklöf with whom I first started on my TED-career. Svante Enlund at Telia and Göran Linder, Teracom, provided me with boreholes for my field tests, as did SKB in cooperation with Golder Ass., and many other borehole owners. Helge Skarphagen, NGU, and Rune Helgesen have been most generous with Norwegian data and experience. My dear friends Prof. Halime Ö. Paksoy and Prof. Hunay Evliya and their students at Çukurova University, have been a great support and inspiration during my work and visits at their university in Turkey, and have provided me with valuable data and experience from Turkish response tests. Special thanks go to Claes-Göran Andersson, for the beautiful illustrations in this thesis.

Without the financial support from Luleå University of Technology, the Swedish Council for Building Research (BFR), the Swedish Heat Pump Association (SVEP), and Bengt Ingeström's foundation, this doctorate work and thesis would never have been realised.

My loving thanks also to my fiancé Peter for all support and encouragement through my work, and for administering the dishes, laundry and vacuum-cleaning and all that in the household when I failed to do my part of it.

...and finally, my thanks to TED, himself, for being my companion all the way through my doctoral studies. I will miss you, chuck.

Signhild Gehlin

Nynäshamn, September 2002

NOMENCLATURE

a	=	Diffusivity $= \frac{\lambda}{c}$	m^2s^{-1}
A_h	=	Hydraulic area $A_h = \pi \cdot (r_b^2 - 2 \cdot r_{\text{pipe}}^2)$	m^2
C	=	e^γ	
c	=	Volumetric heat capacity	$\text{Jm}^{-3}\text{K}^{-1}$
c_{cyl}	=	Cylinder heat capacity per m borehole	$\text{Jm}^{-2}\text{K}^{-1}$
D_h	=	Hydraulic diameter $D_h = 2r_b - 2\sqrt{2} \cdot r_{\text{pipe}}$	m
E_1	=	The exponential integral	
g	=	Gravitational constant	ms^{-2}
H	=	Effective borehole depth	m
h	=	$2\pi \cdot \lambda_{\text{ground}} \cdot R_b$	
I	=	Hydraulic gradient $\frac{dh}{dx}$	
K	=	Hydraulic conductivity	$\text{m}^3\text{s}^{-1}\text{m}^{-2}$
n	=	Porosity	
PF	=	Proportionality factor	
Q	=	Injected heat power rate	W
q	=	Heat flux	Wm^{-1}
q_w	=	Volumetric groundwater flow rate	$\text{m}^3\text{s}^{-1}\text{m}^{-2}$
R	=	Thermal resistance	KmW^{-1}
r	=	Radius	m
T	=	Temperature	$^\circ\text{C}$
t	=	Time	s
v	=	Flow velocity	$\text{m}^3\text{s}^{-1}\text{m}^{-2}$
z	=	Vertical depth	m
α	=	Heat transfer coefficient	$\text{Wm}^{-2}\text{K}^{-1}$
γ	=	Euler's constant = 0.5772...	
λ	=	Thermal conductivity	$\text{Wm}^{-1}\text{K}^{-1}$
ρ	=	Density	kgm^{-3}
ν	=	Kinematic viscosity	m^2s^{-1}

μ	=	Dynamic viscosity	$\text{kgm}^{-1}\text{s}^{-2}$
τ	=	$\frac{a_{\text{ground}} \cdot t}{r_b^2}$	
ζ	=	Hydraulic skin factor	
ξ	=	Friction factor	
Δp	=	Pressure difference	Pa

Subscripts

b	=	Borehole
cond	=	Conductive
eff	=	Effective
eq	=	Equivalent
f	=	Fluid
fr	=	Fracture
in	=	Inlet
ug	=	Undisturbed Ground
w	=	Water
z	=	Porous zone

OUTLINE OF THESIS

This thesis is presented as the partial fulfilment of the requirements for the degree of Doctor of Philosophy (Ph.D.). The research was carried out at the Division of Water Resources Engineering, Luleå University of Technology, Sweden. This thesis summarises the method of thermal response test for evaluating the thermal behaviour of a BTES system and discusses the influence of flowing groundwater in fractures.

The thesis consists of a short introduction and the following papers:

- I Gehlin S., G. Hellström. (2000). Recent Status of In-situ Thermal Response Tests for BTES Applications in Sweden. *Proc. Terrastock'2000*, August 28-September 1 2000, Stuttgart, Germany, pp 159-164.
- II Gehlin S., J. D. Spitler. (2002). *Thermal Response test – State of the Art 2001*. Report IEA ECES Annex 13.
- III Gehlin S., B. Nordell. Determining Undisturbed Ground Temperature for Thermal Response Test. *Accepted for publication in ASHRAE Transactions 2003, Vol 109, Pt.1*.
- IV Gehlin S., G. Hellström. Comparison of Four Models for Thermal Response Test Evaluation. *Accepted for publication in ASHRAE Transactions 2003, Vol 109, Pt.1*.
- V Gehlin S., G. Hellström. Influence on Thermal Response Test by Vertical Fractures in Hard Rock. *Submitted to Renewable Energy 2002*.
- VI Gehlin S., G. Hellström, B. Nordell. 2002, Influence on Thermal Response Test by Thermosiphon Effect. *Submitted to Renewable Energy 2002*.

The first paper sums up the Swedish research on thermal response test as a measurement method, and presents performed measurement in Sweden, until the beginning of 2000.

The IEA ECES Annex 13 State of the Art report summarises the collected knowledge on thermal response test and data evaluation models, used worldwide until the end of 2001.

Paper III and IV describe additional studies on specific issues related to the response test measurement procedure, and a discussion on the consequences of the use of different approximations in the data evaluation procedures.

Paper V and VI deal with the effect of groundwater flow in general and fracture flow in particular, on response test and BTES systems, and present a theory about thermosiphon effects under specific conditions.

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PAPERS:

- I. Gehlin S., G. Hellström (2000). Recent Status of In-situ Thermal Response Tests for BTES Applications in Sweden. *Proc. Terrastock'2000*, August 28-September 1 2000, Stuttgart, Germany, pp 159-164.
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- V. Gehlin S., G. Hellström. Influence on Thermal Response Test by Vertical Fractures in Hard Rock. *Submitted to Renewable Energy, 2002*.
- VI. Gehlin S., G. Hellström, B. Nordell. Influence on Thermal Response Test by Thermosiphon Effect. *Submitted to Renewable Energy, 2002*.

1. INTRODUCTION

1.1 General

Borehole Thermal Energy Storage (BTES) systems for storage and/or extraction of heat or cold (e.g. ground-source heat pump systems, GSHP) are now well established. Around 20 000 boreholes are drilled every year in Sweden, mostly separate boreholes for single family houses, but also for large systems with several boreholes. In Norway, where BTES has been established more recently, around 30 large systems have been initialised between the years 1998 and 2002 (HELGESEN 2002). About half a million boreholes for BTES systems are drilled every year in North America, which is today the largest market for BTES systems in the world. BTES is used throughout the world, however too scarce in developing countries. The size of the systems varies from single boreholes up to 400 boreholes in e.g. Stockton, USA (STILES et al. 1998) and in Australia. A 600 boreholes system is presently being constructed in Oslo, Norway. Knowledge of the local geology is essential for the dimensioning of the BTES system. The larger system, the more is to gain on a proper estimation of the ground thermal conductivity and the temperature loss between the heat carrier fluid and the ground. The conditions are site-specific, and therefore in situ measurements are necessary. Studies have shown that field measurements result in higher conductivity values than laboratory estimations on core samples (CARLSSON 1978, ERICSSON 1985, GEHLIN 1998). Influence from groundwater explains this difference. The effect of groundwater on BTES systems and in situ measurement of ground thermal conductivity needs further investigation.

1.2 Problem illustration

Knowledge of the effective heat transfer capacity of a borehole is important for the design of larger BTES systems. Knowledge of the effects of groundwater flow is of interest for all sizes of BTES systems. In situ measurements of groundwater filled boreholes indicate influence from groundwater movements. Recent theoretical studies dismiss significant effects of groundwater flow for typical conditions in a porous ground (CHIASSON et al. 2000, CLAEISSON and HELLSTRÖM 2000). However groundwater flow in fractures results in higher flow velocities, and the hydraulic pressure difference between corresponding fractures may be potentially important. If groundwater flow in fractures significantly influences the heat transport to and from a borehole, this must be considered when designing and sizing BTES systems.

1.3 Objectives

This thesis is part of a research project aiming at finding a way to determine the effective heat transporting capacity of a BTES borehole in situ, in order to improve and optimise BTES systems. The aim was to develop a measurement and evaluation method, and to spread this knowledge so that the method if possible would become a routine in the design of larger BTES systems. Obtained “effective” heat transfer data include the effect of both conductive and convective heat transport for dimensioning of BTES systems and separate boreholes.

1.4 Scope

The work on this project started as a Master’s project in 1995–96 when a pre-study of a mobile thermal response test apparatus was done and a first prototype was constructed at Luleå University of Technology, Sweden. The prototype was named TED. It was tested in several field measurements during this period. Experience from the Master’s project led to further technical development of the apparatus and data

analysis process within this doctoral research project. The method was presented and discussed at international conferences and workshops within the framework of IEA IEA ECES (International Energy Agency Implementing Agreement on Energy Conservation through Energy Storage). Further evaluation and technical development was done in cooperation with international expert groups, mainly within the work of IEA. Several of response test apparati have been built in other countries based on the Swedish TED.

An international state-of-the-art, December 2001, of thermal response test is included, however the focus of this work is laid upon Swedish BTES technology and groundwater filled boreholes in crystalline rock. A special study on how to determine the initial ground temperature was performed. The effects of groundwater flow on the thermal response test measurements have been generally treated. An initial study of the thermosiphon effect was also included.

2. THERMAL RESPONSE TEST

2.1 The Borehole

Energy wells

Energy wells are boreholes through which heat is exchanged, to or from the ground. The term refers to systems where the underground heat source or sink is groundwater from an aquifer (aquifer thermal energy storage, ATES), or ground in the form of hard rock or more or less consolidated sedimentary layers (borehole thermal energy storage, BTES). This study treats only energy wells for BTES applications.

BTES systems consist of several borehole heat exchangers (BHE), also called ground heat exchangers (GHE). Applications where thermal energy is injected or extracted through the borehole with the use of heat pumps are commonly referred to as ground-coupled heat pump systems (GCHP), or ground-source heat pump (GSHP) systems. There are also feasible applications for ground heat exchangers, where heat pumps are not used, e.g. dissipative systems for direct cooling, or high temperature thermal storage for low-temperature applications.

BHEs are boreholes of a diameter normally in the range 0.09-0.15 m, drilled in the ground to a typical depth of 30-200 m. A heat carrier fluid is circulated through the borehole, usually in a closed circuit, exchanging the heat or cold from the ground to the user unit.

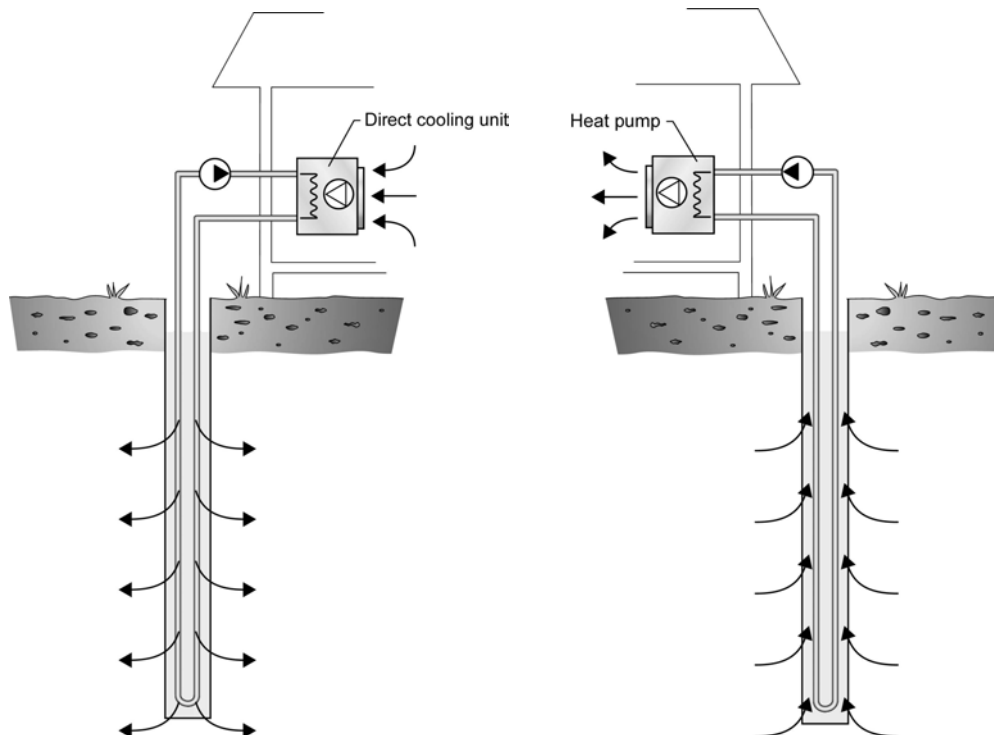


Figure 2.1. Borehole heat exchanger (BHE) in a dissipative application for direct cooling of electronic equipment (left) and in a heat pump application for domestic space heating (right)

Drilling

The commonly used drilling methods in hard rock are top hammer drilling, rotary drilling and down-hole drilling. Top hammer drilling is fast but can only be used for relatively shallow holes, i.e. 70–80 m (AVANTI 1996), because of the energy loss when transferring the percussive pulses to larger depths. Rotary drilling is a universal method that can be used for deep boreholes, but has a slow penetration rate and is therefore expensive. The most commonly used method, down-hole drilling, is based on the air-driven down-hole hammer. The percussive work is performed at the bottom of the hole. A major disadvantage with the method is the limitation in drilling depth when drilling in water rich rock. The commonly used driving pressure at 2–2.4 MPa corresponds to the pressure of 200–240 m water, which thereby is the theoretical limiting depth for such conditions (TUOMAS 2001, SGI 2001). In practice the maximum depth in fractured rock with rich water supply is considerably less (NORDELL et al. 1998). Water-driven down-hole hammer drilling is a relatively new and promising method for BHE and is still under development. The use of water instead of air as drilling fluid eliminates the drilling depth limitation, but introduces some difficulties with water supply and wearing. Successful hydraulic down-hole hammers are however now commercially available (TUOMAS 2001).

When drilling through soil layers or in unconsolidated rock, stabilisation of the borehole may be needed. Steel or plastic tube casing is used to prevent collapse of the borehole. Swedish regulations recommend at least 6 m casing below ground surface, of which at least 2 m should reach into the hard rock. The casing must be sealed with concrete (SGI 2001).

ANDERSSON (1981) and SACHS & DINSE (2000) provide good overviews of BHE drilling methods, their strengths and weaknesses.

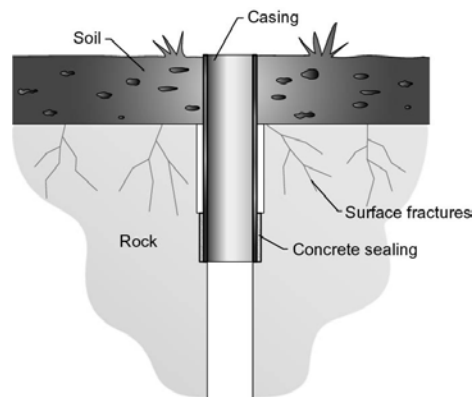


Figure 2.2. Upper part of borehole with casing and sealing.

The Collector

Vertical ground heat exchangers are classified based on their cross-sectional geometry and how the heat exchange from the flow channels takes place. Figure 2.3 shows the two fundamental designs. In the U-pipe type BHE, both the downward and the upward flow channel participate in the heat exchange with the surrounding ground. U-pipe type BHE exists with two or more channels. Most common is the single U-pipe BHE, but double U-pipe BHE has become increasingly popular, with increasing drilling depths, due to its lower thermal resistance and head loss.

The characteristics of the coaxial (also called tube-in-tube) type BHE is that heat exchange occurs from either the upstream or downstream flow channel (the flow direction may also be different during injection or extraction of heat). The inner pipe is often thermally insulated in order to avoid thermal short-circuiting between the upward and downward flow channel. Coaxial BHEs may be designed with or without liner or outer tube, i.e. as a closed or open flow circuit. HELLSTRÖM (2002) gives a thorough description of BHE design and experience during the passed 30 years.

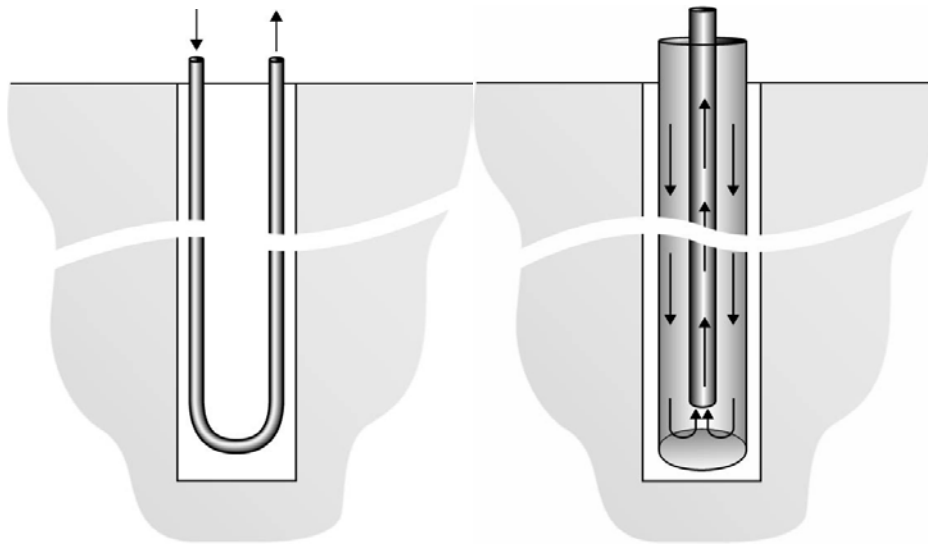


Figure 2.3. The two fundamental borehole heat exchanger designs – the U-pipe and the coaxial pipe.

Borehole filling

A vertical borehole may require that some kind of backfilling material is used to fill the space between the flow channels and the borehole wall. One reason is to provide a good thermal contact with the surrounding ground due to low thermal conductivity of natural filling material or low groundwater level. Another important issue is to limit vertical water movement along the borehole to avoid migration of polluted water, drainage of soil layers near the ground surface and disturbance of the hydraulic characteristics of artesian formations (ECKHART 1991). There is no regulation for backfilling of BHEs in Sweden, but in e.g. USA and Germany, BHEs are always backfilled according to national regulations and recommendations.

Special grouts are used to provide a low permeability. It is important that these grouts have the capability to bond against both borehole wall and pipes. The mixtures must be workable and pumpable during installation with little shrinkage during settling. If shrinkage occurs, this may cause a pathway for fluid migration. Common grouts, such as bentonite, usually have low thermal conductivity. Special grouts have been developed to enhance the thermal conductivity.

Laboratory tests to investigate thermal resistance and thermal conductivity of grouts have been reported by REMUND and LUND (1993), KAVANAUGH and ALLAN (1999), ALLAN and KAVANAUGH (1999) and PHILIPPACOUPOULOS and BERNDT (2001). HELLSTRÖM (2002) provides a good overview of experience on grouted boreholes and various grouts.

In Sweden and Norway it is most common to leave the boreholes un-grouted, i.e. the boreholes are filled with groundwater. Boreholes are commonly drilled in hard rock with the groundwater table a few meters below ground surface. Stagnant water has low thermal conductivity, however thermal gradients that will necessarily occur in BHEs cause natural convection, thus enhancing the heat transfer between the heat exchanger and the surrounding ground.

Thermal resistance

An important factor for the design of borehole systems is the thermal resistance between the heat carrier fluid in the borehole flow channels and the borehole wall. The fluid-to-borehole wall thermal resistance (R_b) gives the temperature difference between the fluid temperature in the collector (T_f) and the temperature at the borehole wall (T_b) for the specific heat transfer rate q (W/m):

$$T_f - T_b = R_b \cdot q \quad (2.1)$$

This so-called borehole thermal resistance depends on the arrangement of the flow channels and the thermal properties of materials involved. The values observed in field tests range from $0.01 \text{ KW}^{-1}\text{m}$ for an open system, to $0.20 \text{ KW}^{-1}\text{m}$ for single U-pipes in bentonite grout where no special precautions have been made to keep the pipes close to the borehole wall. The temperature difference between the heat carrier fluid and the borehole wall is proportional to the heat transfer rate. For a typical heat transfer rate of 50 Wm^{-1} , the corresponding temperature difference becomes 0.5°C to 10°C . The borehole thermal resistance may have a significant effect on the system performance and should be kept as small as possible. Filling materials (e.g. bentonite, concrete etc.) in grouted boreholes usually provide better heat transfer than pure stagnant water. However, in water-filled boreholes, the heat transfer induces natural convection of the borehole water and in surrounding permeable ground. This phenomenon, which is more pronounced at large heat transfer rates, leads to a reduction of the overall borehole thermal resistance (KJELLSSON and HELLSTRÖM 1997, KJELLSSON and HELLSTRÖM 1999). The overall thermal performance of the borehole field that is subject to a certain heat load variation depends not only on the borehole thermal resistance, but also on the transient thermal resistance of the surrounding ground and the thermal influence from other boreholes.

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 BHE, these effects are usually important when the flow is laminar or when the borehole depth exceeds 200 m.

REMUND (1999) discusses thermal resistance in BHE, relating the borehole thermal resistance to a grout thermal conductivity and a borehole shape factor and presents laboratory and field test of the borehole thermal resistance.

Figure 2.4 illustrates the principle of borehole thermal resistance.

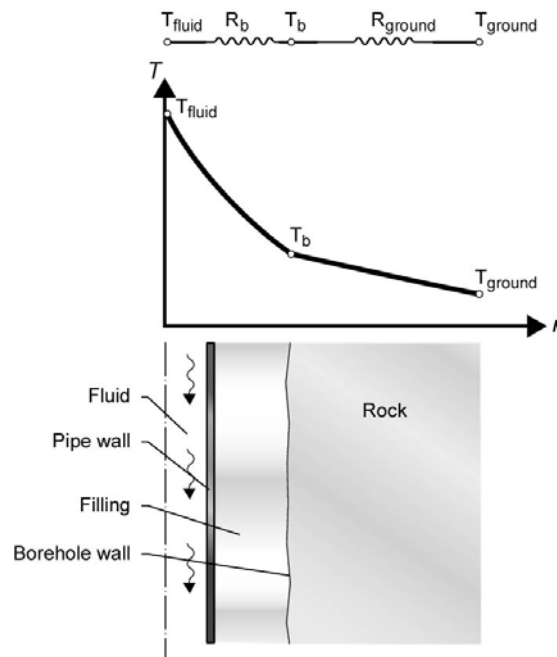


Figure 2.4. Borehole thermal resistance.

The importance of determining the undisturbed ground temperature, and various ways of doing it, is discussed in KAVANAUGH et al. (2000), who also presents measurements. Kavanaugh recommends activating the pump and recording the minimum temperature as a good estimate of the initial ground temperature.

In **Paper III**, three temperature estimation methods are compared in a field experiment conducted in Luleå.

The ground is necessarily disturbed by the drilling process. This may result in heating of the ground (due to energy input or exothermic heating with cementitious grouts) or wetter (due to circulation of drilling fluid) or dryer (due to circulation of air) than it would otherwise be. The time required for the ground to return to an approximately undisturbed state has not received enough systematic studying. LILJA (1981) presents a study of temperature disturbance of rock caused by hammer drilling, however drilling techniques have developed much since then.

2.2 Thermal Response

Temperature development

The borehole temperature response is the temperature development over time when a known heating or cooling load is imposed, e.g. by circulating a heat carrier fluid through the borehole heat exchanger. By evaluating the fluid temperature versus time, information about the thermal properties in and around the borehole is obtained. A low thermal conductivity is e.g. indicated by a more rapid temperature response. The response also gives information about the temperature difference between the heat carrier fluid and the surrounding ground, i.e. the thermal resistance of the borehole heat exchanger.

The temperature development in the heat carrier fluid may be estimated by analytical solutions of the heat equation. Mean fluid temperature (T_f) is defined as the average of the inlet and outlet temperatures of the BHE. The estimated injected heat is used to calculate the average borehole temperature (T_b). When injecting a constant heat pulse, the temperatures T_f and T_b will vary over time, but after a short initial period, the temperature difference $\Delta T = T_f - T_b$ reaches a constant value. This condition is the so called *steady-flux* state, for which ΔT is proportional to the injected heat rate q (Wm^{-1}) per meter BHE, see Equation 2.1.

Heat injection or extraction from a BHE is rarely constant but may normally, with sufficient accuracy, be represented by piecewise constant values. Using superposition of heat transfer in a solid material, complicated processes may be simplified by summing the partial heat transfer processes from each piecewise constant pulse:

$$\Delta T(q_1, q_2, \dots, q_n) = \Delta T(q_1) + \Delta T(q_2) + \dots + \Delta T(q_n) \quad (2.2)$$

This step-pulse analysis is thoroughly described in ESKILSON (1987) and HELLSTRÖM (1991).

Thermal response test

There are several ways to estimate the ground thermal properties for a BHE design. The simplest way is to use standard values for the type of rock at the location of the BTES system. There are also several laboratory methods to determine the thermal conductivity of solid materials (SUNDBERG 1988), however these methods require expensive samples, and will not give the entire picture of the ground profile at the site.

MOGENSEN (1983) first presented the thermal response test as a method to determine the in situ values of ground thermal conductivity and thermal resistance in BHE systems. He suggested a system with a chilled heat carrier fluid being circulated through a BHE system at constant heat extraction (or cooling) rate, while the outlet fluid temperature from the BHE was continuously recorded. The temperature data over time (i.e. the thermal response) is compared with a mathematical model of the heat transfer processes occurring in the borehole and surrounding ground. The model depends primarily on the ground thermal conductivity and borehole thermal resistance. Mogensen's method was used to evaluate existing BHE systems at several occasions, e.g. MOGENSEN (1985), ESKILSON (1987), NORDELL (1994), HELLSTRÖM (1994).

2.3 Response Test Devices

The first mobile measurement devices for thermal response testing were independently constructed in Sweden and USA in 1995. The Swedish response test apparatus "TED" was developed at Luleå University of Technology and reported by EKLÖF and GEHLIN (1996). At the same time a similar device was developed at Oklahoma State University as reported by AUSTIN (1998). Both apparati are based on Mogensen's concept but with a heater instead of a chiller. Similar test units were later developed in other countries.

Paper II documents the December 2001 state-of-the-art of thermal response test utilities and experience and the appendix of **Paper II** contains comparing tables of the various existing test facilities and their use. The fundamental thermal response test set-up is illustrated in Figure 2.6.

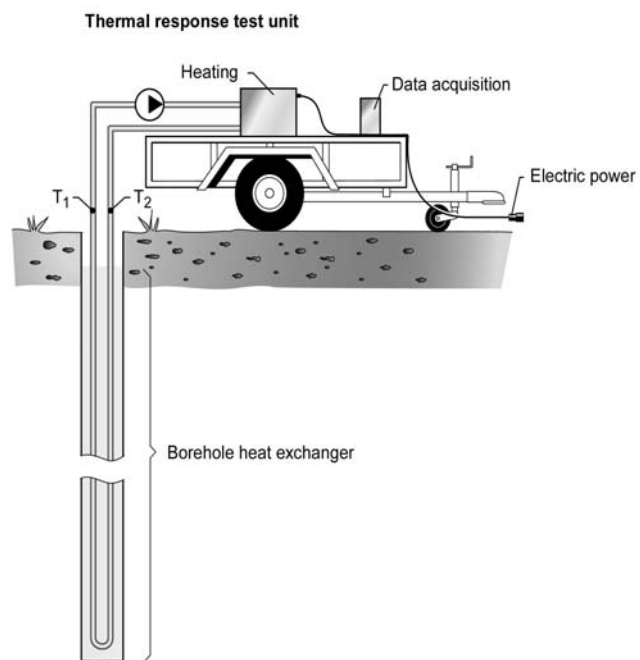


Figure 2.6. Thermal response test set-up

TED

The Swedish response test device, TED, was constructed at Luleå University of Technology in 1995-96 (EKLÖF and GEHLIN 1996; GEHLIN and NORDELL 1997). It is set up on a small covered trailer and consists of an in-line electric resistance heater, instrumentation, and an 85-litre tank used for purging and as an expansion tank. The tank also contains fluid for the initial filling of the pipe system. A 1.75 kW pump circulates the heat carrier fluid through the borehole. The heater has step-wise adjustable power rates in the range of 3-12 kW. Fluid temperatures are measured by thermocouples at the inlet and outlet of the borehole. The fluid temperatures, ambient air temperature, air temperature inside trailer, and power rate are recorded at an optional pre-set time interval.

When running the test the response test facility, placed as close as possible to the test borehole, is connected to the fluid-filled borehole pipes. The connection pipes are filled with fluid from the purge tank and the test loop (i.e. the collector pipes and the response test device) is purged. Exposed parts between the borehole and the response test apparatus are well insulated. The purge tank is connected to the pipe system to collect air bubbles, though the fluid is not flowing through the tank. Once the pipe system is filled-up no fluid is added to the pipe system from the tank, in fact a small inflow into the tank is caused by the volume expansion of heated fluid. The test procedure is fully automated as soon as the test has started.

TED has been used in over 30 response tests. Typical for Swedish response tests is groundwater filled boreholes in granitic rock. Due to the use of groundwater filled boreholes, effects of natural convection in the borehole and local groundwater flow have been observed.

A number of measurements have been performed at Luleå University of Technology for research and evaluation of different BHE. Tests on single U-pipe and double U-pipe BHE, both on groundwater filled and grouted boreholes have been studied. Also tests on co-axial BHE and tests with several power injection pulses have been performed. A few measurements have been performed in sedimentary rock. EKLÖF & GEHLIN (1996) described measurements at two locations, where the test rig could not be connected directly to the borehole but the heat carrier fluid had to pass through several meters of horizontal piping buried in the ground. Thus the effect of the horizontal piping has been included in the measurements.

A more thorough description of the response test apparatus is given in GEHLIN (1998) where also results and experience from the first three years of operation are reported. **Paper I** provides a summary of the work reported in GEHLIN (1998).

American response tests

There are a number of response test devices in operation in USA. The first one described in the literature – developed at Oklahoma State University in 1995 – is housed in a trailer that is towed to the site and contains everything needed to perform a test. A detailed description of the test apparatus is available in AUSTIN (1998) and AUSTIN et al. (2000).

In addition, several commercial thermal response test devices have been developed. An Oklahoma company, Ewbanks and Associates, have developed a number of test rigs, starting with a version mounted on a trailer, and progressing to versions that fit in airline-shippable crates. Another Oklahoma company, Tri-Sun has developed a unit that fits in a medium-sized suitcase. A utility in Nebraska (SPILKER 1998) has developed one unit and other commercial units have been fabricated by companies in Texas and Tennessee.

Test conditions vary widely throughout the USA and hundreds of tests have been made for commercial clients, without the results being published. Results are published by SPILKER (1998), SKOUBY (1998), SMITH (1999a), SMITH (1999b), SMITH and PERRY (1999a), SMITH and PERRY (1999b), SPITLER et al. (1999), SPITLER et al. (2000), REMUND (1999), KAVANAUGH (2000), KAVANAUGH et al. (2000). Validation tests have been reported by AUSTIN et al. (2000), SHONDER and BECK (1999) and SHONDER and BECK (2000b). SHONDER and BECK (2000a) compare in situ tests with operating data from a BTES system and a detailed numerical model to estimate effective thermal conductivity.

The Dutch version

GroenHolland B.V. in Netherlands built their large response test rig in a sea shipping container (IF TECHNOLOGY 1999, VAN GELDER et al. 1999, WITTE et al. 2000a, WITTE et al. 2000b, WITTE et al. 2002). It is operated with a reversible heat pump, and thus can be run in either heating or cooling mode. The heat pump generates a supply of warm or cold fluid, which is used to maintain a certain temperature difference between fluid entering and leaving the borehole. The test rig may be used for response tests on single or multiple boreholes.

The thermal response test rig at Groenholland and IF Technology has been used both for research and commercial measurements.

Other thermal response tests

Environment Canada in Halifax had a response test apparatus built in 1999–2000, based on experience from Sweden and USA. The first response tests in Canada were reported by CRUICKSHANKS et al., (2000). The tests were performed on groundwater filled boreholes in mixed slate/quartzite geology.

In Germany, the response test method was established in 1999. One test rig is operated by Landtechnik Weihestephana and another at UBeG GbR in Wetzlar (SANNER et al., 2000a). A third response test device is run by Aetna Energiesysteme GmbH in Wildau (SANNER et al. 2000b). The construction of the German test equipment is based on the Swedish TED. The Landtechnik Weihestephana rig consists of two portable containers, and the UbeG rig consists of a frame with the heating equipment and a control cupboard. Both rigs are mounted on a light trailer. The AETNA test rig is also mounted on a trailer. It uses a heat pump instead of a heater and may be operated both in heating and cooling mode (BRANDT 2001).

Since 1998, a thermal response test apparatus manufactured by the same firm that built the Swedish apparatus, has been used by a company in Norway. It has the same operation and construction. It is described by NGU (2000) and SKARPHAGEN and STENE (1999). A second apparatus was bought by the Norwegians in summer 2002. Around 30 response tests, mostly commercial and concentrated to the Oslo area, have been performed in Norway in recent years. The hilly landscape causes a high groundwater flow in fissures, which strongly influences the performance of BHE.

Switzerland has two mobile test rigs in operation since 1998 for measurements of boreholes and energy piles. The EPFL rig has a three-step heater unit with variable fluid flow. The EKZ has a two step in-line electric heater and a fixed fluid flow rate.

In late 2000, the Centre for Environmental Research at Çukurova University in Adana, Turkey, took over one of the two Swedish test rigs. The first two response tests were carried out in Istanbul in December 2000.

A British version of thermal response test apparatus was constructed by GeoSciences, Falmouth, Cornwall in the summer of 1999. The unit is mounted on a small two-wheeled cart. Response tests in UK have been performed by GeoScience Limited and the Dutch company Groenholland.

Three other countries are in the process of taking thermal response test units in use. France has shown recent interest in a test facility in their communication with Switzerland and technology transfer has been discussed. The Japanese company GEO-E has prepared a test rig, similar to the Swiss EKZ-unit. Totally six response test units have been built in Japan during the recent years. Measurements have been performed in Japan and China.

2.4 Response Analysis

Different mathematical models – analytical and numerical – are used for the evaluation of response test temperature data. The different models require somewhat different sets of input data. **Paper II** and **Paper IV** describe the currently used analysis methods to estimate the thermal properties of the ground formation. In **Paper IV**, four different analysis models are compared using the same response test data sets.

Analytical models

Analytical models, such as the line source and cylinder source adopt the analytical solution of the heat transfer problem between the borehole and the nearby infinite region. They require several simplifying assumptions regarding the geometry of the borehole and heat exchanger pipes. For the purpose of the thermal response test evaluation, the heat flow to or from the borehole may be represented as an infinitely long heat source or sink in the ground with negligible influence of heat flows in a direction along the borehole axis. In the ground outside the borehole it is common practice to assume that the thermal process depends only on the radial distance from the borehole axis. The one- or two-dimensional heat flow process from the circulating fluid to the borehole wall is assumed to be represented by a thermal resistance that characterises the temperature loss between heat carrier fluid and borehole wall. Some models also include the thermal mass of the materials in the borehole.

INGERSOLL and PLASS (1948) applied the *line source* model to design of ground loop heat exchangers. MOGENSEN (1983) proposed to use the borehole similar to the probe to estimate the ground thermal conductivity from an experimental field test. This method is now commonly used for thermal response test evaluation in Europe. In practice, researchers have made use of this approach in somewhat different ways although they essentially follow MOGENSEN (1983).

The equation for the temperature field as a function of time (t) and radius (r) around a line source with constant heat injection rate (q) (CARSLAW and JAEGER 1959) may be used as an approximation of the heat injection from a BHE:

$$T(r,t) = \frac{q}{4\pi\lambda} \int_{\frac{r^2}{4at}}^{\infty} \frac{e^{-u}}{u} du = \frac{q}{4\pi\lambda} E_1(r^2/4at) \quad (2.3)$$

E_1 is the so-called exponential integral. For large values of the parameter at/r^2 , E_1 can be approximated with the following simple relation:

$$E_1(r^2/4at) = \ln\left(\frac{4at}{r^2}\right) - \gamma \quad \frac{at}{r^2} \geq 5 \quad (2.4)$$

where the term $\gamma = 0.5772\dots$ is Euler's constant. The maximum error is 2.5% for $at/r^2 \geq 20$ and 10% for $at/r^2 \geq 5$. Ground thermal conductivity is denoted λ and $a = \lambda/c_p$, where c_p is the ground specific heat capacity. The condition means that the accuracy increases as the thermal front reaches further beyond the borehole wall, and the velocity of the thermal front is dependent on the ratio between thermal conductivity and heat capacity of the ground i.e. ground thermal diffusivity.

The fluid temperature is evaluated by taking the line source temperature at the borehole radius ($r = r_b$) and adding the effect of the borehole thermal resistance (R_b) between the fluid and the borehole wall. Thus the fluid temperature as a function of time can be written:

$$T_f(t) = \frac{q}{4\pi\lambda} \cdot \left(\ln\left(\frac{4at}{r^2}\right) - \gamma \right) + q \cdot R_b + T_o \quad (2.5)$$

where T_o is the undisturbed ground temperature.

The *cylinder source* model, of which the line source model is a simplified variation, may be used for approximating the BHE as an infinite cylinder with a constant heat flux. The heat exchanger pipes are normally represented by an "equal diameter" cylinder. The cylindrical source solution for a constant heat flux is as follows:

$$T(r,t) = \frac{q}{\lambda} \cdot G(z,p) \quad \begin{cases} z = \frac{at}{r^2} \\ p = \frac{r}{r_o} \end{cases} \quad (2.6)$$

where $G(z,p)$ is the cylindrical source function as described by INGERSOLL et al. (1954):

$$G(z,p) = \frac{1}{\pi^2} \int_0^\infty f(\beta) d\beta \quad (2.7)$$

$$f(\beta) = (e^{-\beta^2 z} - 1) \cdot \frac{[J_0(p\beta)Y_1(\beta) - Y_0(p\beta)J_1(\beta)]}{\beta^2 [J_1^2(\beta) + Y_1^2(\beta)]} \quad (2.8)$$

where J_0 , J_1 , Y_0 , Y_1 are Bessel functions of the first and second kind.

CARSLAW and JAEGER (1959) developed analytical solutions with varying boundary conditions for regions bounded by cylinder geometry. DEERMAN and KAVANAUGH (1991) and KAVANAUGH and RAFFERTY (1997) describe the use of the cylinder source model in designing ground loop heat exchangers. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground loop heat exchanger. Based on a short-term in situ test, the measured effective thermal resistance of the ground of a daily heat pulse is fitted to a value computed from a dimensionless cylinder source function by varying the thermal conductivity and diffusivity of the ground.

Numerical models

Numerical models can be designed to handle detailed representations of the borehole geometry and thermal properties of the fluid, pipe, borehole filling and ground, as well as varying heat transfer rates. The more extensive set of required input data often make these models more difficult and time-consuming to use than the

analytical methods, which sometimes may be implemented as simple spreadsheet applications.

BERBERICH et al. (1994) describe a response test type of measurement in groundwater filled ducts in water saturated clay stone where temperature sensors were placed along the borehole wall. The measured data were analysed with both an analytical line source model and a numerical two-dimensional finite difference model using parameter estimation with ground thermal conductivity and volumetric heat capacity as variables.

SHONDER and BECK (1999) developed a parameter-estimation-based method, which is used in combination with a one-dimensional numerical model. This model is similar to a cylinder-source representation, in that it represents the two pipes of the U-pipe as a single cylinder. However, it adds two more features - a thin film that adds a resistance without heat capacity, and a layer of grout, which may have a thermal conductivity and heat capacity different from the surrounding soil Figure 2.7. This model accommodates time-varying heat input.

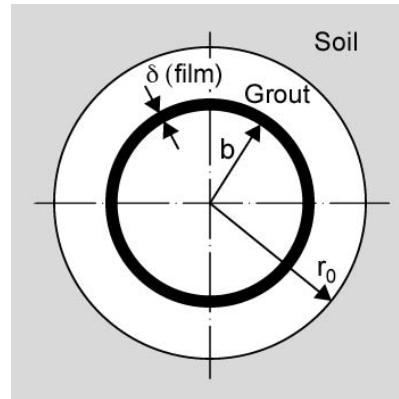


Figure 2.7. One-dimensional numerical model geometry for Oak Ridge National Laboratory Method (SHONDER, et al. 1999).

A transient two-dimensional numerical finite volume model in polar co-ordinates for response test evaluation is reported in AUSTIN (1998) and AUSTIN et al. (2000). The geometry of the circular U-pipes is approximated by “pie-sectors” over which a constant flux is assumed. The convection resistance due to the heat transfer fluid flow inside the U-pipes is accounted for using fluid properties through an adjustment on the conductivity of the pipe wall material. A thorough description of the numerical model is found in YAVUZTURK et al. (1999). The model has since been improved by introducing a boundary-fitted grid system (Figure 2.8) that is more flexible and better represents the U-pipe geometry (SPITLER et al. 2000).

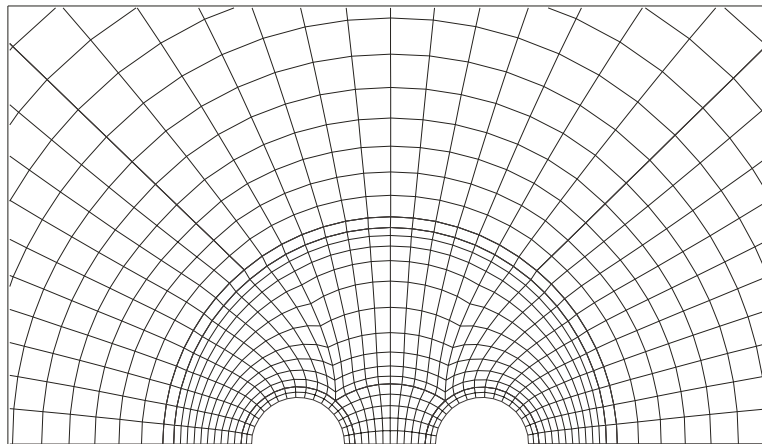


Figure 2.8. Boundary-fitted co-ordinate grid (SPITLER, et al. 2000)

Error discussion

Uncertainties in the estimated ground thermal conductivities come from several sources; random and systematic experimental error, approximations made in the analytical or numerical model, estimate of the far field temperature, and test length. These uncertainties have been discussed in AUSTIN (1998), AUSTIN et al. (2000), KAVANAUGH et al (2000) and WITTE et al. (2002). The overall uncertainties of the estimations made by different analysis procedures with different test equipment are on the order of $\pm 10\%$. AUSTIN (1998) has shown that error in the measurement of heat transfer rate to the borehole results in a similar percentage error in the estimation of ground thermal conductivity. Therefore, care must be taken to either measure the heat transfer rate using a temperature difference at the borehole inlet and outlet or, if the heat transfer rate is measured elsewhere, to minimise any unmeasured heat losses or gains.

Uncertainties due to approximations in the analysis procedure may be due to the assumption of constant heat transfer rate. AUSTIN (1998) showed highly variable thermal conductivity predictions made with the line source procedure, when there were significant variations in the heat transfer rate to the borehole. In this situation, the parameter estimation procedure, which does not assume a constant heat transfer rate, can provide more accurate estimates. However, with a constant heat transfer rate, WITTE et al. (2002) have shown that the line source and parameter estimation methods may give similar answers.

2.5 Groundwater Influence

The influence of groundwater flow on the performance of borehole heat exchangers has long been a topic of discussion. Field observations indicate that groundwater movements result in convective heat transport which influences the effective borehole performance as reflected in **Paper I** and in several other publications, e.g. GEHLIN (1998), SANNER et al. (2000a), CHIASSON et al. (2000), HELGESEN et al. (2001), WITTE (2001).

Some theoretical studies have been published on the subject. ESKILSON (1987), CLAEISSON & HELLSTRÖM (2000), CHIASSON et al (2000) present models for the influence of regional groundwater flow based on the assumption that the natural groundwater movement is reasonably homogeneously spread over the ground volume. This applies well on a homogeneous and porous ground material. ESKILSON and CLAEISSON & HELLSTRÖM use the line source theory for modelling the groundwater effect on a single vertical borehole. They conclude that under normal conditions, the influence of regional groundwater flow is negligible. CHIASSON et al. use a two-dimensional finite element groundwater flow and mass/heat transport model. They come to the conclusion that it is only in geologic materials with high hydraulic conductivity (sand, gravel) and in rocks with secondary porosities (fractures and solution channels in e.g. karst limestone), that groundwater flow has a significant effect on the borehole performance. Simulations of the effect on thermal response tests showed high effective thermal conductivity values.

WITTE (2001) performed a thermal response test where groundwater flow was induced by pumping in an extraction well located 5 m from the thermal well. Clear indications of enhanced heat transfer due to the induced groundwater flow were observed.

Continuum flow

Groundwater flow rate is proportional to the hydraulic conductivity, K , and the hydraulic gradient, I , in the ground. The hydraulic gradient is usually of the same order or smaller than the ground surface slope (ANDERSSON et al. 1982). It is calculated as the change in hydraulic head along the ground surface. Common hydraulic gradients are 0.01-0.001 or less (ÅBERG & JOHANSSON 1988).

In fractured crystalline rock, the interconnected fractures are the main passages for groundwater flow, and the solid rock may be considered practically impermeable. Two main approaches – continuum and discrete – are used when dealing with groundwater flow in fractured rock.

The continuum approach assumes the fractured rock mass to be hydraulically equivalent to a porous medium. The advantage of this approach is the applicability of Darcy's law. Much research has shown that macroscopic hydraulic flow in a large enough volume of fractured medium can be reasonably well represented by flow through a porous medium, i.e. by an equivalent continuum model. The equivalent hydraulic conductivity, K , of a fractured rock mass is then defined by Darcy's law:

$$v_{\text{darcy}} = K \cdot \frac{dh}{dx} = K \cdot I \quad (2.9)$$

where v_{darcy} is the darcy velocity in ms^{-1} , and I is the hydraulic gradient defined as the change in hydrostatic pressure as we move along the x-direction. Darcy's law is only valid for laminar flow in porous media.

SNOW (1968) showed that the permeability decreases with depth in fractured rocks, usually attributed to reduction in fracture aperture (perpendicular distance between the adjacent rock walls of a fracture) and fracture spacing due to increasing pressure. The equivalent hydraulic conductivity in normally fractured igneous rock is in the range 10^{-5} to 10^{-9} ms^{-1} , and varies with depth from ca 10^{-5} – 10^{-6} ms^{-1} nearest the surface, to 10^{-8} – 10^{-9} ms^{-1} down to 100–150 m depth (ANDERSSON et al. 1982). Fracture aperture may vary from very tight to wide. Commonly, subsurface rock masses have small apertures. Table 2.1 gives aperture ranges as usually classified in rock mechanics (SINGHAL and GUPTA (1999).

TABLE 2.1.
Aperture classification by size after (BARTON, 1973)

<i>Aperture (mm)</i>	<i>Term</i>
< 0.1	Very tight
0.1 – 0.25	Tight
0.25 – 0.50	Partly open
0.50 – 2.50	Open
2.50 – 10.0	Moderately wide
> 10.0	Wide

Fracture flow

If conditions for a continuum approach do not exist, the flow must be described in relation to individual fractures or fracture sets (discrete). Two-dimensional and three-dimensional network models have been developed, but the application of these theoretical models has been limited. The models are complex and there is no guarantee that a model reproducing the apparent geometric properties of a fracture network will capture its essential flow or transport features (SINGHAL and GUPTA 1999).

Natural fractures vary widely as far as planerity and surface geometry is concerned. Bedding plane fractures in fine-grained sedimentary rocks like shales may be relatively smooth and parallel, but in crystalline rock such as granites, fracture surfaces are usually rough and the aperture varies. SKB (1992) presents a simplified model for fracture zones and fractures in undisturbed granitic rock (Table 2.2). The model is based on extensive mapping, compiling and statistical modelling of rock structures of all ranges in crystalline rock in Sweden, and theoretical and experimental studies of fracture development. The classification is rather arbitrary and the limits are vague.

TABLE 2.2.
Fracture spacing and hydraulic conductivity (after SKB, 1992)

<i>Fracture class</i>	<i>Typical spacing</i>	<i>Typical hydraulic conductivity</i>
	<i>(m)</i>	<i>($\text{m}^3 \text{s}^{-1} \text{m}^{-2}$)</i>
1 st order	3000	10^{-6}
2 nd order	500	10^{-7}
3 rd order	50	10^{-8}
4 th order	5	10^{-11}
5 th order	0.5	0

The fracture permeability in hard rock is affected by a number of factors such as stress, temperature, roughness, fracture geometry, aperture, and intersection. Cementation, filling and weathering of fractures are other factors that affect the permeability. Natural fractures have a certain roughness. This roughness is however difficult to measure, which makes the practical use of a roughness factor small. The fracture is commonly treated as two parallel planes with a certain aperture. The parallel plate model uses the so-called cubic law, which is valid for laminar flow between two parallel plates with smooth surfaces. The cubic law expresses the volumetric flow as a function of fracture aperture:

$$q_w = K_s \cdot I = \frac{\rho \cdot g}{\mu \cdot l} \cdot \frac{t_{fr}^3}{12} \cdot I \quad (2.10)$$

In *Paper V* simulations of the effect on groundwater flow in a vertical fracture are presented and discussed.

Hydraulic and thermal properties of rock

The flow velocity of groundwater is dependent on the rock porosity and the driving gradient. Primary porosity is the inherent character of a rock that is developed during formation, whereas secondary porosity is developed subsequently due to various geological processes, e.g. fracturing, weathering and solution activity. In unconsolidated rocks, primary porosity is of importance but in hard rocks secondary porosity is of greater significance.

Naturally occurring hydraulic and thermal properties of some soils and rocks are listed in Table 2.3.

TABLE 2.3
Typical Values of Hydraulic and Thermal Properties of Soils and Rocks (after CHLISSON et al. 2000)

Medium	Hydraulic Properties		Thermal Properties	
	Hydraulic conductivity (K) [ms ⁻¹]	Porosity (n) [-]	Thermal conductivity (λ) [Wm ⁻¹ K ⁻¹]	Volumetric heat capacity (c _p) [Jm ⁻³ K ⁻¹]
Gravel (dry)	3·10 ⁻⁴ –3·10 ⁻²	0.24 – 0.38	0.70 – 0.90	1.4·10 ⁶
Coarse sand (dry)	9·10 ⁻⁷ –6·10 ⁻³	0.31 – 0.46	0.70 – 0.90	1.4·10 ⁶
Fine sand (dry)	2·10 ⁻⁷ –2·10 ⁻⁴	0.26 – 0.53	0.70 – 0.90	1.4·10 ⁶
Silt	10 ⁻⁹ –2·10 ⁻⁵	0.34 – 0.61	1.20 – 2.40	2.4·10 ⁶ –3.3·10 ⁶
Clay	10 ⁻¹¹ –4.7·10 ⁻⁹	0.34 – 0.60	0.85 – 1.10	3·10 ⁶ –3.6·10 ⁶
Limestone	10 ⁻⁹ –6·10 ⁻⁶	0 – 0.20	1.50 – 3.30	2.13·10 ⁶ –5.5·10 ⁶
Karst limestone	10 ⁻⁶ –10 ⁻²	0.05 – 0.50	2.50 – 4.30	2.13·10 ⁶ –5.5·10 ⁶
Sandstone	3·10 ⁻¹⁰ –6·10 ⁻⁶	0.05 – 0.30	2.30 – 6.50	2.13·10 ⁶ –5·10 ⁶
Shale	10 ⁻¹³ –2·10 ⁻⁹	0 – 0.10	1.50 – 3.500	2.38·10 ⁶ –5.5·10 ⁶
Fractured igneous and metamorphic rock	8·10 ⁻⁹ –3·10 ⁻⁴	0 – 0.10	2.50 – 6.60	2.2·10 ⁶
Unfractured igneous and metamorphic rock	3·10 ⁻¹³ –2·10 ⁻¹⁰	0 – 0.05	2.50 – 6.60	2.2·10 ⁶

Thermosiphon

Groundwater flow may occur as a horizontal regional flow of groundwater due to a natural groundwater gradient, or induced by pumping in the nearby region. Drilling through zones that are not in hydrostatic equilibrium may cause artesian groundwater flow through boreholes. This vertical groundwater flow may take place also through sand filled boreholes and may damage the backfill (SANNER et al. 2000a). There is also the possibility of a thermally induced groundwater flow due to the volumetric expansion of heated water. In relatively porous media convection cells may form. The thermally induced groundwater flow is referred to as a thermosiphon.

Paper VI is a qualitative study of the influence of a temperature induced fracture flow during a thermal response test. The paper treats the situation with one fracture providing the borehole with groundwater of an undisturbed ground temperature while heated borehole water leaves at the upper part of the borehole, thus inducing a regional natural convection movement of groundwater along the borehole. The phenomenon was analysed in 1994 by CLAEISSON et al., for the case of a rock cavern heat store in Lyckeby, Sweden, where the heat losses were 50% higher than expected. The losses were explained by unintended convection around the cavern. In **Paper VI**, the same theory is applied on a groundwater filled borehole heat exchanger in crystalline rock.

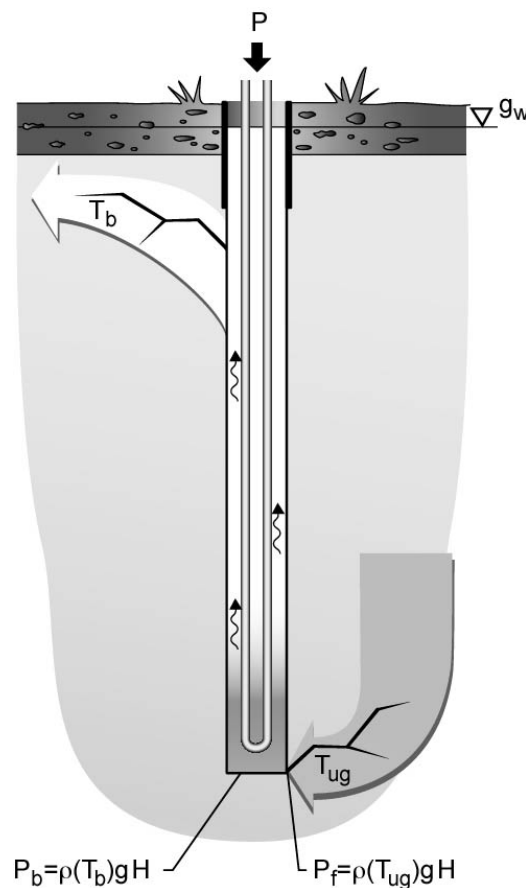


Figure 2.9. The principle of a thermosiphon induced by the pressure difference between heated water in a groundwater filled borehole and groundwater at undisturbed temperature. The heated and less dense water at the temperature T_b is leaving the borehole at the top while groundwater at the temperature T_{ug} is entering the hole at the bottom.

3. SUMMARY OF RESEARCH

3.1 Thermal response test

The Swedish response test apparatus TED has been used at over 30 tests all over Sweden since 1996. The main purpose has been to determine in situ values of effective ground thermal conductivity, including the effect of groundwater flow and natural convection in the boreholes. Tests were conducted at well documented BHE in Luleå (NORDELL 1994). The thermal conductivity from the thermal response tests is greater than the mean value obtained from four drill core samples ($\lambda = 3.4 \text{ Wm}^{-1}\text{K}^{-1}$) tested in the laboratory. According to ERICSSON (1985), in situ determined thermal conductivity is generally slightly greater than corresponding laboratory estimations, due to the laboratory measurements not taking into account water-filled cracks, fissures in the rock and corresponding groundwater movements. The effect of borehole grouting was investigated by filling one BHE with sand to eliminate the influence of natural convection. The effective thermal conductivity from the test data was $3.45 \text{ Wm}^{-1}\text{K}^{-1}$, which is close to the results from laboratory test of the drill core samples, and lower than the average effective thermal conductivity from the response tests in the borehole when filled with groundwater ($\lambda = 3.62 \text{ Wm}^{-1}\text{K}^{-1}$). This indicates that natural convection may influence the thermal behaviour of groundwater filled BTES.

The field tests in Luleå and Sweden confirm laboratory estimations of thermal resistance by KJELLSSON and HELLSTRÖM (1997) and KJELLSSON and HELLSTRÖM (1999) showing significantly lower values for collectors with double U-tubing than with single U-tubing. In the test on grouted borehole with single U-pipe, the thermal resistance was of the same magnitude as for the borehole when groundwater filled, but unlike the un-grouted borehole, the thermal resistance did not change noticeably when the power injection rate was increased. The test results from Luleå are presented in Table 3.1.

TABLE 3.1

Mean values of thermal conductivity and thermal resistance from response tests and core drilling sample.

Installation Type	λ [Wm ⁻¹ K ⁻¹]	Laboratory R _b [KmW ⁻¹]	In Situ R _b [Wm ⁻¹ K ⁻¹]
Single U-pipe	3.62	0.052-0.065	0.056 [0.05-0.06]
Double U-pipe	3.62	0.026-0.038	0.025 [0.02-0.03]
Concentric pipe			0.015 [0.01-0.02]
Single U-pipe, grouted	3.45		
Core drilling sample	3.4★		

★) NORDELL (1994)

Paper II summarises known thermal response testing activities in the world and the state of the art until December 2001. Eight countries (Sweden, Canada, Germany, Netherlands, Norway, Turkey, UK, and USA) have mainly developed the technique. Recently also France and Switzerland have taken up using the method. The report describes thermal response test facilities, test procedures, analysis methods, and test experience. Report appendices 1 and 2 overview the findings. Experience from Swedish field tests and response tests is summarised in **Paper I**.

3.2 Determination of undisturbed ground temperature

In *Paper III* a well-documented BHE at Luleå University of technology (NORDELL 1985, 1986, 1994) was used to compare different ways of estimating the undisturbed ground temperature before a thermal response test. The BHE is drilled in hard crystalline rock to a depth of 60 m and fitted with a single water/glycol mixture filled U-pipe. The borehole is groundwater filled and not grouted and is part of a high temperature storage that was closed down in 1990. The normal annual mean ground surface temperature in the area is 3.5°C but even 10 years after the closing down of the heat storage, the peripheral boreholes were still measuring around 13°C.

A manual temperature logging was done by lowering down a temperature sensor at the end of a 70 m cable in the groundwater filled borehole. The borehole was in thermal equilibrium with the surrounding when the logging started. Temperatures were read every meter for the uppermost 10 meters of the borehole, and every second meter below that level, all the way down to the bottom of the borehole. The resulting temperature profile along the borehole is shown in Figure 3.1. An arithmetic mean temperature of 11.8°C was calculated from the groundwater table and down to the bottom of the borehole.

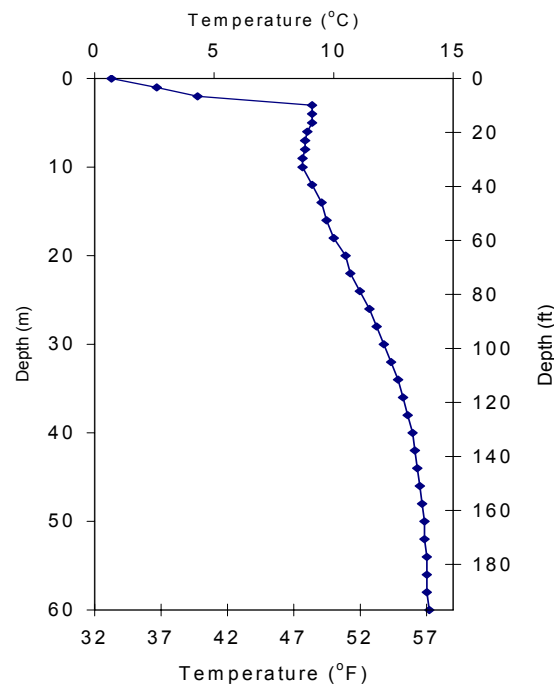


Figure 3.1. Temperature profile along the test borehole

After the manual temperature logging was completed, the borehole collector pipes were connected to the thermal response test device (TED). The data logger was set to record the inlet and outlet temperatures every 10 sec. The electric heater was off during the test. The temperature measurements were analysed assuming plug flow and no delay in temperature recording, which means that measurements taken at certain times correspond to certain depths. The plug flow assumption is reasonable in small diameter pipes and the temperature recordings are reliable as small temperature sensors, immersed in the fluid, were used. The ambient air temperature was about 0°C so the ambient air was cooling the heat carrier, through the pipes between TED and the borehole. Arithmetic mean temperatures were calculated for the first up-flow and for the first down-flow. The up-flow gives a mean temperature of 11.7°C, and the down-flow gives 10.3°C. Thus, the cooling effect of the ambient conditions is seen in the latter.

After approximately 15 min, the temperature fluctuations along the borehole evened out at the mean borehole temperature of 11.8°C. As seen in Figure 3.2 the fluid temperature increases with time. After 30 min, the fluid temperature is 12.2°C and after 60 min it reads 13.8°C. The increase of the mean fluid temperature is caused by the heat gain from the circulation pump.

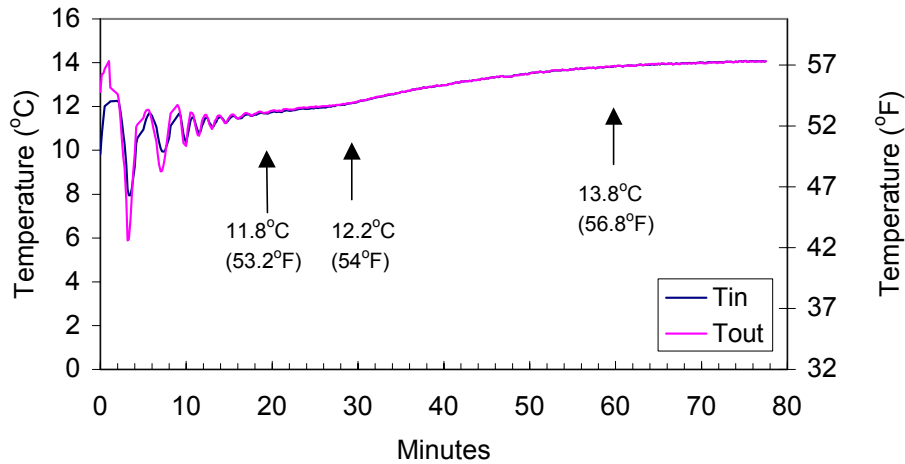


Figure 3.2. 10 sec interval temperature loggings in borehole

The undisturbed ground temperature calculated from the manual log, and the temperature calculated from the recordings from the first few min of circulation in the pipes show an agreement within 0.1°C. After about 15 min the temperature fluctuations in the pipe ceased. The temperature readings of the fluid after 20, 30 and 60 min showed that the value at 20 min circulation agreed well with the manual log, whereas the heat gain from the circulation pump to the fluid over-estimates the undisturbed temperature by 0.4°C already after 30 min. After 60 min, the over-estimation is 2°C.

The occurring temperature disturbance from the circulation pump is proportional to the specific power load on the measured borehole. In this test, a 60 m borehole and a 1.75 kW circulation pump were used. A smaller pump or deeper borehole would result in a less disturbed temperature. At the time of the measurement, the ambient air temperature was considerably lower than the ground temperature, and although the connection pipes and coupling of the test device were thermally insulated, some cooling of the circulation circuit occurred. In the case of warmer weather or solar radiation during the response test, the circuit will be warmed. The disturbance from the ambient conditions will be smaller for deeper boreholes, and better insulation of exposed parts of the test device.

3.3 Analysis models

Four evaluation models – three analytical models and one numerical model – are compared in **Paper IV** when used for analysis of the same three temperature response data sets. In all four models the following three assumptions are made:

- Heat transport in the ground is purely conductive
- Radial symmetry around the borehole axis
- Heat conduction in the direction along the borehole axis is negligible

It is also assumed that the heat transfer rate is constant, although the numerical models can handle varying heat transfer rates without problems.

Model 1 is based on the line source theory as in Equation 2.3. In this model the following approximation of the exponential integral was used (ABRAMOWITZ and STEGUN 1964):

$$E_1 \approx -\gamma - \ln x + A \cdot x - B \cdot x^2 + D \cdot x^3 - E \cdot x^4 + F \cdot x^5 \quad (3.1)$$

$$\text{where} \quad A = 0.99999193 \quad B = 0.24991055 \quad D = 0.05519968$$

$$E = 0.00976004 \quad F = 0.00107857 \quad \gamma = 0.5772... \quad x = \frac{r_b^2}{4a_{\text{ground}} \cdot t}$$

It should be noted that the line source solution includes a kind of thermal capacity in the borehole, namely, the thermal capacity of a borehole completely filled with ground material.

Model 2 is the further simplification of the line source approximation as shown in Equation 2.5

Model 3 is the cylinder source analytical model (Equation 2.6) that CARSLAW and JAEGER (1959, p. 345) presented as a ‘probe’ method of determining thermal conductivity. For large values of the time or a small radius, the temperature of the conductor becomes:

$$T(t) = T_{\text{ug}} + \frac{Q}{4\pi\lambda_{\text{ground}} \cdot H} \cdot \left(2h + \ln \frac{4\tau}{C} - \frac{4h - \alpha_1}{2\alpha_1\tau} + \frac{\alpha_1 - 2}{2\alpha_1\tau} \cdot \ln \frac{4\tau}{C} + \dots \right) \quad (3.2)$$

where

$$h = 2\pi \cdot \lambda_{\text{ground}} \cdot R_b \quad \alpha_1 = \frac{2 \cdot \pi \cdot r_b^2 \cdot c_{\text{ground}}}{c_{\text{cyl}}} \quad \tau = \frac{a_{\text{ground}} \cdot t}{r_b^2} \quad (3.3)$$

$$a_{\text{ground}} = \frac{\lambda_{\text{ground}}}{c_{\text{ground}}} \quad C = e^{\gamma} \quad \gamma = 0.5772... \text{ (Euler's constant)}$$

The borehole heat exchanger is approximated by a cylinder filled with a backfill material of a certain volumetric heat capacity. The borehole cylinder heat capacity is calculated by assuming the U-pipes as one concentric pipe with an equal radius.

Model 4 is an explicit one-dimensional finite difference (FDM) numerical model. The numerical grid consists of 18 cells in the radial direction from the centre of the borehole. The first cell represents the volume and thermal mass of the heat carrier fluid, the second cell represents the filling material, and the remaining cells are used for the surrounding ground. The grid size in the surrounding ground expands outwards. The borehole heat exchanger is a single U-pipe that is approximated by a coaxial pipe filled with heat carrier fluid and surrounded by the borehole filling material. The thermal process between the heat carrier fluid and the borehole wall is accounted for as a borehole thermal resistance. The borehole thermal resistance is divided into two components – a thermal resistance between the fluid and the borehole filling material and a thermal resistance between the borehole filling material and the borehole wall.

The thermal state in the borehole filling is represented by one average temperature. The thermal resistance of the borehole filling material is further divided into two parts – one for the heat flow between the outer surface of the flow channel pipes and the borehole filling temperature, and one between this temperature and the borehole wall.

The specific heat flow is calculated from the heat conductance and the temperature difference between two points at different radial distance from the borehole centre, and the change in temperature over time depends on the change in specific heat flow over time and the specific heat capacity.

Data sets from three thermal response tests conducted at different locations were used for the simulations. All three boreholes were fitted with single U-pipe heat exchangers, however pipe materials and dimensions vary.

Data set A is collected from a response test conducted in Oklahoma, USA (AUSTIN 1998). The grouted borehole was drilled in sedimentary bedrock. *Data set B* comes from a Norwegian measurement of a groundwater filled borehole drilled in slate. *Data set C* is from a Swedish borehole drilled from an underground rock cavern, 240 m below sea level, which meant that the borehole was filled with saline groundwater. The hole was sealed at the top to prevent over-flow due to the high water table. The surrounding rock was granitic, and the air temperature in the cave was constantly 15°C during the measurement. The heat exchanger was made of aluminium pipes to resist the pressure in the borehole. It should be noted that it is quite likely that the thermal process in and around the borehole was influenced by groundwater flow, since the geohydrological conditions are disturbed by the presence of the tunnel.

The four evaluations models were compared with regard to model behaviour. Comparison of the two versions of the line-source theory show no significant difference between model 1 and model 2. The deviation is less than 1%, with the maximum deviation during the first hours of the test. Model 2 represents the line source models in all figures.

The two analytical and the numerical models are compared in Figure 3.3. Thermal conductivity for data set A, B and C were determined for increasing length of data interval. Start point is fixed at hour ten; i.e. the first nine hours of measurement data are excluded from the analysis. The first point in the figures is the estimation for the data interval between hour ten and hour 15. The last point is the estimation for the data interval between hour 10 and hour 50 (A), hour 69 (B) and hour 89 (C). This type of sensitivity test has also been discussed in AUSTIN (1998) and WITTE et al. (2002).

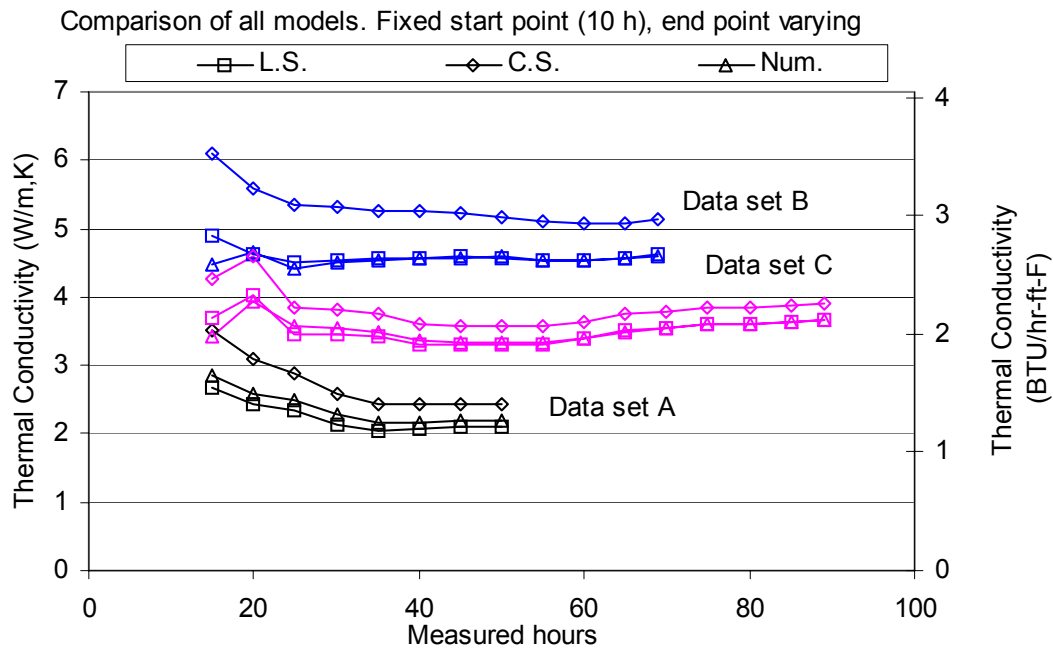


Figure 3.3. Ground thermal conductivity for data sets A, B and C, parameter estimated with the line source approximation (L.S.), the cylinder source solution (C.S.) and the numerical model (Num.). The leftmost data points show the conductivity estimation from the data interval between hour 10 and hour 15. Stability increases with increasing length of data interval.

The results from the line source model and the numerical model are very similar. The average deviation between these models is of the magnitude 1-5 %, whereas the estimate from the cylinder source model is found to be around 10-15 % higher than for the other models. This may be explained as follows; The temperature response of the cylinder source exhibits a slower initial increase due to the thermal mass of the materials inside the borehole wall. As time increases, and the borehole thermal mass gradually becomes less important, the temperature curve will rise more steeply to approach the level of the line source model. Given the same thermal conductivity, the slope of the cylinder source response is steeper than that of the line source. In order to match the slope of the measured response, the thermal conductivity of the cylinder source must be larger than for the line source. This typically also requires that the borehole resistance estimated by the cylinder source is larger, so that the total thermal resistance of the ground and the borehole is appropriate. The deviation between the models decreases with longer measurement time.

TABLE 3.2.

Best fit parameter estimations for the three data sets and the three analysis models

Model	Data set A			Data set B			Data set C		
	λ [Wm ⁻¹ K ⁻¹]	R_b [KW ⁻¹ m]	ΔT [K]	λ [Wm ⁻¹ K ⁻¹]	R_b [Wm ⁻¹ K ⁻¹]	ΔT [K]	λ [Wm ⁻¹ K ⁻¹]	R_b [Wm ⁻¹ K ⁻¹]	ΔT [K]
Line Source	2.12	0.141	0.049	4.59	0.061	0.015	3.31	0.070	0.050
Cylinder Source	2.45	0.164	0.054	5.23	0.070	0.016	3.57	0.079	0.053
Numerical	2.20	0.146	0.050	4.57	0.060	0.015	3.34	0.070	0.051

The best fit between measured and simulated temperatures is found for the conductivity estimated from the data interval between hour 10 and hours 50 (A), 45 (B) and 55 (C). The resulting ground thermal conductivity and borehole thermal resistance are found in Table 3.2 for each of the three models. Best-fit simulated temperatures for the three models are presented together with the measured temperatures in Figure 3.4.

Comparison of model results. First data point varying, last datapoint fixed.

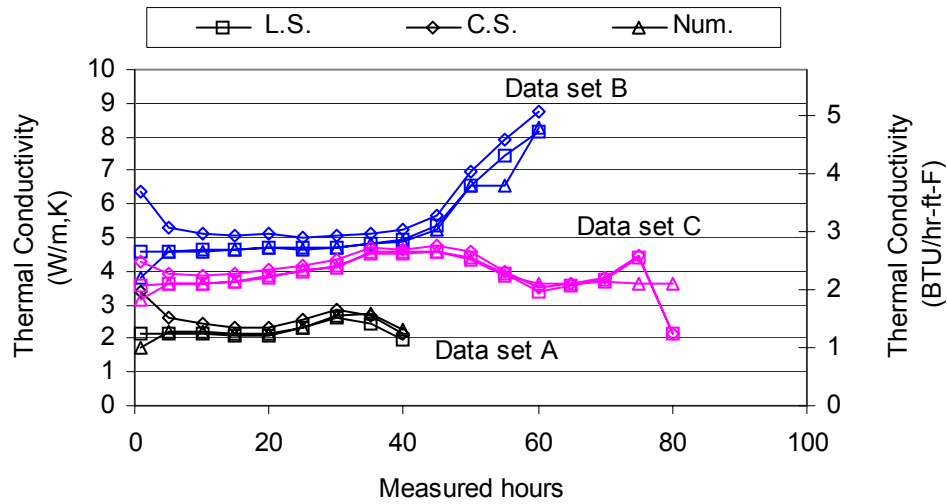


Figure 3.4. Ground thermal conductivity for data sets A, B and C, parameter estimated with the line source approximation (L.S.), the cylinder source solution (C.S.) and the numerical model (Num.). The last data point is fixed, and the first data point is varied.

It is common practice to disregard the measured data during a certain initial time. This is done to avoid the complexity of the transient heat transfer process in the borehole and to use a period when the ground thermal properties have a relatively larger influence on the thermal response. KAVANAUGH et al. (2000) point at several reasons for disturbance of the initial temperature response e.g. disturbances from the drilling procedure, injection of drilling mud, and grouting. The effect of the early measurement data and test length is illustrated in Figure 3.5. The thermal conductivity becomes stable for data series starting at 10-15 h, and becomes unstable again when the data series become too short (<30 h). The line source solution gives results that are least sensitive to the inclusion of early values, whereas the numerical model tends to result in a lower estimate and the cylinder source model a higher estimate of the thermal conductivity when early data is included.

The issue of required response test duration has been discussed in several papers (e.g. AUSTIN et al. 2000, SMITH 1999b). In Figure 3.6 the thermal conductivity estimated with the line source, cylinder source and numerical models are plotted for the three data sets and various test lengths. Five curves with start data point at hour one, five, ten, fifteen and twenty respectively (see legend in Figure 3.6) are plotted using increasing data intervals. As discussed earlier, the line source model gives results most similar to measured data when early data points are included. However, the plots converge around the estimates for ten initial hours excluded, and become relatively

stable when including at least 40 h measurement. In literature recommendations of required response test duration vary from 12-14 h (SMITH 1999b), to 48 h (SPILKER 1998), 50 h (AUSTIN et al., 2000), and 50-60 h (GEHLIN 1998).

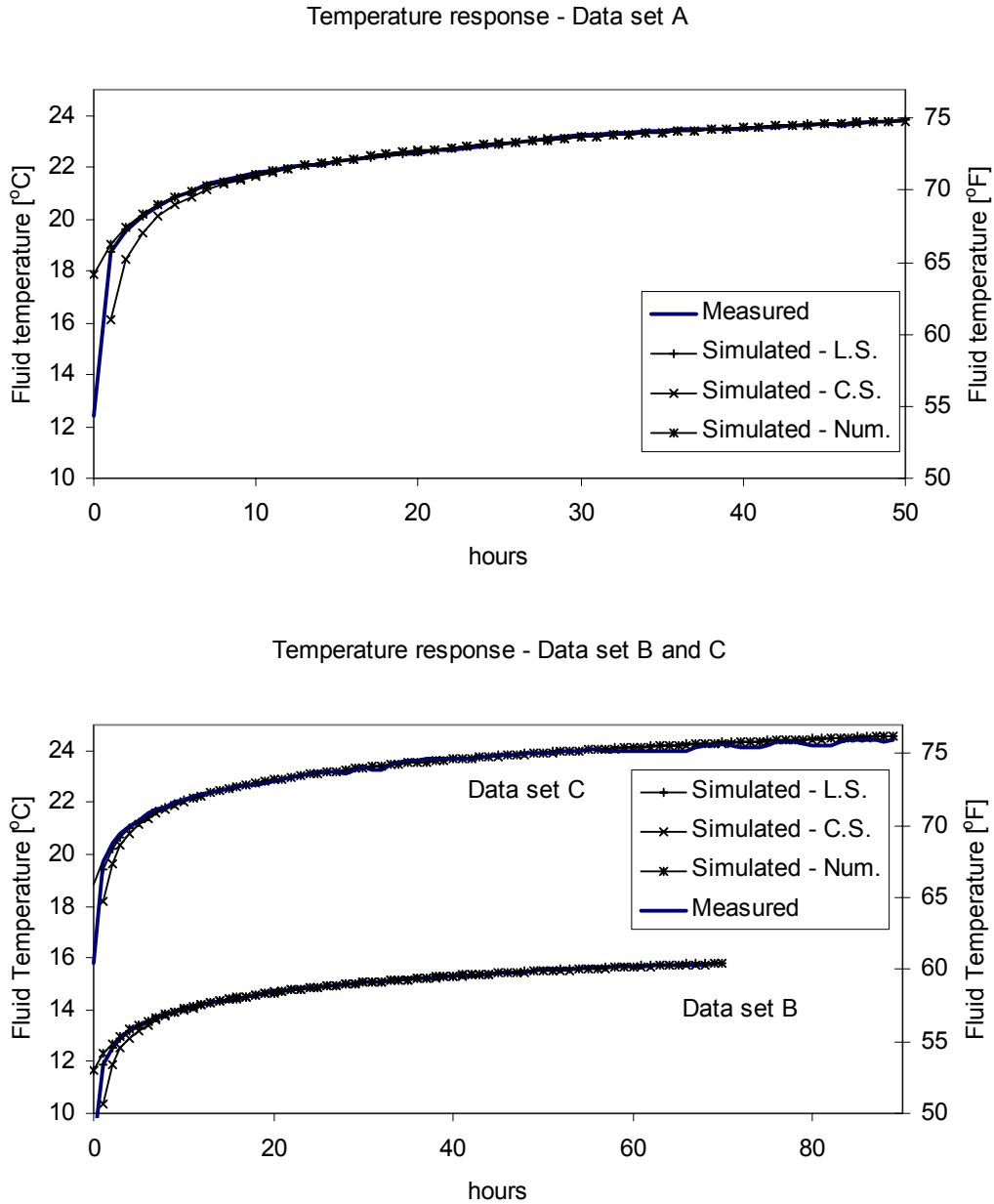


Figure 3.5. Experimental data for data set A, B and C compared to best fit response for the line source approximation (L.S.), the cylinder source solution (C.S.) and the numerical model (Num.).

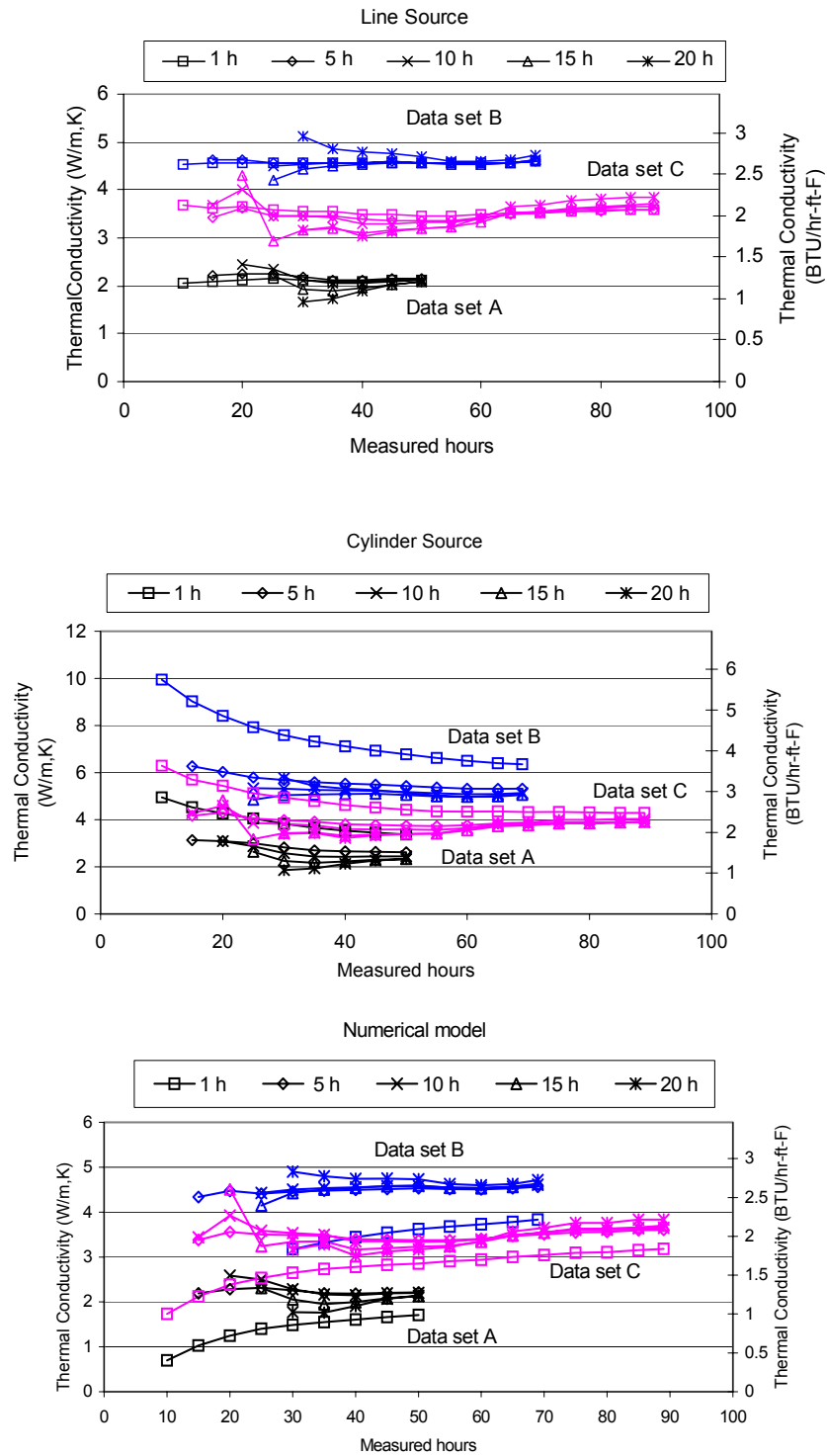


Figure 3.6. Ground thermal conductivity for data sets A, B and C, parameter estimated with the line source approximation, cylinder source and numerical models. The first data point in the data interval used for the estimation is fixed at the hour shown in the legend, and the end point in the interval is shown on the x-axis.

3.4 Fracture flow

In *Paper V*, three models for groundwater flow around a ground heat exchanger in fractured rock are discussed. All models are based on the same two-dimensional numerical finite difference representation of the borehole and its surroundings. A water-filled single (circular) u-pipe ground heat exchanger is represented by four square grids with a thermal capacity of water and a borehole thermal resistance. An equivalent borehole diameter is calculated. A constant initial temperature is assumed for the surrounding ground. The three models are outlined in Figure 3.7.

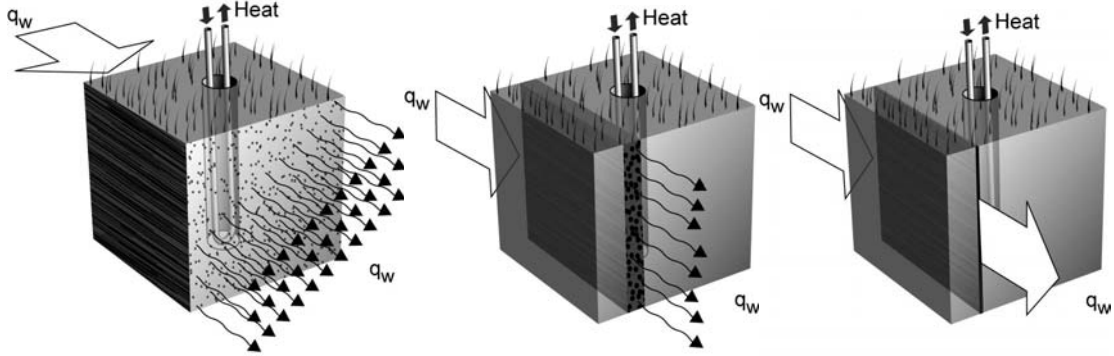


Figure 3.7. (Left) Model A: Homogeneous flow around a borehole surrounded by a porous medium. (Middle) Model B: Homogeneous groundwater flow in a porous zone near a borehole in an impermeable medium. (Right) Model C: Groundwater flow in a fracture near a borehole in an impermeable medium.

Equivalent Porous Medium Model

The first model regards the fractured rock volume as a homogeneous medium equal to a porous medium with a certain (small) porosity. The groundwater flow is evenly spread over the rock volume and water flows through the pore openings between the mineral grains. The darcy velocity, v_{darcy} , is calculated from Darcy's law (Equation 2.9), and the flow velocity, v_w , is the specific flow that passes through the pores between the grains. The equivalent porosity of the rock volume is n_{eq} :

$$v_w = \frac{v_{darcy}}{n_{eq}} \quad [ms^{-1}] \quad (3.5)$$

The incoming groundwater has the same temperature as the undisturbed ground and flows from left to right, only in the x-direction. No vertical water flow is assumed.

Porous Zone Model

The second model assumes the rock to be completely impermeable, and all groundwater flows through a fracture zone of a certain width and at a certain distance from the borehole. The fracture zone is modelled as a zone with a homogeneous porosity equal to that of karst limestone. The distance from borehole to fracture zone is varied. No vertical heat flow is assumed. The groundwater flow rate is the same as for the above model, but since groundwater flow merely occurs in the porous zone, the flow velocity and thus the thermal velocity will be higher. The porous zone has a porosity n_z . No thermal resistance between the impermeable medium and the porous

zone is assumed, and the in-flowing groundwater has the same temperature as the undisturbed ground. Heat capacity in the porous zone is that of water. The width of the porous zone is one grid width, and the flow velocity v_z is

$$v_z = \frac{v_{\text{darcy}} \cdot 1 \cdot 1}{b_z \cdot 1 \cdot n_z} = \frac{v_{\text{darcy}}}{b_z \cdot n_z} \quad [\text{ms}^{-1}] \quad (3.6)$$

where b_z is the width of the porous zone (m), and n_z is the equivalent porosity of the porous zone.

Single Fracture Model

The third model regards the ground as completely impermeable, but with one plane vertical fracture (slot) at varying distance from the borehole. All groundwater passes through this fracture. Heat transfer coefficients at the two fracture walls are used for the heat flow between rock and groundwater. The fracture is located between two grid cells and stretches in the x-direction with water flowing from left to right. The specific groundwater flow is the same as before, however the surrounding ground medium is impermeable and the groundwater flow occurs within the fracture, thus the thermal velocity will be even greater.

The steady-state temperature distribution in the fracture when the fluid is exposed to a constant temperature T_1 on one side of the fracture and a constant temperature T_2 on the other side is calculated. The heat transfer between the fluid and the surrounding temperatures takes place via a heat transfer coefficient α_1 (to T_1) and α_2 (to T_2). The temperature in the flow direction is denoted $T(x)$.

$$T(x) = T_\infty + (T_{\text{in}} - T_\infty) \cdot e^{-bx} \quad (3.7)$$

$$T_\infty = \frac{\alpha_1 T_1 + \alpha_2 T_2}{\alpha_1 + \alpha_2} \quad b = \frac{\alpha_1 + \alpha_2}{c_w \cdot v_{\text{fr}}}$$

In-flowing groundwater from the left has the same temperature as the undisturbed ground and the temperature of the fracture is calculated in the x-direction. Flow velocity v_{fr} in the fracture is calculated from:

$$v_{\text{fr}} = \frac{v_{\text{darcy}} \cdot 1 \cdot 1}{t_{\text{fr}} \cdot 1} = \frac{v_{\text{darcy}}}{t_{\text{fr}}} \quad (3.8)$$

where B is the width of the rock matrix (m) and t_{fr} is the fracture aperture (m).

Model Input

In all cases of modelling, the same ground volume is used, and the same specific groundwater flow rate, hence also the same equivalent hydraulic conductivity for the complete rock volume. When modelling the ground as a continuum, the equivalent ground porosity of $n_{\text{eq}} = 0.05$ is chosen to represent the rock mass. For the case of a porous zone in an impermeable rock volume, the equivalent porosity of $n_z = 0.25$ is used, as to regard the porous zone as a fracture zone, similar to karst limestone.

Values of the effective hydraulic conductivity are in the range $10^{-4} - 10^{-9} \text{ ms}^{-1}$. A comparison of groundwater velocity for the case of a continuum, a porous zone and a fracture for the chosen range of hydraulic conductivity is shown in Table 3.3.

TABLE 3.3
Flow velocity and fracture aperture as a function of effective hydraulic conductivity

K_{eff} [$\text{m}^3 \text{s}^{-1} \text{m}^{-2}$]	q_w [$\text{m}^3 \text{s}^{-1} \text{m}^{-2}$]	Continuum	Porous zone	Fracture	
		v_w [m per year]	v_z [m per year]	v_{fr} [m per year]	t_{fr} [mm]
10^{-9}	10^{-11}	0.0063	0.075	61	0.015
10^{-8}	10^{-10}	0.063	0.75	285	0.03
10^{-7}	10^{-9}	0.63	7.5	1300	0.07
10^{-6}	10^{-8}	6.3	75	6100	0.15
10^{-5}	10^{-7}	63	750	28500	0.33
10^{-4}	10^{-6}	630	7500	130000	0.72

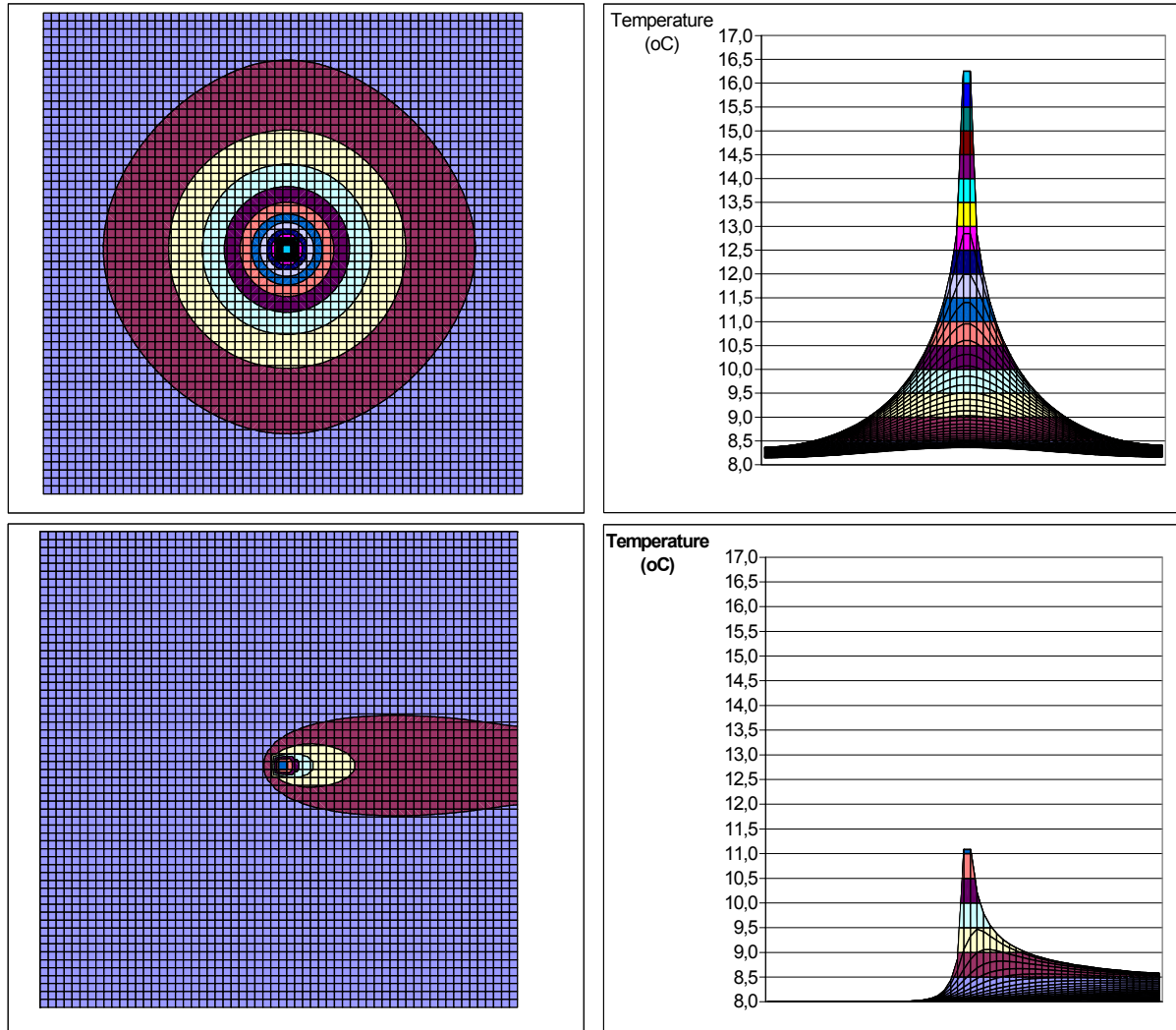


Figure 3.8. Temperature field around the borehole after 100 hours and $K_{\text{eff}} = 10^{-4} \text{ ms}^{-1}$. Only conduction (top) and continuum (bottom).

Temperature fields

In Figure 3.8 and Figure 3.9 the temperature fields around the borehole after 100 hours are calculated with the three flow models and the case of a specific flow rate of 10^{-6} ms^{-1} . The specific flow rate for which the temperature fields are plotted is high, however the temperature field patterns are the same although on a smaller scale for lower flow rates. Flow models are compared with the case of only conductive heat transfer. The bilaterally symmetric temperature pattern around the borehole affected only by thermal conduction is transformed into a considerably cooler borehole with a laterally symmetric temperature field for the case of a continuum with a specific flow rate. The heat transport transverse the flow direction is very small whereas the heat is transported in a narrow streak downstream. The porous zone causes a highly unsymmetrical temperature field where little heat is transferred to the opposite side of the flow zone, and a considerable amount of heat follows the flow in the porous zone. The effect of the convective heat transport is not as effective as the continuum, but yet causes a significantly lower borehole temperature than for the pure conductive case.

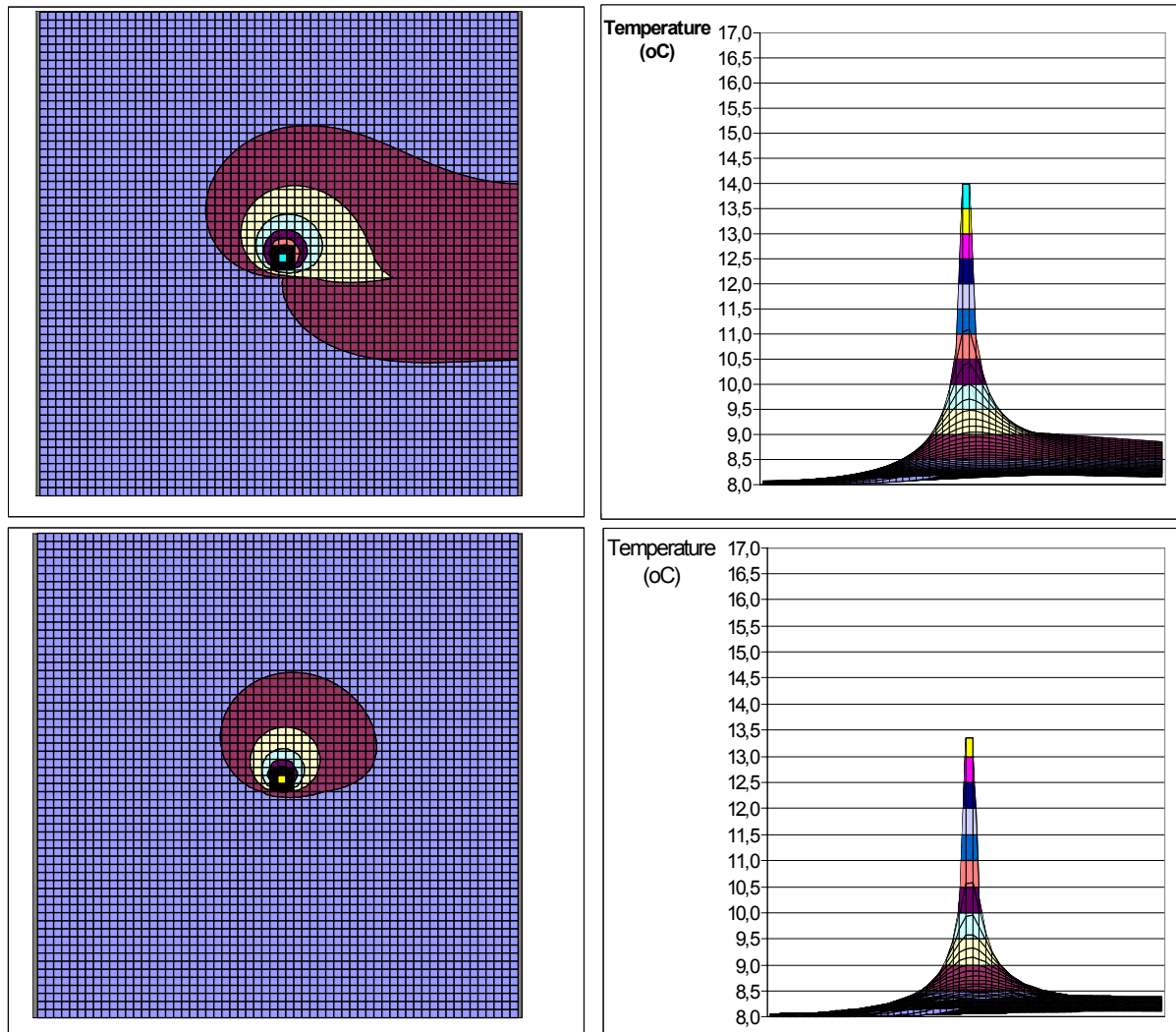


Figure 3.9. Temperature field around the borehole after 100 hours and $K_{eff} = 10^{-4} \text{ ms}^{-1}$. Porous zone at 0.05 m distance from borehole wall (top) and fracture at 0.05 m distance from borehole wall (bottom).

Although narrow and at a distance of 0.05 m from the borehole wall, the high flow velocity in the fracture causes a legible distortion of the temperature field around the borehole. The temperature field is no longer centred round the borehole and hardly any heat is transferred past the fracture. The borehole temperature is lower than for the case of a porous zone at the same distance, but not as low as for the case of a continuum.

Thermal response

Figure 3.10 depicts the temperature development over time for the three models at specific flow rates of 10^{-6} ms^{-1} and 10^{-7} ms^{-1} compared to the case with pure conduction. The borehole temperature development is strongly inhibited for all three flow models at the higher specific flow rate. There is a distinct bend in the initial temperature development after which the further development becomes more or less horizontal. It is noteworthy that the effectiveness among the three flow models alters when the flow rate changes. For the higher flow rate, the continuum is outstandingly most effective, followed by the fracture flow and the porous zone. However, as the flow rate becomes a ten-fold lower, the fracture is now the more effective flow case, followed by the continuum and the porous zone. The break point for the fracture flow becoming more effective than the continuum, appears at a flow rate of ca $5 \cdot 10^{-7} \text{ ms}^{-1}$, as shown in Figure 3.11.

The ratio between the effective thermal conductivity and the actual thermal conductivity (i.e. a kind of Nusselt number) versus specific flow rate is plotted in Figure 3.11. The three models show little or no effect at flow rates less than 10^{-8} ms^{-1} , however the fracture flow starts to cause additional heat transport already at a flow rate of $2.5 \cdot 10^{-8} \text{ ms}^{-1}$ and is the most effective flow model up to flow rates of ca $5 \cdot 10^{-7} \text{ ms}^{-1}$. After that, the continuum model becomes decidedly more effective. At specific flow rate $2.5 \cdot 10^{-8} \text{ ms}^{-1}$, the fracture flow model causes a heat transport corresponding to an effective thermal conductivity that is 6% higher than the purely conductive case. This may seem a small effect, but for a rock with a thermal conductivity of $3.5 \text{ Wm}^{-1}\text{K}^{-1}$, this would correspond to an effective thermal conductivity of $3.7 \text{ Wm}^{-1}\text{K}^{-1}$. The effective thermal conductivity is a measure of average thermal system performance, however it must be noticed that the actual heat transport is larger in the down-stream direction of the fracture.

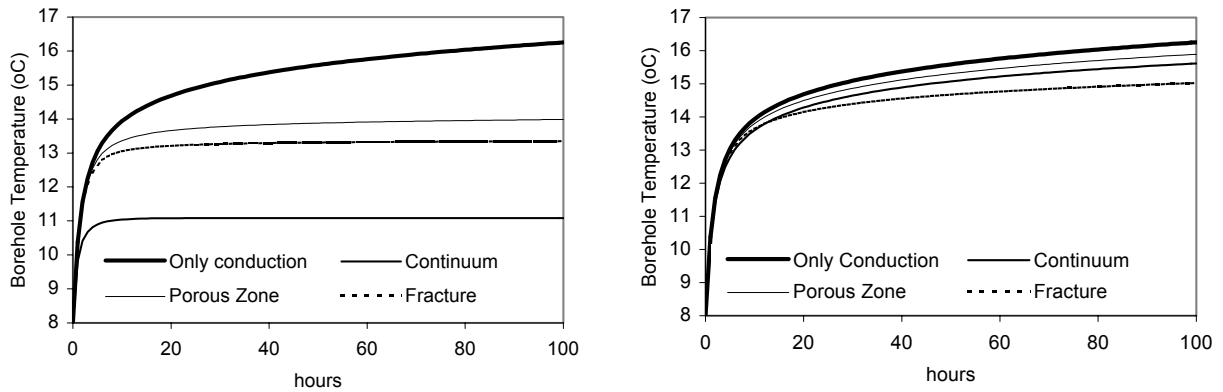


Figure 3.10. Temperature response in borehole for a continuum, a porous zone and a fracture, compared to the case of no convection, for the case of a specific flow rate of 10^{-6} ms^{-1} (left) and 10^{-7} ms^{-1} (right).

Figure 3.12 shows the effect of the distance between fracture or porous zone and the borehole. As expected, the effect of the flow in the fracture or porous zone decreases with the distance from the borehole. Noteworthy, though, is that the porous zone causes a 10% higher effective thermal conductivity still at a distance of 0.1 m for a flow rate of 10^{-7} ms^{-1} and at 0.6 m for 10^{-6} ms^{-1} flow rate. The corresponding distances for the fracture are 0.4 m and 0.75 m respectively.

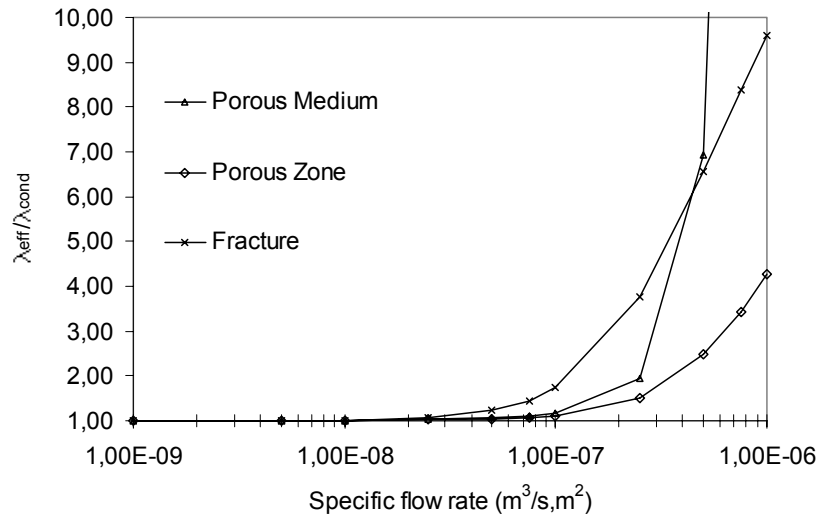


Figure 3.11. The ratio between effective thermal conductivity and real thermal conductivity plotted versus specific flow rate for the case of a continuum, a porous zone at the distance 0.05 m from the borehole wall, and a fracture at the distance 0.05 m from the borehole wall.

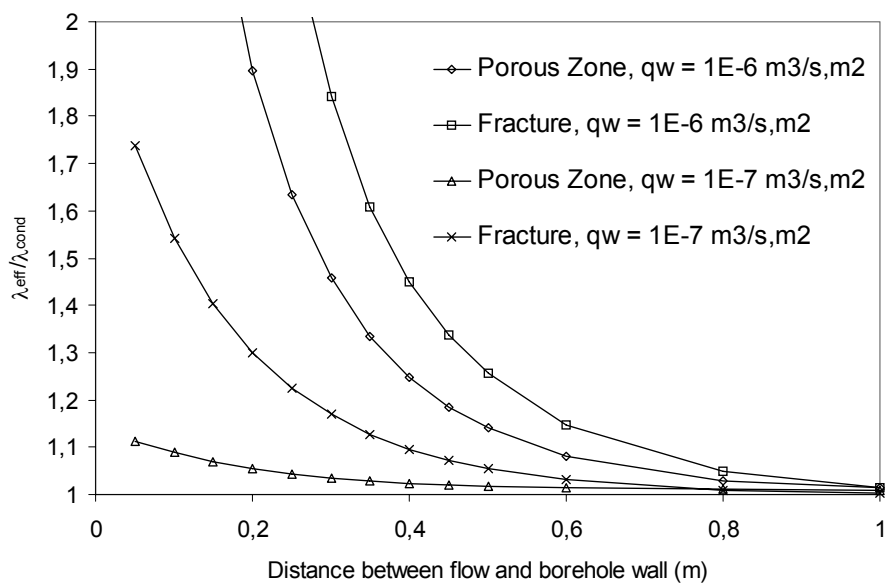


Figure 3.12. The ratio between effective thermal conductivity and real thermal conductivity plotted versus distance between borehole wall and the flow channel.

3.5 Thermosiphon

Laboratory experiment

A small-scale laboratory model of a thermosiphon was constructed at Luleå University of Technology in 1998. The model consisted of two 500 mm high and 70 mm diameter transparent plastic cylinders interconnected with a short 7 mm diameter plastic pipe at the bottom of the cylinders. The upper parts of the two cylinders were brimmed at the same level. One cylinder simulated the borehole and was heated with an immersion heater with variable power level. The outflow from the “borehole” cylinder was weighed on an electronic balance. The other cylinder, simulating the undisturbed groundwater table, was kept at constant temperature and water level throughout the measurements. Five heat power injection rates were used for the measurements. The water mass outflow and its temperature were measured with short time intervals until temperature and flow rate stabilised. The mass flow rate showed a near linear relation to injected power rate. Encouraged by the indications from the laboratory experiment, a numerical simulation model for thermosiphon effect in a full-scale ground heat exchanger borehole in hard rock was developed in order to quantify its influence on the ground heat exchanger efficiency.

Siphon model simulation

An explicit two-dimensional axi-symmetrical finite difference (FDM) numerical heat conduction model was developed to illustrate the thermosiphon effect in a borehole ground heat exchanger. The model takes into account convective flow in the borehole water. The effect of axial heat conduction is found to be negligible. The borehole heat exchanger is a single U-pipe with a borehole thermal resistance, R_b , between the heat carrier fluid and the borehole wall. Half of this resistance is assumed to be between the borehole water and the borehole wall. Undisturbed ground temperature is allowed to increase with depth due to a thermal gradient.

The siphon effect is driven by the pressure difference between the borehole water and the undisturbed groundwater table, due to the density decrease of heated water. Thermal response was calculated for several heat transfer cases.

1. Response with pure conductive heat transport.
2. No flow resistance except that in the borehole, and free availability of groundwater at undisturbed ground temperature.
3. Three different models (A, B and C) adding various restrictions to the inlet and outlet flow of the borehole.

Model A adds an inlet flow resistance in the fracture at the bottom of the borehole. The inlet flow resistance is given by a steady state hydraulic flow resistance between the borehole and an outer radius r_{ug} . The fracture has a hydraulic conductivity K . A hydraulic skin factor ζ , is added at the borehole wall. The pressure difference Δp between undisturbed groundwater conditions and the borehole then becomes:

$$\Delta p = \xi \cdot \frac{\rho(\overline{T_b}) \cdot H \cdot v^2}{2 \cdot D_h} + v \cdot A_h \cdot \left[\frac{\ln\left(\frac{r_{ug}}{r_b}\right) + \zeta}{2\pi \cdot \frac{K}{\rho(\overline{T_b}) \cdot g} \cdot H} \right] \quad (3.9)$$

where ξ is the friction factor in the borehole, $\rho(T_b)$ is the density of the borehole water, H is the total borehole depth, v is the flow velocity, D_h is the hydraulic diameter, A_h is the hydraulic area and r_b is the borehole radius.

Model B is based on model A, but the convective heat transfer from fluid to borehole water is set proportional to the difference between the average fluid temperature T_f and the borehole water temperature T_b varying with depth, z . The heat transfer $q(z)$ then becomes

$$q(z) = PF \cdot (\overline{T_f} - T_b(z)) \quad (3.10)$$

Model C is based on model A, but adds an outlet flow resistance to the fractures at the borehole top. The outlet flow resistance is the same as the inlet flow, thus the flow resistance contribution from the fractures becomes twice as large.

The convective models assume a fracture at the bottom of the borehole, corresponding to undisturbed groundwater table, and fractures letting out heated water at the top of the borehole. As input to the models, a groundwater filled, 0.115 m diameter borehole drilled in hard rock to the depth of 100 m was used. Diameter for the concentric plastic pipe was chosen to 0.040 m. Hydraulic conductivity was varied in the interval 10^{-6} - $5 \cdot 10^{-5} \text{ ms}^{-1}$ and for model C and the case of $K = 10^{-6} \text{ ms}^{-1}$ heat input rate was varied in steps of 25 Wm^{-1} from 25 Wm^{-1} to 100 Wm^{-1} .

Simulation results

Simulating thermosiphon effect during a 100 hours thermal response test in a single groundwater filled borehole without flow restrictions resulted in an effective thermal conductivity of almost $400 \text{ Wm}^{-1}\text{K}$ and volumetric flow rate near 1.5 ls^{-1} through the borehole. Flow conditions in the borehole were turbulent. After 100 hours the Reynolds number was over 3500. Although the assumption of no flow resistance at inlet and outlet is unrealistic, the temperature response had characteristics of a borehole with artesian groundwater conditions, with a near horizontal temperature development, indicating infinite effective thermal conductivity. The temperature profile along the borehole is linearly decreasing with depth, which is the opposite situation from pure conductive conditions, when the temperature increases linearly with depth. Introduction of flow resistance in model A, B and C

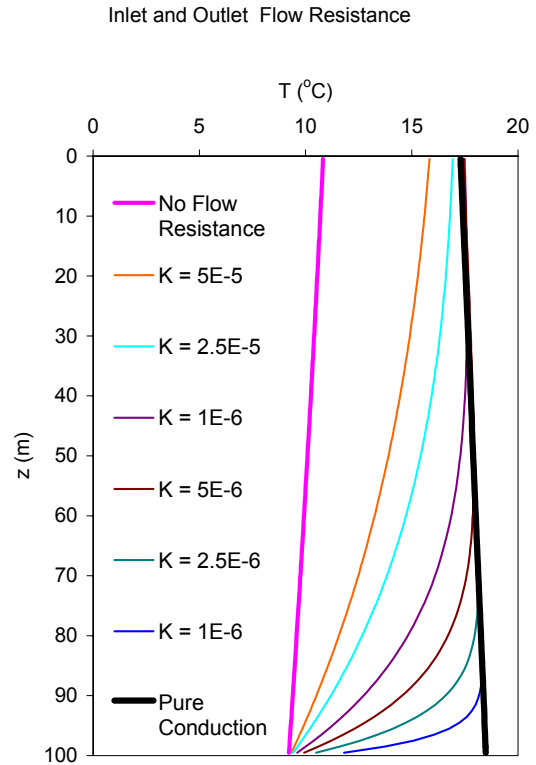


Figure 3.13. Borehole temperature profiles for C at various flow resistance, after 100 hours.

considerably reduced the volumetric flow rate and heat transport. In these three models, flow conditions were well in the laminar zone. Borehole temperature profiles for model C at decreasing hydraulic conductivity from left to right are shown in Figure 3.13, along with the profiles for pure conductive conditions and for unlimited thermosiphon flow.

The thermal response is clearly affected by the thermosiphon effect for all model cases. The ratio of effective thermal conductivity (λ_{eff}) and ground thermal conductivity (λ_{cond}) for model A, B and C is plotted in Figure 3.14 as a function of hydraulic conductivity for 100 hours response. The ratio is lowest for model C, which is the most realistic case, however even for low hydraulic conductivities (i.e. high flow resistance), the thermosiphon effect exists and increases the effective thermal conductivity with several percent. The ratios are 2-9% lower if the data is evaluated for 50 hours response.

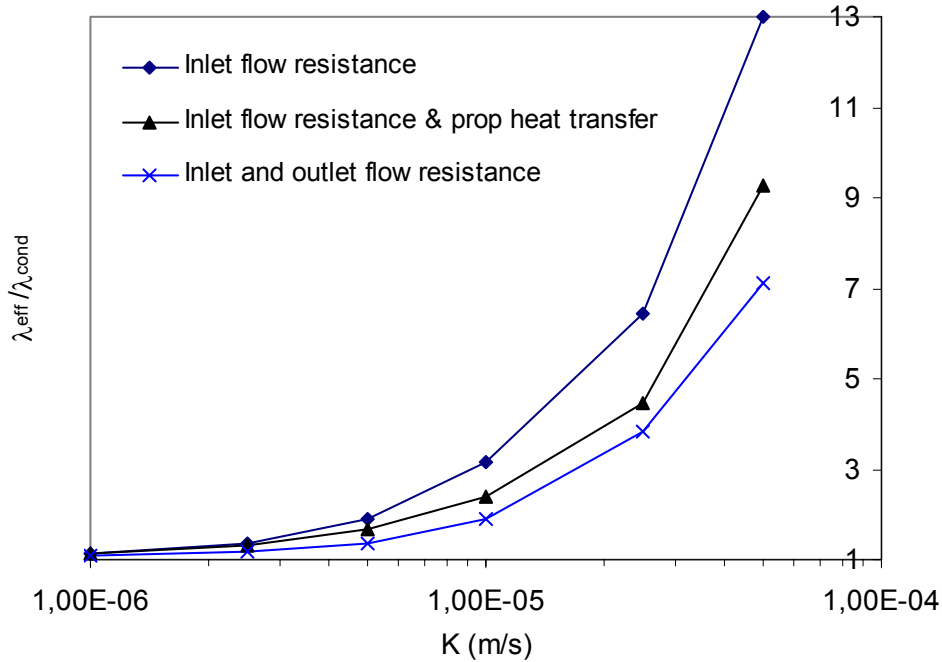


Figure 3.14. Effective thermal conductivity ratio as a function of flow resistance for model A, B and C at 100 hours.

The thermosiphon effect is proportional to the injected heating power rate, as seen in Figure 3.15, where the results from model C and the case of a hydraulic conductivity of 10^{-6} ms^{-1} are plotted. The effect causes a 4% increased effective thermal conductivity even for a low heat load of 25 Wm^{-1} , and for each extra 25 Wm^{-1} , the ratio increases with approximately 0.04.

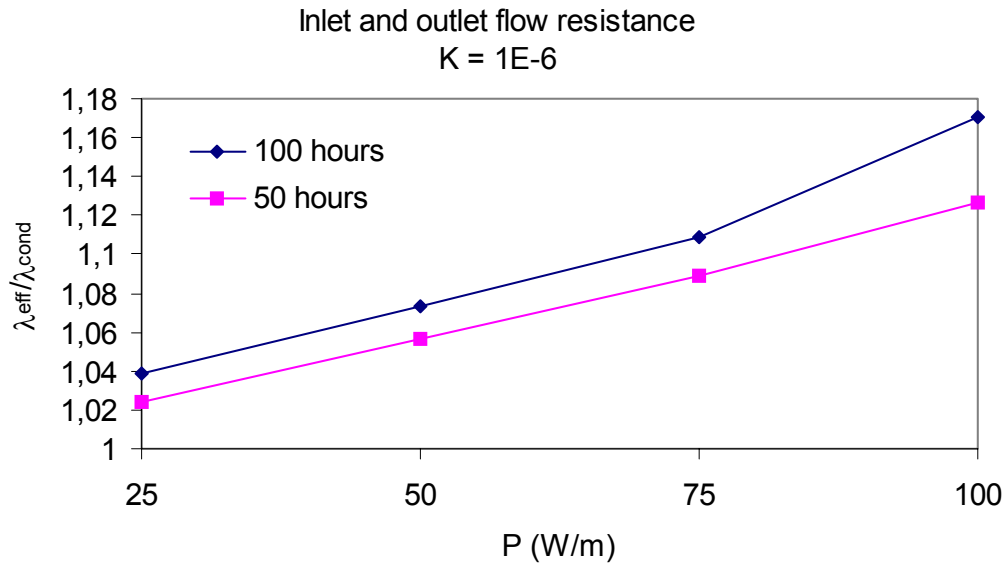


Figure 3.15. Effective thermal conductivity ratio as a function of injected power rate for model C and hydraulic conductivity $K = 10^{-6} \text{ ms}^{-1}$ after 100 hours and 50 hours response.

It is clear that model A over-estimates the thermosiphon effect in the borehole by neglecting outflow resistance. The approach of model B where the heat transfer rate along the borehole is temperature dependent is interesting. However since the effect of the flow resistance in the fractures is considerably larger than the effect of flow resistance in the borehole, model C with flow resistance both at inlet and outlet is more realistic.

In the simulation the simplest geometry was used, with a borehole intersected by two fractures, one in the bottom and one in the top. Real boreholes may be intersected by several fractures at various levels thus complicating the thermal process. Thermosiphon flow may occur for boreholes drilled in porous ground material such as sedimentary rock. Groundwater flow then takes place as a homogeneous flow between the pores or in zones with higher permeability. WITTE (2001) discusses enhanced effective thermal conductivity determined from thermal response tests in sedimentary ground in the Netherlands. A thermal response test was performed with heat extraction instead of injection. The effective thermal conductivity obtained from the heat extraction response test was lower than the result from a response test on the same borehole but with heat injection. The effect was discussed in terms of groundwater flow. Further studies are needed on the behaviour of thermosiphon flow in porous ground.

Several observations of enhanced effective thermal conductivity at thermal response tests have been reported and related to groundwater effects. SANNER et al. (2000a) and MANDS et al. (2001) describe two thermal response tests in boreholes with artesian ground water flow, where the estimated effective thermal conductivity from the temperature response was extremely high. Several Norwegian response tests have measured extreme effective thermal conductivities in shale rich in groundwater. These cases report thermal conductivities measuring 300–600% the expected values. It is likely that the hydraulic conductivity of these shales is relatively high, thus providing good conditions for large thermosiphon flow.

The thermosiphon simulation models presented include several simplifying assumptions. The models do not take into account any heating of the inlet water from the bottom fracture caused by the moving thermal front from the borehole. The models all assume the inlet fracture to be located at the very bottom of the borehole, which is not always the situation. The closer to the top that the fracture connects to the borehole, the smaller will the thermosiphon effect be. The roughness, i.e. the flow resistance factor in the borehole, may need some experimental verification.

4. CONCLUSIONS

4.1 Thermal Response Test

General

Since the introduction of mobile thermal response tests in Sweden and USA in 1995, the method has developed and spread to several other countries in North America and Europe. With the exception of the Dutch system and the AETNA rig, all of the systems rely on imposing a heat injection into the ground, which is intended to be held constant by providing a constant power supply to an electric resistance heater element. The Dutch system can impose either heat injection or heat extraction, and the power output is controlled by maintaining a constant ΔT between inlet and outlet pipes.

A variety of data analysis models have been developed. Various applications of the line source approach are used because of its simplicity and speed. The line source theory is the most commonly used model for evaluation of the response test data in all eight countries, and is dominant in Europe. The use of the cylinder source model for thermal response tests is only reported in the USA, although the theory is used for design of BHE systems in both USA and Canada. Numerical models coupled with parameter-estimation techniques have been used in the USA. Thermal response tests have so far been used primarily for in situ determination of design data for BHE systems, but also for evaluation of grout material, heat exchanger types and groundwater effects. The method is also suitable for verification of design when the BTES system has been constructed.

Swedish response testing

The Swedish response test apparatus TED has been run at a number of tests since 1996. The main purpose has been to determine in situ values of effective ground thermal conductivity, including the effect of groundwater flow and natural convection in the boreholes. The tests indicate that such convective heat transfer may play an important role for the thermal behaviour of groundwater filled BTES. The magnitude of the induced natural convection depends on the heat transfer rate and the temperature level. The influence is small on grouted boreholes. Investigations of thermal resistance in the boreholes show a lower resistance for double U-pipe collectors compared to single U-pipe collectors, which is confirmed by laboratory studies. The two types of concentric collector pipes that have been tested indicate a thermal resistance that is slightly lower or in the same magnitude as double U-pipe collectors.

Undisturbed ground temperature

Temperature logging of the borehole is assumed to give the correct undisturbed ground temperature profile. Short interval fluid temperature logging gives an estimation that is close to the undisturbed temperature. In the measured case with a relatively large circulation pump and a shallow borehole, it can not be recommended to use the temperature reading after 30 min fluid circulation as an estimation of the undisturbed ground temperature. Our study shows that a maximum of 20 min circulation is the limit for a reasonable estimation of the ground temperature from one reading. In a deeper borehole the disturbance from the circulation pump would be smaller, and it will take longer time for the temperature fluctuations in the pipe to cease. A high ambient air temperature could affect the ground temperature estimation.

Analysis models

The line source approximation and the simplified line source approximation give results with negligible difference, thus the commonly used simplified line source approximation may be chosen due to its simplicity. The line source theory and the one-dimensional FDM numerical model result in estimations of the ground thermal conductivities with a difference less than 4%.

Thermal conductivity estimated with the cylinder source model gives 10–15 % higher values than corresponding estimation with the other models. This may be explained by the cylinder source giving a slower initial increase due to the thermal mass of the materials inside the borehole. This effect becomes less important as time increases, and to compensate for this steeper response in the match with the measured response, the thermal conductivity and thermal resistance will both be larger than for the line source estimation.

Of the compared models, the line source representation agrees best with the first hours of the measured data. The cylinder source representation deviates most from the early measured temperatures. The deviation in results between the models is larger for short measurement series, and decrease with longer measurements.

At least 50 h of measurement is recommended. If less than 30 h are used, the convergence of the best fit becomes poor. The conclusion is that if ten hours initial data is excluded and minimum 30 h data from the final hour is needed, then the measurement must continue for > 40 h.

4.2 Groundwater

Fracture flow

Three different models for estimating the heat transfer effect of groundwater flow have been compared and related to the case of no groundwater flow. The three flow models cause significantly different temperature field patterns around the borehole and all three cause lower borehole temperatures. The fracture flow model results in higher effective thermal conductivity than the continuum and porous zone models in the interval $2.5 \cdot 10^{-8} \text{ ms}^{-1}$ to $5 \cdot 10^{-7} \text{ ms}^{-1}$. This illustrates the efficiency of the high flow velocity in the fracture and the large temperature gradient between the borehole and the fracture flow. The effect of the flow in the fracture or porous zone decreases with the distance from the borehole, but even at distances of half a meter or more the porous zone or fracture may result in significantly enhanced heat transfer. Even a relatively narrow fracture close to a borehole may result in higher effective thermal conductivity, although estimations made with a continuum approach may indicate otherwise.

Thermosiphon

The idealised study of the influence of a temperature induced fracture flow during a thermal response test treated a situation with one fracture providing the borehole with groundwater of an undisturbed ground temperature while heated borehole water leaves at the upper part of the borehole. This thermosiphon flow enhancing the convective heat transfer from a heated groundwater filled borehole in hard rock may take place if certain fracture conditions exist in the ground heat exchanger. If such fracture conditions exist, a thermal response test would induce a thermosiphon flow due to the temperature difference between the borehole and its surroundings.

The enhancement of the effective thermal conductivity of the borehole heat exchanger depends on injected power rate and flow resistance in fractures. The fracture flow resistance may be quantified in terms of hydraulic conductivity.

When designing a borehole heat exchanger system where a thermal response test has indicated thermosiphon effects, it is important to relate the result to how the borehole system will be operated. The thermosiphon effect will be in favour for systems with heat injection to the ground, i.e. cooling systems. The groundwater flow will transport more heat from the borehole than under pure conductive conditions. The effect is not occurring in the same way for heat extraction systems due to the lower thermal volumetric expansion at low temperatures, and the prevention of vertical groundwater movements in a frozen borehole.

Multiple borehole systems are not likely to be affected by thermosiphon flow to the same extent as a single borehole during a thermal response test. In multiple borehole systems with short distance between the boreholes, the formation between the boreholes will be thermally disturbed, thus decreasing the potential pressure gradient between borehole water and surrounding groundwater table.

The effective thermal conductivity evaluated from a thermal response test by standard procedure is sensitive to the duration of the measurement. A shorter measurement interval results in lower effective thermal conductivity estimation.

4.3 Further research

The author suggests further studies of the possibility to develop models for estimating and investigating the influence of groundwater from drilling data and hydraulic testing. Natural fractures are not easy to map or picture, though we may be rather sure that they rarely appear so planar, smooth and regular as manmade models assume. The interest in developing more advanced discrete fracture models for the modelling of heat transport effects on borehole ground heat exchangers is limited. Developing models for using drilling data on groundwater flow and fracture zones to estimate the potential groundwater influence on the ground heat exchanger would be of more practical use.

The long-term influence of groundwater effects is another topic that needs further studies. The course of a thermal response test is to be considered a short term operation, but the estimation of effective thermal conductivity from such a test may not necessarily be valid for the long-term operation of the ground heat exchanger. Hydraulic gradients may vary over seasons, which must be considered. The long term effect of thermosiphon flow is likely to decrease due to the increasing temperature field around the borehole, but must be further investigated.

Comparing results from thermal response tests conducted on the same borehole with heat injection and heat extraction respectively, or with more than one power level may provide information about the potential for thermosiphon effects in the borehole. It may also differentiate thermosiphon effect from the effect of artesian borehole flow, since the latter would not be affected by changes in power injection. The temperature profile along the borehole may also provide information about this interesting phenomenon. Another interesting development based on the observed thermosiphon effect would be to stimulate this effect by e.g. fracturing of boreholes used for cooling, i.e. dissipation of heat into the ground. This could strongly reduce the number of boreholes in BTES cooling systems.

An interesting vision is the possibility of performing a thermal response test while drilling. If the heat induced by the hammer could be estimated along with continuous temperature measurement of drilling fluid, ground thermal conductivity could be estimated both for the entire borehole as well as for segments along the borehole. This would make thermal response test a useful tool for geophysical studies and geothermal mapping. It would not evaluate the thermal resistance of the BHE, and the effect of groundwater movement and thermosiphon effect could not be directly evaluated from such a response test. An advantage would however be that the thermal conductivity could be estimated for every borehole in a system.

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PAPER I

Recent Status of In-Situ Thermal Response Tests for BTES Applications in Sweden

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Recent Status of In-situ Thermal Response Tests for BTES Applications in Sweden.

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KEY-WORDS

TED measurement, In-Situ measurement, BTES, thermal resistance, thermal response test

Abstract

In-situ thermal response tests (TED measurements) give reliable design data for BTES systems by providing estimates of the thermal properties of ground and the borehole. Such measurements have been carried out in Sweden on several collector types. Results from performed collector tests (coaxial pipe, single and double U-pipe with 32 mm and 40 mm pipe diameter) were compared with laboratory measurements on the same collector types and with samples from core drilling. Generally, Swedish BTES systems use groundwater-filled boreholes in hard rock, but tests have also been performed on grouted boreholes. Thermal response test also provides information to estimate the effect of groundwater flow and natural convection in and around the borehole. These effects have proved to be of significant importance to the thermal performance of BTES systems. TED evaluations usually result in higher heat transfer properties than those obtained by laboratory measurements. Such differences between the methods are also discussed.

Introduction

Knowledge of ground thermal properties is most important for the proper design of large Borehole Thermal Energy Storage (BTES) systems. The thermal properties of the rock and borehole collector are technical key parameters in designing BTES systems and greatly affect the number of boreholes required for the system. In-situ measured thermal properties improve the reliability of the design and optimisation of BTES systems.

The idea of estimating the ground thermal conductivity and the borehole heat transfer properties by measuring the thermal response of BTES boreholes in-situ was first presented by MOGENSEN (1983). He suggested a simple arrangement with a circulation pump, a chiller with constant power rate, and continuous logging of the inlet and outlet temperatures of the duct. Mogensen's concept was used on several sites for thermal response tests of full-scale BTES during their first days of operation e.g. MOGENSEN (1985), ESKILSON (1987) and HELLSTRÖM (1994). The first mobile thermal response test equipments were developed in 1995-96; TED at Luleå University of Technology, Sweden, (EKLÖF & GEHLIN, 1996) and another at Oklahoma State University, USA (AUSTIN 1998).

TED – The Swedish apparatus for thermal response test

The Swedish mobile thermal response test equipment, TED (GEHLIN 1998, EKLÖF & GEHLIN 1996), was constructed at Luleå University of Technology in 1995-96, see figure 1. The equipment is set up on a small trailer and consists of a 1 kW pump circulating the heat carrier through the borehole collector and through a cross-flow heater with adjustable and stable heating power in the range 3-12 kW. Fluid temperature is measured at the inlet and outlet of the borehole with thermistors, with an accuracy of ± 0.2 K. The temperatures are recorded at a set time interval by a data-logger. The equipment is powered by 16 A electricity. In 1998 TED was slightly altered from its original construction in order to obtain self-venting and automatic pressure control. The thermal insulation of TED has gradually been improved in order to minimise energy losses and influence of temperature changes in the ambient air.

The borehole collector pipes are connected to the equipment with quick couplings at the back of the trailer and the heat carrier fluid is pumped through the system in a closed loop. The fluid passes through the heater, and the inlet and outlet fluid temperatures are recorded every second minute by the data-logger. Also the power supply is recorded during the measurements in order to determine the actual power injection. The power supply has proved to be stable during the measurements. The test is fully automatic including the recording of measured data. The groundwater level is determined manually with a separate fluid alarm during the measurements. To estimate the undisturbed ground temperature, the heat carrier is initially circulated through the system without heating during 20-30 minutes. After this procedure, the heater is switched on and the measurement is proceeding for 60-72 hours.

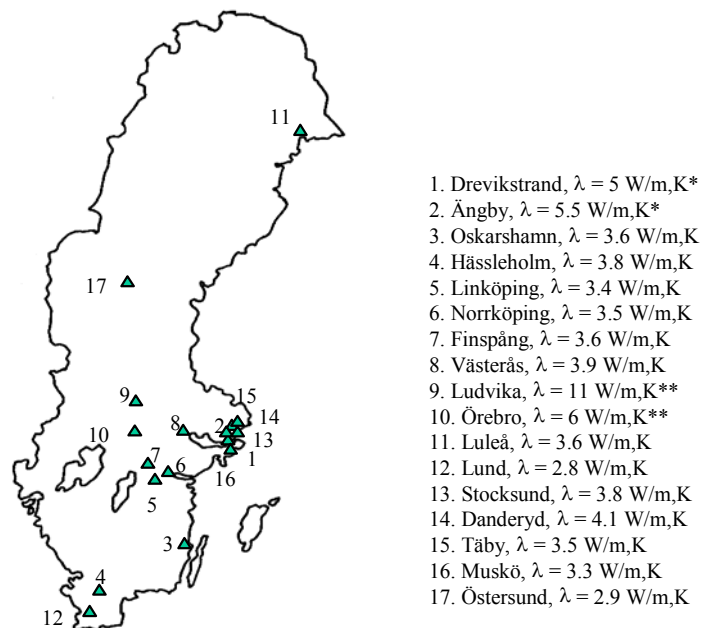
The thermal response of a BTES borehole is pictured by the temperature change in the boreholes when heat is injected or extracted. The transfer of heat to/from the boreholes causes a change in temperature in the surrounding ground. The mathematics are described by HELLSTRÖM (1991, 1994), MOGENSEN (1983) and ESKILSON (1987). Two TED are now in operation in Sweden and since 1999 also one in Norway.



Figure 1. The thermal response test equipment - TED, 1998. Photo: Peter Olsson.

Performed measurements

TED has been used for thermal response tests at many locations all over Sweden since the start in 1996 (GEHLIN, 1998), see figure 2. A series of test holes at Luleå University of Technology has been used for validation of the apparatus and test method. Test length, power rate, reproducibility, and influence of groundwater flow has been investigated. The Luleå test holes are drilled 63 m deep in granite, measure 150 mm in diameter and are filled with groundwater. The boreholes have been used for testing of different borehole collector types, and comparison has been done with grouted boreholes. Tests have also been performed on groundwater filled boreholes at a number of sites in south and middle Sweden. Different types of collectors have been tested. General for Swedish response tests is boreholes drilled in crystalline rock with a high groundwater level. The boreholes are un-grouted and groundwater filled. The ground surface temperature varies from +10°C in the south to +2°C in the north. The supply power rate is very stable, which simplifies the analysis procedure considerably. A line source model suggested by HELLSTRÖM (1991, 1994), MOGENSEN (1983) and ESKILSON (1987) is used. From the measured data, the effective ground thermal conductivity and the thermal resistance of the borehole are calculated.



*) 20 m thermally un-insulated horizontal piping 0.7 m below ground surface to connect boreholes to machine-room (GEHLIN 1998, EKLÖF & GEHLIN 1996).

**) On-going drilling in an adjacent borehole disturbed the measurements (GEHLIN 1998).

Figure 2. Locations in Sweden where TED-measurements have been performed, and measured effective ground thermal conductivity at the location.

In 1999 thermal response tests with TED were initiated in the Oslo region in Norway. The geological and hydrological conditions in Norway are much different from Sweden, which have provided observations of the thermal behaviour of complex shales with large groundwater flow.

Effective thermal ground conductivity

The ground thermal conductivity is a critical parameter for the sizing of the borehole field, and may vary $\pm 20\%$ from the average value of a certain type of rock. As an example, the standard Swedish granite has a thermal conductivity in the range 3.55 ± 0.65 W/m,K (SUNDBERG, 1988). Table 1 shows mean values of thermal conductivity from response tests and core drilling sample at the test site at Luleå University.

Table 1. Mean values of thermal conductivity from response tests and core drilling sample. Measurements by Gehlin.

Test	λ [W/m,K]
Single U-pipe	3.62
Double U-pipe	3.62
Single U-pipe, grouted	3.45
Core drilling sample	3.4*
*) NORDELL (1994)	

The thermal conductivity as measured by the thermal response tests is higher than the mean value obtained from four drill core samples ($\lambda = 3.4$ W/m,K) tested in the laboratory. According to ERICSSON (1985), in-situ determined thermal conductivity is generally slightly higher than corresponding laboratory estimations, due to the laboratory measurements not taking into account water-filled cracks and fissures in the rock.

The effect of borehole grouting was investigated on one of the test holes in Luleå. A well-documented groundwater-filled single U-pipe borehole, was grouted with sand to eliminate the influence of natural convection on the borehole heat transfer capacity. A test with three power injection levels was performed and the thermal conductivity and borehole thermal resistance were evaluated. The effective thermal conductivity calculated from the test data was determined to 3.45 W/m,K, which is very close to the thermal conductivity estimated in laboratory from the core drilling sample ($\lambda = 3.4$ W/m,K), and lower than the average effective thermal conductivity from the response tests on the same borehole when filled with groundwater ($\lambda = 3.62$ W/m,K). This indicates that natural convection may play an important role for the thermal behaviour of groundwater filled BTES.

Thermal resistance of collectors

An important factor for the design of borehole systems is the thermal resistance between the heat carrier fluid in the borehole flow channels and the borehole wall. The fluid-to-borehole wall thermal resistance dictates the temperature difference between the fluid temperature in the collector (T_f) and the temperature at the borehole wall (T_b) for a certain specific heat transfer rate q (W/m):

$$T_f - T_b = R_b \cdot q \quad (1)$$

This so-called borehole thermal resistance depends on the arrangement of the flow channels and the thermal properties of the materials involved. The values observed in field tests range from 0.01 K/(W/m) for the open coaxial arrangement (heat carrier fluid in direct contact with the rock) to about 0.2 K/(W/m) for single U-pipes in bentonite grout where no special precautions have been made to keep the pipes close to the borehole wall. The temperature difference between the heat carrier fluid and the borehole wall is proportional to heat transfer rate. For a typical heat transfer rate of 50 W/m, the corresponding temperature difference becomes 0.5°C to 10°C. The borehole thermal resistance may have significant effect on the system performance and should be kept as small as possible. Filling materials (e.g. bentonite, concrete etc.) in grouted boreholes usually provide better heat transfer than pure stagnant water. However, in water-filled boreholes, the heat transfer induces natural convection in the borehole water. This phenomenon, which is more pronounced at high temperature and large heat transfer rates, leads to a reduction of the overall borehole thermal resistance (KJELLSSON et al. 1997, HELLSTRÖM et al. 2000). The thermal resistance of a borehole collector is calculated from the data from a thermal response test. The overall thermal performance of the borehole field depends not only on the borehole thermal resistance, but also on the transient thermal resistance of the surrounding ground and the thermal influence from other boreholes. Thus, the relative importance of the borehole thermal resistance may differ.

Table 2. Thermal resistance of different collector types

Installation Type	Laboratory R_b [K/(W/m)]	In Situ R_b [K/(W/m)]
Single U-pipe	0.052-0.065	0.056 [0.05-0.06]
Double U-pipe	0.026-0.038	0.025 [0.02-0.03]
Concentric pipe		0.015 [0.01-0.02]

The field tests in Luleå and Sweden confirm laboratory estimations of thermal resistance by HELLSTRÖM et al. (2000) showing significantly lower values for collectors with double U-tubing than with single U-tubing. The laboratory estimations of the thermal resistance for single and double U-tubing were obtained for a heat injection rate of about 100 W/m at fluid temperatures between 22°C and 45°C. These resistances agree well with those obtained from the field measurements with TED. The heat load in the field measurements were 84-113 W per meter. The thermal resistance is dependent on the power load, thus a higher thermal resistance is to be expected at a lower heat injection rate. A recommendation is therefore to run the response test with a power load similar to the expected operational load to obtain accurate estimation of the thermal resistance.

In the test on the grouted borehole with single U-pipe, the thermal resistance was of the same magnitude as for the borehole when groundwater filled, but unlike the un-grouted borehole, the thermal resistance did not change noticeably when the power injection rate was increased.

Conclusions

The Swedish response test apparatus TED has been run at a number of tests since 1996. The main purpose has been to determine in-situ values of effective ground thermal conductivity, including the effect of groundwater flow and natural convection in the boreholes. The tests indicate that such convective heat transfer may play an important role for the thermal behaviour of groundwater-filled BTES. The magnitude of the induced natural convection depends on the heat transfer rate and the temperature level. The influence is small on grouted boreholes. Investigations of thermal resistance in the boreholes show a lower resistance for double U-pipe collectors compared to single U-pipe collectors, which is confirmed by laboratory studies. The two types of concentric collector pipes that have been tested indicate a thermal resistance that is slightly lower or in the same magnitude as double U-pipe collectors. Thermal response test is a useful tool to obtain reliable thermal conductivity data for the design of larger BTES system and for the evaluation of system performance. It may also provide useful information about the thermal performance of different types of borehole heat exchanger, materials and arrangement of flow channels.

Acknowledgments

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PAPER II

Thermal Response Test – State of the Art 2001.

Report IEA ECES Annex 13.

2002

IEA ECES ANNEX 13

DESIGN, CONSTRUCTION AND MAINTENANCE OF UTES WELLS AND BOREHOLES

Thermal Response Test for BTES Applications

State of the Art 2001

October 2002

Thermal Response Test for BTES Applications
State of the Art 2001

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ABSTRACT

Proper design of borehole heat exchangers (BHE) for commercial and institutional buildings utilizing ground source heat pump systems requires a good estimate of the thermal conductivity of the ground in order to avoid significantly over-sizing or under-sizing the ground heat exchanger. A good estimate of the thermal conductivity is also needed when designing a BTES (Borehole Thermal Energy Storage) system. The ground thermal properties may be measured *in situ* at a specific location using what is sometimes referred to as a thermal response test. In a thermal response test, a constant heat injection or extraction is imposed on a test borehole. The resulting temperature response can be used to determine the ground thermal conductivity, and to test the performance of boreholes. Since the initial mobile test rigs were built in 1995 in Sweden and the U.S.A., this technology has been utilized in a number of countries.

Within the framework of the International Energy Agency (IEA), and the Implementing Agreement on Energy Storage through Energy Conservation (ECES), the international co-operation project Annex 13 covers aspects of test drilling, well and borehole design, construction and maintenance of wells and boreholes for UTES applications. This report is the result of the work within the Annex 13 Subtask A2 “Thermal Response Test for UTES Applications”, and describes the current status of the equipment, analysis methodologies, and test experiences of thermal response testing worldwide until December 2001. It also suggests areas of further research and development.

ACKNOWLEDGEMENTS

This state-of-the-art report is the result of the work done within IEA ECES Annex 13, Subtask A2, an international co-operation project within the framework of the International Energy Agency (IEA). Annex 13 covers aspects of test drilling, well and borehole design, construction and maintenance of wells and boreholes for UTES applications and was approved in December 1997.

The aim of Annex 13 Subtask A is to define how to gain information of the underground properties by test drilling, and this report serves to summarise the state-of-the-art of thermal response test for BTES applications.

Economic support by The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning is gratefully acknowledged. Early work on this review was partially supported by the U.S. Department of Energy through contract award DE-FG48-97R810627. Support by the Department of Energy does not constitute endorsement of the views expressed in this article.

NOMENCLATURE

Symbols

a = diffusivity (λ/c)

E_1 = Exponential function

G = cylindrical source function

J_0, J_1, Y_0, Y_1 = Bessel functions

k = slope

$p = r/r_o$

q = heat flow (W/m)

r = radius (m)

r_b = borehole radius (m)

r_o = reference radius (m)

R_b = Borehole thermal resistance (K/(W/m))

t = time (s)

T_b = Borehole wall temperature ($^{\circ}\text{C}$)

T_f = fluid temperature ($^{\circ}\text{C}$)

T_o = Undisturbed ground temperature ($^{\circ}\text{C}$)

T^q = Ground temperature change due to a power pulse ($^{\circ}\text{C}$)

z = Fourier's number = at/r^2

γ = Euler's constant = 0.5772...

λ = ground thermal conductivity (W/m K)

Subscript

f = fluid

1. INTRODUCTION

Underground Thermal Energy Storage (UTES) is a reliable, sustainable and energy-saving technology for cooling and heating of buildings and industrial processes and is now widely spread in the World. In the past 20 years, various applications of UTES have been constructed. Within the IEA Implementing Agreement, Energy Conservation through Energy Storage (ECES) programme, much of the expertise on UTES has developed.

The acronym UTES refers to underground thermal energy storage in general, and is often divided into subgroups according to the type of storage medium that is used. The acronym BTES (Borehole Thermal Energy Storage) refers to storage systems using boreholes or ducts and pipes in the ground.

The thermal conductivity of the ground and thermal resistance of the borehole heat exchanger (BHE) are the two most important design parameters for BTES systems. The two parameters may be determined from *in situ* measurements, which give reliable design data. Such tests are usually economically feasible when designing BTES systems comprising more than a few boreholes. The measurement method has rapidly developed in the last decade and is now usually referred to as Thermal Response Test.

1.1 Historical context of thermal response test

Mogensen (1983) first presented the thermal response test as a method to determine the *in situ* values of ground thermal conductivity and thermal resistance in BHE systems. He suggested a system with a chilled heat carrier fluid being circulated through a BHE system at constant heat extraction (or cooling) rate, while the outlet fluid temperature from the BHE was continuously recorded. The temperature data over time can then be used for determining the ground thermal conductivity and borehole thermal resistance. Mogensen's method was used to evaluate existing BHE systems at several occasions, e.g. Mogensen (1985), Eskilson (1987), Nordell (1994), Hellström (1994).

The first mobile measurement devices for thermal response testing were independently constructed in Sweden and USA in 1995. The Swedish response test apparatus ("TED") was developed at Luleå University of Technology and reported by Eklöf and Gehlin (1996). At the same time a similar device was developed at Oklahoma State University as reported by Austin (1998). Both apparati are based on Mogensen's concept but with a heater instead of a chiller.

Similar test units were later developed in other countries. In the U.S.A., several commercial units have been developed which fit into small (airliner-transportable) shipping containers. In the Netherlands, a large (housed in a sea shipping container) thermal response test measurement unit was later constructed (IF Technology and Groenholland, 1999). The Dutch version uses a heat pump for heating or cooling of the heat carrier fluid.

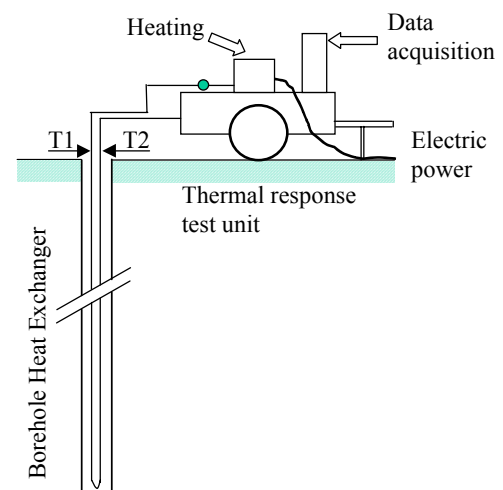


Figure 1: Thermal response test set-up

1.2 Objective and scope

This state of the art report gives a summary of known thermal response testing activities in the world and the state-of-the-art of the technology until December 2001. Mainly eight countries (Sweden, Canada, Germany, Netherlands, Norway, Turkey, United Kingdom, and the U.S.A) have developed the technique. Recently also France and Switzerland have taken up using the method. The report describes the various thermal response test facilities, test procedures, analysis methods, and test experience. Areas of future research and development are highlighted.

2. MEASUREMENT EQUIPMENT

This section describes the measurement equipment utilized in each country. As several countries utilize adapted Swedish equipment, the Swedish equipment is described first. Equipment of the other countries is described in alphabetical order. In all cases, the test apparatus injects or extracts heat into/from the borehole by circulating a heated or cooled fluid and measure its temperature response. A constant heat transfer rate is desirable, as the most commonly used analysis procedures depend on this. The units differ in heating and cooling power, type of instrumentation, size and mobility. Features of the response test apparatus are summarized in Appendix 1.

2.1 Description of equipment by country

2.1.1 Sweden

The mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995-96 (Eklöf and Gehlin 1996; Gehlin and Nordell 1997). The equipment was set up on a small covered trailer and consists of a purge tank holding 85 litres (22.45 gallons) of fluid, a 1 kW (3,400 Btu/hr) pump circulating the heat carrier fluid through the borehole, an in-line electric resistance heater, and instrumentation. The heater has step-wise adjustable power rates in the range of 3-12 kW (10,200-41,000 Btu/hr). Fluid temperatures are measured at the inlet and outlet of the borehole by thermocouples. The fluid temperatures, ambient air temperature, air temperature inside trailer, and power rate are recorded at an optional pre-set time interval.



*Figure 2: The Swedish response test rig (TED).
Photo: Peter Olsson.*

2.1.2 Canada

Environment Canada in Halifax had a response test apparatus built in 1999-2000, based on experience from Sweden and U.S.A. (Cruickshanks et al., 2000). The apparatus consists of a covered, climate-controlled trailer fitted with an 0.75 kW (2,600 Btu/hr) in-line pump, 3 kW (10,200 Btu/hr) in-line electrical water heater, data logger/computer, 2 temperature sensors, 2 pressure gauges, air-bleed valve, etc.



Figure 3: The Canadian response test rig. Photo: Environment Canada.

2.1.3 Germany

In Germany, the response test method was established in 1999. One test rig is operated by Landtechnik Weihenstephan (LTW) and another at UBeG GbR in Wetzlar (Sanner et al., 2000). A third response test device is run by Aetna Energiesysteme GmbH in Wildau (Sanner et al 2001). The construction of the German test equipment is based on the Swedish TED. The Landtechnik Weihenstephan rig consists of two portable containers, and the UbeG rig consists of a frame with the heating equipment and a control cupboard. Both rigs are mounted on a light trailer. The Aetna test rig is also mounted on a trailer. It uses a heat pump instead of a heater and may be operated both in heating and cooling mode (Brandt 2001).



*Figure 4: The German (UbeG) thermal response test rig.
Photo: UBeG GbR, Wetzlar*



Figure 5: The German (Landtechnik Weihenstephan) thermal response test rig.

Photo: Landtechnik Weihenstephan

2.1.4 Netherlands

GroenHolland B.V. in Netherlands built their large response test rig in a sea shipping container (van Gelder et al., 1999, Witte et al. 2000). It is operated with a reversible heat pump, and thus can be run in either heating or cooling mode. The heat pump generates a supply of warm or cold fluid, which is used to maintain a certain temperature difference between fluid entering and leaving the borehole. By selecting an appropriate temperature difference and flow rate, any energy load between 50 and 4500 W (170-15,350 Btu/hr) can be applied. The test rig may be used for response tests on single or multiple boreholes.



Figure 6: The Dutch response test unit with cooling and heating mode. Photo: Groenholland.

2.1.5 Norway

Since 1998, a thermal response test apparatus fabricated by the same firm that built the Swedish apparatus, has been used by a company (“Geoenergi”) in Norway. It has the same operation and construction (but a different Norwegian electrical system). It is described by NGU (2000) and Skarphagen and Stene (1999).



Figure 7: The Norwegian response test rig (TED-model).

Photo: Geoenergi.

2.1.6 Switzerland

Switzerland has two mobile test rigs in operation since 1998 (Eugster 2002) for measurements of boreholes and energy piles. The EPFL rig has a three-step heater unit with variable fluid flow. The EKZ has a two step in-line electric heater and a fixed fluid flow rate.

2.1.7 Turkey

In late 2000, the Centre for Environmental Research at Çukurova University in Adana took over one of the two Swedish test rigs. Slight alterations of the apparatus had to be made to adapt to Turkish standards.



Figure 8: The Turkish response test rig was built in Sweden and is of the TED-model. Photo: Bekir Turgut.

2.1.8 United Kingdom

A British version of thermal response test apparatus was constructed by GeoSciences, Falmouth, Cornwall (Curtis, 2001) in the summer of 1999. The unit is mounted on a small two-wheeled cart for easy transportation. Two 3 kW (10,200 Btu/hr) electric flow heaters can be used to give two different levels of heat injection. A variable speed pump delivers flow rates between 0.25 l/s (4 GPM) and 1 l/s (16 GPM). The electrical power input is measured, and a flow meter combined with two platinum RTD temperature sensors is used to estimate injected heat.



Figure 9: The response test facility in United Kingdom in operation. Photo: Geoscience

2.1.9 U.S.A.

There are a number of response test devices in operation in U.S.A. The first one described in the literature, developed at Oklahoma State University in 1995, is housed in a trailer that is towed to the site and contains everything needed to perform a test – the apparatus, two generators, and a purge tank containing 300 litres (80 gallons) of water. The heating elements are rated 1, 1.5 and 2 kW (3,400; 5,100; 6,800 Btu/hr). By use of a power controller on one of the heating elements, the power can be adjusted continuously between 0 and 4.5 kW (15,300 Btu/hr). Temperatures are measured with two high accuracy thermistors immersed in the circulating fluid, and the flow rate is measured using an in-line flow meter. A typical flow rate of approximately 0.2 l/s (3 GPM) is used.

The power consumption of the heaters and the circulating pumps is measured by a watt transducer. Data is collected every 2.5 minutes. Injected power, the inlet/outlet fluid temperatures and the volumetric flow rate are downloaded to an on-board computer. A detailed description of the test apparatus is available in Austin (1998).

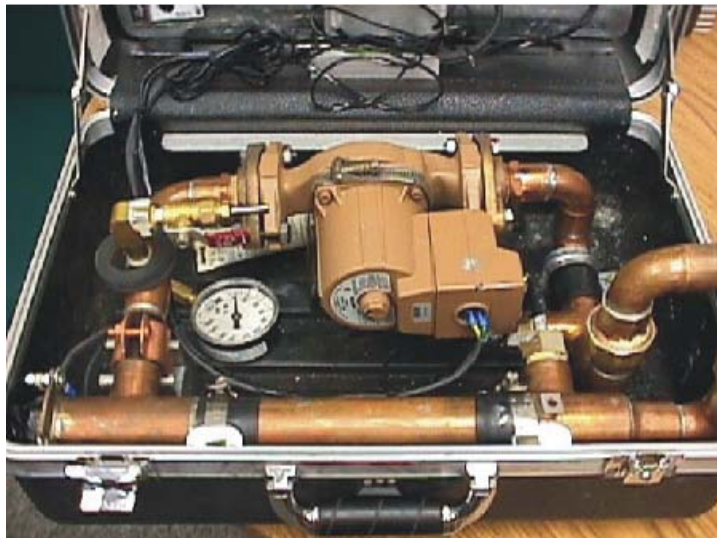
In addition, several commercial thermal response test devices have been developed. An Oklahoma company, Ewbanks and Associates, have developed a number of test rigs, starting with a version mounted on a trailer, and progressing to versions that fit in airline-shippable crates. Another Oklahoma company, Tri-Sun has developed a unit that fits in a medium-sized suitcase. A utility in Nebraska (Spilker 1998) has developed one unit and other commercial units have been fabricated by companies in Texas and Tennessee.



Figure 10: The Oklahoma State University Test Trailer. Photo: Jeffrey Spitler



Figure 11: The suit-case response test set-up of Ewbanks, USA. Photo: Signhild Gehlin.



*Figure 12: Suitcase Unit Fabricated by TriSun Construction, Oklahoma, USA.
Photo: Jeffrey Spitler*

2.1.10 Other Countries

Three other countries are in the process of taking thermal response test units in use. France has shown recent interest in a test facility in their communication with Switzerland and technology transfer has been discussed. The Japanese company GEO-E has prepared a test rig, similar to the Swiss EKZ-unit. Totally six response test units have been built in Japan during the recent years. Measurements have been performed in Japan and China.

3. OPERATIONAL EXPERIENCE

3.1. Running the test

3.1.1 Starting and ending the measurement

Thermal response tests are conducted on one or more test boreholes, representative of the rest of the boreholes needed for the full BTES system. In case of large BTES systems more than one response test may be conducted at several test holes on the site. The test borehole should be drilled to the design depth and fitted with the same type of piping, heat carrier and borehole filling as will be used for the rest of the BTES system. The response test facility is placed as close as possible to the test borehole and is connected to the borehole pipes. The test loop (i.e. the collector pipes and the response test device) is filled with brine and purged. All exposed parts between the borehole and the response test apparatus must be thermally insulated.

The test procedure normally starts with determining the undisturbed ground temperature (see below) and then the heat/cold injection starts. The temperature development of the circulating brine is recorded at a set time interval, normally in the range 2-10 minutes. The test proceeds for several hours (see below) until steady-state conditions are obtained. When a sufficient number of measured hours have passed, the heat/cold injection is switched off. Normally this is the end of the measurement and the test device is disconnected, but in case the temperature decline will also be measured, the circulation pump is left on for another number of hours until the borehole temperature is back to the approximate initial conditions. After the response test, the test borehole is included in the full BTES system.

3.1.2 Determining undisturbed ground temperature

For some analysis procedures, estimates of the ground thermal conductivity depend on the undisturbed ground temperature, which must be determined before the response test has started. The undisturbed ground temperature may possibly also be determined after the ground has reached thermal equilibrium after the test. This will however take several days.

The geothermal gradient is a factor that cannot be neglected, and causes the undisturbed ground temperature to increase with depth. The temperature gradient varies globally, but is normally in the range 0.5-3 K per 100 meter (0.3-1.6 F per 100 ft). Eskilson (1987) showed that for BTES applications, it is not necessary to consider the temperature variation along the borehole. The mean temperature along the borehole may be used as a homogeneous undisturbed ground temperature around the borehole.

The undisturbed ground temperature may be determined in two ways. One commonly used method is to circulate the fluid through the borehole for about half an hour before the heater is switched on for the test. The collected temperature data is used to decide the average borehole temperature. One problem with this method is that the circulation pump will inject some heat into the system, which thus induces an increased temperature increase. Another method, which may be more reliable, is to lower a thermocouple down the water-filled U-tube before the measurement has started. The temperature is measured every few meters along the U-pipe. The temperatures are used to calculate an arithmetic mean borehole temperature.

Gehlin (2001) compares the result from three methods of estimating the undisturbed ground temperature for thermal response tests. A manual temperature log was first conducted on a well documented 60 m (197 ft) borehole in hard rock, fitted with a single U-pipe collector. After the manual log, the collector was connected to a response test facility (the Swedish TED) and the collector fluid was circulated without heat injection for more than 70

minutes while inlet and outlet temperatures were recorded every 10 seconds. The undisturbed ground temperature calculated from the manual log and the temperature recordings of the first few minutes of circulation in the pipes were compared and showed an agreement within 0.1°C (0.2°F). These estimates were also compared to temperature readings of the fluid after 20, 30 and 60 minutes and showed clearly that the heat gain to the fluid from the circulation pump gives an over estimation of the undisturbed temperature by 0.4°C (0.7°F) already after 30 minutes. The value at 20 minutes circulation agreed well with the manual log. The influence of the heat gain from the circulation pump depends on the power rate of the pump related to the borehole depth.

3.1.3 Duration of measurement

The measurement time necessary for obtaining sufficient data for a reliable analysis has been discussed much since the beginning of response test measurements. Austin, et al. (2000) found a test length of 50 hours to be satisfactory for typical borehole installations. Gehlin (1998) recommends test lengths of about 60 hours. Smith and Perry (1999a) claim that 12-20 hours of measurement is sufficient, as it usually gives a conservative answer, i.e. a low estimate of thermal conductivity. Witte, et al. (2002) performed tests over 250 hours for research purposes; their normal commercial tests are 50 hours in length. Austin, et al. (2000) and Witte, et al. (2002) have compared tests of different duration. Test cost is related to test length. One contractor (Wells 1999) who performs in situ tests in the Ohio area, estimated the cost to the customer for a 12 hour test at \$4500; and \$6800 for a 48 hour test. About \$2000 represents the cost of drilling the borehole, installing the U-tube, and grouting the borehole. Labour costs for this contractor are about \$42/hour. Furthermore, according to the contractor, since many of the in situ tests are done as part of utility-funded feasibility studies, the additional cost for a 50-hour test is hard to justify.

3.2 Operational problems and considerations

Operational experiences of the test units have shown some sources of error that can affect the results. These include heat leakage to or from the air, fluctuations in electrical power, and inaccurate measurements of the undisturbed ground temperature.

3.2.1 Heat losses or gains

Uncontrolled heat losses or gains to or from the environment due to insufficient thermal insulation cause problems (Austin 1998; Witte, et al., 2002) in the analysis of the experimental data. Even though the heat transfer to or from the environment may be relatively small compared to the heat transfer to or from the earth, it can have a significant adverse influence when the results are analysed with the line source method. This problem may be overcome by adequate insulation of the experimental apparatus and piping. In systems where the injected/extracted heat is determined by measuring the inlet and outlet fluid temperatures and flow rate, moving the temperature sensors into the piping in the ground (Witte, et al. 2002) may also help. It is helpful to measure ambient air temperatures during the test so that the effects of changing ambient air temperature may be investigated. It may be possible to correct for these effects with some analysis procedures if a good estimate of the heat loss or gain can be made.

3.2.2 Power stability

A common problem is fluctuations in the electrical power supply (Austin 1998). This can cause problems with line source analysis, which usually assumes a constant heat injection rate. A recommended solution reported in the U.S.A. (Ewbanks 1999) is to use a significantly oversized generator (e.g. a 50 kW generator for a 5 kW load), which should maintain a relatively constant power. Another solution is to control the temperature difference directly, while maintaining a constant flow rate or to control the temperature difference while measuring the flow rate, so as to maintain a constant heat injection or extraction rate. This approach has been utilized by Groenholland (Witte 2002). A third solution is to use an analysis procedure that can account for fluctuating power.

3.2.3 Ground temperature

All analysis procedures depend on the ground being thermally undisturbed. The ground is necessarily disturbed by the drilling process, which may result in the ground surrounding the borehole being warmer (due to energy input or exothermic heating with cementitious grouts) or wetter (due to circulation of drilling fluid) or dryer (due to circulation of air) than it would otherwise be. The time required for the ground to return to an approximately undisturbed state has not received enough systematic study. Kavanaugh (2000) recommends that a thermal response test be delayed at least 24 hours after drilling, and at least 72 hours if cementitious grouts are used. Earlier work by Lilja (1981), Bullard (1947), Lachenbruch and Brewer (1959) might also be helpful in determining temperature disturbances caused by drilling.

3.2.4 Influence of variations in thermal conductivity with depth

For the analysis of a thermal response test it is normally assumed that the ground thermal conductivity along the borehole is homogeneous. However, there is normally a different top-soil layer with a considerably lower thermal conductivity than the deeper rock or sediments. According to Eskilson (1987), a numerical simulation of a deep borehole in granite ($\lambda = 3.5 \text{ W/m,K} = 2 \text{ Btu/hr-ft-F}$) with a 5 m thick top-soil layer ($\lambda = 1.5 \text{ W/m,K} = 0.9 \text{ Btu/hr-ft-F}$) shows that the thermal performance changes less than 2% for a 100 m (328 ft) deep borehole. His conclusion is therefore that the effect of a top-soil layer of less than 10 m (33 ft) can be neglected.

This may be further complicated by a difference in conductivity above and below the static groundwater level. The thermal response test naturally gives an aggregate value of all the layers. Some insight into the variation of conductivity with depth may be obtained by measuring the temperatures along the borehole after the test. (Witte 2001) In the case of a heat rejection test, areas of the ground with higher conductivities will have lower temperatures, and areas with lower conductivities will have higher temperatures.

3.2.5 Groundwater flow

The influence of groundwater flow on the performance of borehole heat exchangers has been a topic of discussion. Field observations have suggested that there is a groundwater aspect on the borehole performance (Gehlin 1998, Helgesen 2001). Some theoretical studies have been published on the subject. Eskilson (1987), Claesson & Hellström (2000) and

Chiasson et al (2000) presented models for the influence of regional groundwater flow based on the assumption that the natural groundwater movements are reasonably homogeneously spread over the ground volume. This applies well on a homogeneous and porous ground material. Eskilson and Claesson & Hellström use the line source theory for modelling the groundwater effect on a single vertical borehole. They conclude that under normal conditions, the influence of regional groundwater flow is negligible.

Chiasson et al. (2000) use a two-dimensional finite element groundwater flow and mass/heat transport model and come to the conclusion that it is only in geologic materials with high hydraulic conductivities (sand, gravels) and in rocks with secondary porosities (fractures and solution channels in e.g. karst limestone), that groundwater flow is expected to have a significant effect on the borehole performance. Simulations of the effect of groundwater flow on thermal response tests give artificially high conductivity values.

The influence of single or multiple fractures and fracture zones has not been thoroughly studied, and may give some explanation to field observations where groundwater flow has occurred.

3.2.6 General Operational Experience

In addition to the problems described, which may have a more or less subtle influence on the results, practitioners also face problems that can have a catastrophic effect on the results. These include more or less unpredictable disturbances such as:

- Blocked U-tubes. Practitioners have arrived at a test site and then found that the flow in the U-tube was blocked by pea gravel (apparently caused by spilling some of the backfill material into a U-tube) or pecans (apparently caused by a squirrel).
- Power failure. Power failures will almost always require that the test be redone due to the interruption of the heat injection pulse. Power failures have occurred due to generators running out of fuel, electrical power plugs vibrating out of the generator, the power cord being disconnected by construction workers or cows.
- Fluid leakage. Since the equipment is mobile, with time it is likely to develop small leaks. In the right combination, this can result in air entering the fluid loop and, with enough air in the system, the system will begin to undergo rapid transients as large air bubbles form.

4. ANALYSIS METHODS

Currently used methods to estimate the thermal properties of the ground formation may be divided into direct methods such as the line source and cylinder source approaches and methods that use formal parameter estimation techniques. The following six methods, based on four theoretical approaches, have been reported:

1. Line source theory as used by Eklöf and Gehlin (1996), Gehlin and Nordell (1998).
2. Line source theory as used by Smith (1999a)
3. Line source theory as used by Curtis (2001).
4. Cylinder source theory (used by Kavanaugh and Rafferty 1997),
5. Parameter estimation with 1D finite difference borehole model (Shonder and Beck 1999).
6. Parameter estimation with 2D finite volume borehole model (Austin et al. 2000).

4.1 Line source

The equation for the temperature field as a function of time and radius around a line source with constant heat injection rate (Carslaw and Jaeger, 1959) may be used as an approximation of the heat injection from a BHE:

$$T^q(r, t) = \frac{q}{4\pi\lambda} \int_{\frac{r^2}{4at}}^{\infty} \frac{e^{-u}}{u} du = \frac{q}{4\pi\lambda} E_1(r^2/4at) \quad (1)$$

With increasing time, the radius of influence will increase. Ingersoll and Plass (1948) show that the equation can be used for cylindrical heat injection ducts with an error less than 2% if

$$t > \frac{20r_b^2}{a} \quad (2)$$

For a normal borehole, t is in the range 10-20 hours.

E_1 is the so-called exponential integral. For large values of the parameter at/r^2 , E_1 can be approximated with the following simple relation:

$$E_1(r^2 / 4at) = \ln\left(\frac{4at}{r^2}\right) - \gamma \quad \frac{at}{r^2} \geq 5 \quad (3)$$

where the term $\gamma = 0.5772\dots$ is Euler's constant. The maximum error is 2.5% for $at/r^2 \geq 20$ and 10% for $at/r^2 \geq 5$.

The measured temperature during a response test is the fluid temperature, and the relationship between the fluid temperature and the temperature at the borehole wall (T_b at r_b) is:

$$T_f^q(t) = T_b^q(t) + q \cdot R_b \quad (4)$$

where R_b is the thermal resistance between the fluid in the pipes and the borehole wall. The index q in the temperatures denotes that it is the temperature change due to the heat pulse q . Thus the fluid temperature as a function of time can be written:

$$T_f(t) = \frac{q}{4\pi\lambda} \cdot \left(\ln\left(\frac{4at}{r^2}\right) - \gamma \right) + q \cdot R_b + T_o \quad (5)$$

where T_o is the undisturbed ground temperature.

In practice, researchers have made use of this approach in somewhat different ways although they essentially follow Mogensen (1983).

Eklöf and Gehlin (1996), Gehlin and Nordell (1998), Sanner et al. (2000) and Cruickshanks et al. (2000) apply the line source solution to determine the thermal conductivity of ground formation for underground thermal energy storage systems. The implementation is done by determining the slope of the average fluid temperature development versus the natural log of time curve:

$$T_f(t) = k \cdot \ln t + m \quad k = \frac{q}{4\pi\lambda} \quad (6)$$

where k is the slope of the curve.

Gehlin and Eklöf (1996) recognize that it is, in practice, difficult to keep the heat injection constant during the entire test period due to unstable power supply. To account for such power variations, the heat input may be decomposed into stepwise constant heat pulses that are then superimposed in time. Thus, the average borehole temperature at any given time step is expressed as a sum of the heat input contributions from a series of past time intervals. The effective conductivity of the ground formation is then computed by considering the stepwise change in the heat injection. However, pulses of shorter duration than 2-3 hours may be neglected since the heat capacity of the borehole will buffer the effect.

The use of Equation 6 for the evaluation of the thermal conductivity may be misleading if the data series are disturbed by ambient air temperature. It also requires that an initial few hours of measurements be ignored when calculating the slope. An alternative procedure, used in Sweden (Gehlin 1998) and Norway, is a parameter estimation that adjusts the thermal conductivity of the ground and the thermal resistance between the fluid and the borehole wall. Equation 5 is used to obtain the best match to the experimentally determined temperature response. This approach indicates where data intervals are disturbed (e.g. increased temperature due to solar radiation), thus the disturbances may be observed and adjusted for in the parameter estimation. The difference between the two methods is illustrated in Figure 13.

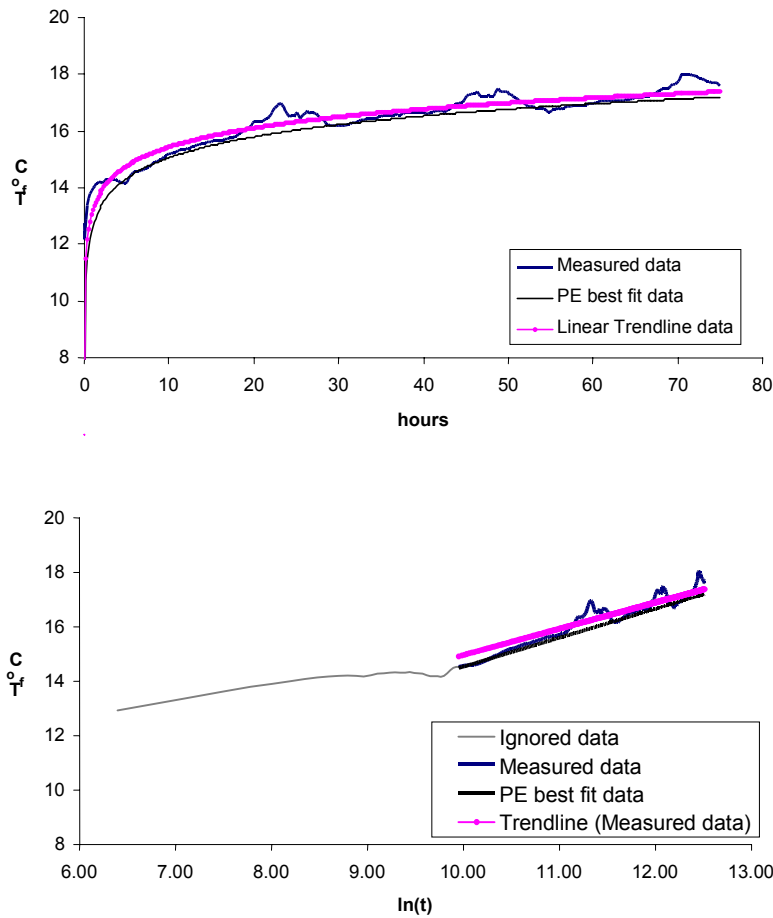


Figure 13: The two graphs show the same data sets; Measured data, Parameter estimation best fit data and Trendline data, presented versus time (upper) and linearized (lower).

Smith (1999a, 1999b) also uses the line source approach to estimate the thermal conductivity on several test boreholes at the Oklahoma State University. In Smith's (1999b) implementation, a great deal of care was applied in manually selecting time periods when the heat input and fluid flow rates were "nearly" constant. That is since even small perturbations in the power input or the fluid flow rate can, as demonstrated by Austin (1998), cause significant variations in the results

The approach to response test data analysis in the UK is to make a direct analogy of the thermal response test to a hydraulic single well test. A period of constant heat injection is followed by a period of near-zero heat injection. Two line source solutions are superposed and fit with least squares. From this, the thermal conductivity and borehole resistance can be estimated.

4.2 Cylinder source

The cylinder source model, of which the line source model is a simplified variation, may be used for approximating the BHE as an infinite cylinder with a constant heat flux. The heat exchanger pipes are normally represented by an "equal diameter" cylinder. The cylindrical source solution for a constant heat flux is as follows:

$$T^q(r, t) = \frac{q}{\lambda} \cdot G(z, p) \quad \begin{cases} z = \frac{at}{r^2} \\ p = \frac{r}{r_0} \end{cases} \quad (7)$$

where $G(z, p)$ is the cylindrical source function as described by Ingersoll (1954):

$$G(z, p) = \frac{1}{\pi^2} \int_0^\infty f(\beta) d\beta \quad (8)$$

$$f(\beta) = (e^{-\beta^2 z} - 1) \cdot \frac{[J_0(p\beta)Y_1(\beta) - Y_0(p\beta)J_1(\beta)]}{\beta^2 [J_1^2(\beta) + Y_1^2(\beta)]} \quad (9)$$

where J_0 , J_1 , Y_0 , Y_1 are Bessel functions of the first and second kind.

Deerman and Kavanaugh (1991) and Kavanaugh and Rafferty (1997) suggested an iterative procedure, which uses the cylinder source method to inversely determine the ground thermal conductivity. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground loop heat exchanger. Based on a short-term *in situ* test, the effective thermal resistance of the ground of a daily heat pulse is compared to a value computed from the Fourier number (z) and the cylinder source function $G(z, p)$ with assumed value for the thermal conductivity and the diffusivity of the ground formation until the ground resistance values are the same.

4.3 Parameter estimation with 1D finite difference borehole model

Shonder, et al. (1999) developed a parameter-estimation-based method which is used in combination with a 1D numerical model. This model is similar to a cylinder-source representation, in that it represents the two pipes of the U-tube as a single cylinder. However, it adds two additional features -- a thin film, that adds a resistance without heat capacity; and a layer of grout, which may have a thermal conductivity and heat capacity different from the surrounding soil, Figure 14. In addition, unlike a standard cylinder-source solution, this model accommodates time-varying heat input.

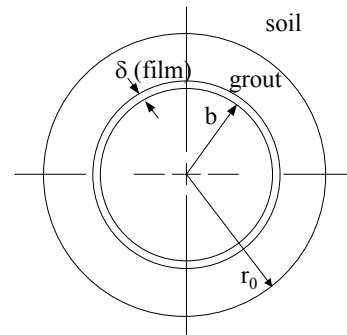


Figure 14: One-dimensional numerical model geometry for Oak Ridge National Laboratory Method (Shonder, et al. 1999)

4.4 Parameter estimation with 2D finite volume borehole model

The procedure developed by Austin, et al. (2000) utilizes a parameter estimation technique, which adjusts the thermal conductivities of the grout and ground. A numerical model is used to obtain the best possible match to the experimentally determined temperature response. These thermal conductivities are the best estimates of actual thermal conductivities.

A two-dimensional (polar coordinates) finite volume model is utilized. The inner part of the numerical domain is shown in Figure 15. For a typical borehole, a grid resolution of about 100 finite volume cells in the angular direction and about 150 to 200 cells in the radial direction is utilized. The exact grid resolution is a function of the borehole and U-tube pipe geometry and is determined by an automated parametric grid generation algorithm. The radius of the numerical domain is 3.6 m to allow for a reasonably long simulation time. The geometry of the circular U-tube pipes is approximated by “pie-sectors” over which a constant flux is assumed to be entering the numerical domain for each time step. The pie-sector approximation attempts to simulate the heat transfer conditions through a circular pipe by matching the inside perimeter of the circular pipe to the inside perimeter of the pie-sector and by establishing identical heat flux and resistance conditions near the pipe walls. The heat flux at the pipe wall is time-dependent – the heat flux is determined from experimentally-measured power input. Accordingly, the method has no problems associated with fluctuating power levels. The convection resistance due to the heat transfer fluid flow inside the U-tubes is accounted for through an adjustment on the conductivity of the pipe wall material.

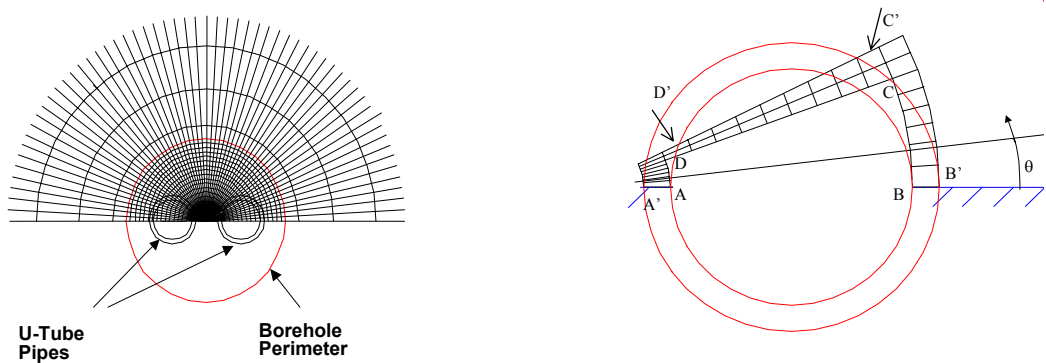


Figure 15: Numerical grid used by Austin, et al. (2000)

The parameter estimation algorithm minimizes the sum of the squares of the errors between the numerical model and the experimentally determined temperature response. A number of optimisation methods have been tested. For this problem, which involves searching along a narrow turning valley, the Nelder-Mead Simplex method with O'Neill's modifications seems to be the best method (Jain 2000).

This approach was further refined by a boundary-fitted coordinate grid, as shown in Figure 16, with the finite volume method. (Spitler, et al. 2000). However, for real-world applications, there is a point of diminishing returns here, as the down-hole geometry is not known precisely, even under the best circumstances. Spacers that force the U-tube against the borehole wall may help significantly, though.

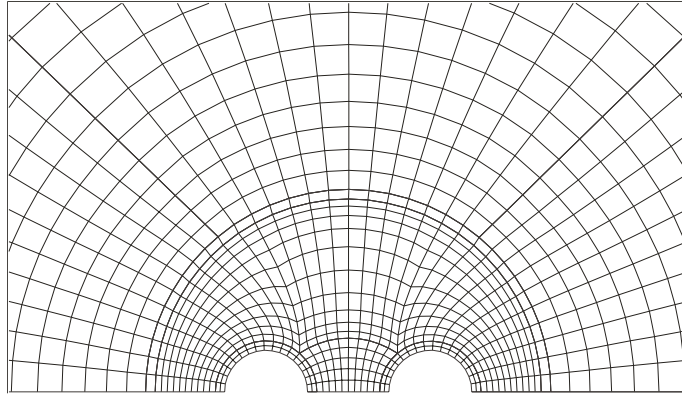


Figure 16: Boundary-fitted coordinate grid (Spitler, et al. 2000)

4.5 Discussion of models

There are a number of ways used to analyse the temperature data from thermal response tests. Analytical solutions of the line source or cylinder source theory and various numerical models mostly based on some cylinder approach. Most models also use parameter estimation to determine the ground thermal conductivity, although varying variables are used. The European countries use ground thermal conductivity and thermal resistance between heat carrier fluid and borehole wall, whereas the American models analyse for ground thermal conductivity and grout thermal conductivity. There is however an obvious correlation between the borehole thermal resistance (R_b) and the grout thermal conductivity (λ_{grout}), since the thermal resistance is a product of the heat losses in the pipe material as well as the grout and contact resistance between fluid/pipe, pipe/grout and grout/borehole wall.

The models also differ in the representation of the borehole. Line source approaches do not take into account heat capacity effects in the borehole whereas cylinder based models may do that. This effects the simulated initial temperature development in particular. The cylinder models also give possibilities in the representation of the borehole geometry and heat capacities of borehole filling, piping and heat carrier fluid. Simple cylinder models approximate the borehole to be a cylinder with a certain temperature and heat capacity. Other models use various "equal diameter" representations of the pipes and the boreholes. The most advanced model here is the one described by Spitler et al. (2000) where the fine grid describing the borehole allows for very detailed characterisation of the materials and geometry of the borehole.

Gehlin & Hellström (2001) compared four different analysis models for evaluation of the same sets of response test data. This evaluation meant parameter estimation with the two variables λ_{ground} and R_b . Two analytical line source solutions were used; the E1 (Equation 1) model and the Line source approximation in Equation 5. An analytical cylinder source model from Carslaw and Jaeger (1959) including the effect of borehole filling heat capacity was also used and finally a two-dimensional numerical model including borehole filling heat capacity. The four models were compared with respect to test length and amount of data used in the analysis. No significant difference was found between the two line-source models. The numerical model tends to give slightly higher values of ground thermal conductivity and borehole thermal resistance than the line source, and the cylinder source even higher than that.

4.6 Error Analysis

Uncertainties in the estimated ground thermal conductivities come from several sources: random and systematic experimental error, approximations made in the analytical or numerical model, estimate of the far field temperature, and length of test. These uncertainties have been discussed by Austin (1998), Austin, et al. (2000), and Witte, et al. (2002). The overall uncertainties of the estimations made by different analysis procedures with different test equipment are on the order of $\pm 10\%$. Austin (1998) has shown that error in the measurement of heat transfer rate to the borehole results in a similar percentage error in the estimation of ground thermal conductivity. Therefore, care must be taken to either measure the heat transfer rate using a temperature difference at the borehole inlet and outlet or, if the heat transfer rate is measured elsewhere, to minimize any unmeasured heat losses or gains.

Uncertainties due to approximations in the analysis procedure may be due to the assumption of constant heat transfer rate. Austin (1998) showed highly variable thermal conductivity predictions made with the line source procedure, when there were significant variations in the heat transfer rate to the borehole. In this situation, the parameter estimation procedure, which does not assume a constant heat transfer rate, can provide more accurate estimates. However, with a constant heat transfer rate, Witte, et al. (2002) have shown that the line source and parameter estimation methods may give very similar answers.

5. MEASUREMENTS

This section reports briefly on measurements made until December 2001 in the different countries. Appendix 2 summarises these measurements.

5.1 Sweden

The Swedish TED has been used in over 30 response tests. Typical for Swedish response tests is groundwater filled boreholes in granitic rock. Due to the use of groundwater filled boreholes, effects of natural convection in the borehole and local groundwater flow have been observed.

A number of measurements have been performed at Luleå University of Technology for research and evaluation of different BHE. Tests on single U-tube and double U-tube BHE, both on groundwater filled and grouted boreholes have been studied, and also tests with several power injection pulses have been performed (Gehlin 1998, Gehlin & Hellström, 2000).

Eklöf & Gehlin (1996) described measurements at two locations, where the test rig could not be connected directly to the borehole but the heat carrier fluid had to pass through several meters of horizontal piping buried in the ground. Thus the effect of the horizontal piping has been included in the measurements.

A few measurements have been performed in sedimentary rock as reported by Gehlin & Hellström (2000), where also two measurements on co-axial BHE are presented.

5.2 Canada

The first response tests in Canada were reported by Cruickshanks et al., (2000). The tests were performed on groundwater filled boreholes in mixed slate/quartzite geology.

Problems with disturbance on the temperature measurements from variations in the ambient air temperature are mentioned.

5.3 Germany

In Germany, thermal response tests have been performed on pilot boreholes for larger BHE systems since 1999. Seven response tests were reported by Sanner et al. (2000). Six of the tests are run on double U-tube BHE, the seventh on a single U-tube BHE. The geological conditions at the test site are all sedimentary. Boreholes were grouted or sand filled. Details on German measurements are also given in Sanner et al. (1999).

A response test on a sand filled borehole with suspected high groundwater flow, giving unrealistic (much too high) values of the ground thermal conductivity is mentioned in Sanner et al. (2000).

5.4 Netherlands

The thermal response test rig at GroenHolland and IF Technology has been used both for research and commercial measurements. About 20 measurements have been performed so far in the Netherlands, as well as 3 tests in Belgium and 3 in the United Kingdom (Witte 2001). Response tests on different loop configurations have been done (single borehole with single U-tube, 3 boreholes with U-tubes and horizontal piping, single concentric loop and U-tube with small shank spacing). Different loading profiles have been used and measurements have been compared during summer and winter conditions. An experiment was also performed where temperature measurements were made every 2.5 m (8 ft) along the borehole next to the loop in order to determine how the heat extraction rate per meter borehole changes as a function of soil stratigraphy and water content (Van Gelder, 1999).

A response test in Horst, the Netherlands, where the influence of groundwater flow on the determination of the ground thermal conductivity was observed, is described in a report in Dutch, from IF Technology (1999).

Witte et al. (2000) present a response test for the St. Lukes Church site in central London. Two test holes were drilled in the layered, sedimentary ground, and the ducts were grouted after the single U-tubes were inserted. A heat extraction experiment was done on one of the boreholes, and a heat injection experiment was done on the other. The estimated conductivities from the two tests matched within 4%.

5.5 Norway

Norwegian response test conditions are similar to those in Sweden. Groundwater filled boreholes in crystalline hard rock are used. The hilly landscape causes a high groundwater flow in fissures, which improves the performance of BHE. Measurements in selected wells have demonstrated that the heating capacities may be twice as high as that of “dry” wells, where heat flux is mainly due to the rock thermal properties (Skarphagen & Stene, 1999).

Around 30 response tests, mostly commercial, have been performed in Norway in recent years (Midttomme, 2000). The measurements have been concentrated to the Oslo area.

The National Geological Survey of Norway (NGU) and the Norwegian Water Resources and Energy Directorate (NVE) are currently developing a database of thermal conductivity in the Norwegian bedrock. The plan for the future is to combine the ground

thermal conductivity database with a groundwater well database and topological data of the area, thus improving the basis for the design of BHE.

NGU has published a report on a thermal response test performed in Lorenskog, along with a thorough study of the geology in the area, as a pre-study for a hospital heating/cooling BHE system (NGU 2000).

5.6 Switzerland

Switzerland started measuring in 1998. They have so far made seven measurements, mainly on grouted double U-pipes and energy piles.

5.7 Turkey

The two first Turkish response tests were carried out in Istanbul in December 2000 (Paksoy, 2000). The option of measuring the effective average thermal properties of the ground profile surrounding a borehole, makes thermal response test especially valuable in the complex and varying geology of Turkey. Geologic formations with several sedimentary layers of very different thermal properties are common in Turkey. The test method is also used for evaluation and development of grouts from domestic material, since different types of bentonite occur naturally in many places in Turkey.

5.8 United Kingdom

Response tests in UK have been performed by GeoScience Limited and the Dutch company, Groenholland. Measurements have been made at six sites in England (Cornwall, Chesterfield, Exeter, London) and Scotland since September 1999 (Curtis, 2000). Groenholland (Witte 2001) has reported three tests. Results from tests in London are presented by Witte, et al. (2000a, 2000b).

5.9 U.S.A.

Test conditions vary widely throughout the U.S.A. and hundreds of tests have been made for commercial clients, without the results being published. This section emphasizes published test results.

Spilker (1998) reported four tests made in Nebraska with three different back fill materials in two different diameter boreholes. Thermal conductivities and borehole resistances were estimated, but not reported. Instead, the impact on a design for a specific building was reported. Required borehole depth for a 144 borehole BHE varied between 59 m (194 ft) and 88 m (289 ft). Skouby (1998) described five tests performed in South Dakota and Nebraska used to support design of ground source heat pump systems for schools. A thermal conductivity test is recommended for commercial projects with installed cooling capacities in excess of 88 kW (25 tons).

Smith and Perry (1999b) evaluated borehole grouts with the aid of thermal response tests. Remund (1999) showed results from thermal response tests that were compared with laboratory measurements. The measurements were used for evaluation of different grouts and borehole thermal resistance.

Smith (1999b) reported on 16 tests performed by the Middleton Corporation of Akron, OH. The duration of these tests were generally 12 hours, and for 7 of the tests for which the BHE were designed, the systems were reported to be operating within design parameters.

Two validation tests have been reported by Austin et al. (2000). One test was performed on a core drilled hole. The core samples were carefully preserved in sealed PVC cases and stored in climate-controlled rooms to avoid changes in the moisture content of the sample. The conductivities of 19 representative samples were then measured in a guarded hot plate apparatus (Smith 1998) to obtain an independent estimate for its thermal conductivity. The in situ test, analysed with the 2-D finite volume parameter estimation procedure, matched the independent measurement within 2%, which is considerably better than might be expected with the uncertainty of the in situ test and analysis procedure being estimated at $\pm 10\%$.

Two other tests were performed using a medium-scale laboratory experiment where the geometry and thermal characteristics of a borehole are replicated under controlled conditions. The thermal conductivity of the soil material (fine quartz sand) used in the experiment was determined independently with a calibrated soil conductivity probe. Two tests were run: one with dry sand, and one where the sand was saturated. In both cases, the in situ test matched the independently measured estimates within 2%.

Shonder and Beck (1999) also used a thermal response test for validation of their 1D parameter estimation model. The data set is from the medium-scale laboratory experiment, described by Austin et al. (2000). The 1D parameter estimation model matches the independently made estimate of the thermal conductivity within 3%.

Shonder and Beck (2000) also report on three in situ tests performed in Lincoln, Nebraska, at sites where ground source heat pump systems are being used to provide heating and air conditioning for elementary schools. For these cases, operating data from one of the schools were used in conjunction with a detailed numerical model to estimate effective thermal conductivity for that site. The conductivity estimated with a 50 hour test, was within 4% of that determined from one year of operating data. Sequential conductivity estimates are made with three different methods (line source, cylinder source and the 1D finite volume parameter estimation method) for each of the three tests. The time period at which the results converge is instructive. It varies significantly from test to test and method to method. For these three tests, where the power output of the generators was fairly constant, the line source method approached the final value from below – in other words, using a shorter test, say 12 hours, would result in a conservative (low) estimate of the thermal conductivity. Presumably, this would be true for most cases, where the grout thermal conductivity is lower than the ground thermal conductivity.

However, in a fourth test, performed at an undisclosed location, two periods of significant power fluctuation two and five hours respectively occurred about 10 and 30 hours into the test. The line source methods and cylinder source methods were both applied assuming that the heat injection power was constant. Where it fluctuated, fluctuations in the conductivity estimates made by the line source and cylinder source methods are clearly observed. In this case, the thermal conductivity is over estimated by as much as 30% at the 15th hour, apparently due to the power fluctuations.

5.10 Cost

The thermal response test cost varies between countries, as does the service included in the test. Brief cost estimates for a thermal response test conducted on one borehole in different countries are given in Table 1.

Table 1: Approximate costs for a thermal response test in some countries.

Country	Cost	Comment
Germany	2500 EURO	Includes test, analysis and report
Sweden	2500 EURO	Includes test, analysis and report
Norway	3800 EURO	The service is offered as a total pre-investigation including 160 m drilling, pipe fitting, measurement, analysis and preliminary dimensioning for a cost of 10700 EURO
Netherlands	3000 EURO	Test, analysis and report
USA	4000-7000 USD	Includes cost of drilling test borehole, at 2000 USD.

6. WORKSHOP AND TEST COMPARISON IN MOL, BELGIUM

On Oct. 14, 2000 a workshop was held in the Flemish Research Centre (VITO) in Mol, to discuss international experiences in thermal response testing of boreholes. It was a joint activity of the Annex 12 and Annex 13 of the IEA Energy Storage Implementing Agreement. Thermal response testing experts in Europe came together, adding up to 20 participants from 9 countries.

The Mol site also allowed making a comparison of tests with three different test devices. Three boreholes spaced only a few meters apart, in virtually identical geology, were used. The holes had been drilled for the subsurface investigations of the planned borehole thermal energy store “TESSAS”. In all boreholes, each of 30.5 m (100 ft) depth, double U-pipes has been installed with different grouting material in each borehole:

- Mol-sand (re-filling of the sand produced while drilling)
- Graded sand (filling with a sand of specially optimised grain size distribution)
- Bentonite (grouting with a standard bentonite-cement-grout)

During the previous summer, thermal response tests had been conducted at all three BHE by Groenholland (NL). In the days before and during the workshop in October, tests with the LTW and UBeG equipment were done at individual boreholes.

In the following, the evaluation of the UbeG test is shown. The basic data are given in Table 2, the measured temperature curve in Figure 17.

Table 2: Basic data of Thermal Response Test in Mol by UBeG

Length of borehole	30.5 m (100 ft)
Type of borehole	Polybutylene-Double-U
Borehole diameter	150 mm (6 in)
Test duration	71.8 h (11.-13-10.2000)
Extracted heat	129 kWh (440.2 kBtu)
Extraction power	1797 W (6131 Btu/hr)
Initial ground temperature (average over 30.5 m length of borehole)	12.5 °C (54.5 °F)

The regression lines for T3 and T4 are shown in Figure 18. With the slope of the lines, the thermal conductivity can be calculated:

$$T3 \quad \lambda_{eff} = \frac{1797}{4\pi \cdot 30.5 \cdot 1.884} = 2.49$$

$$T4 \quad \lambda_{eff} = \frac{1797}{4\pi \cdot 30.5 \cdot 1.890} = 2.48$$

The average of all sensors results in $\lambda_{eff} = 2.49$ W/m/K

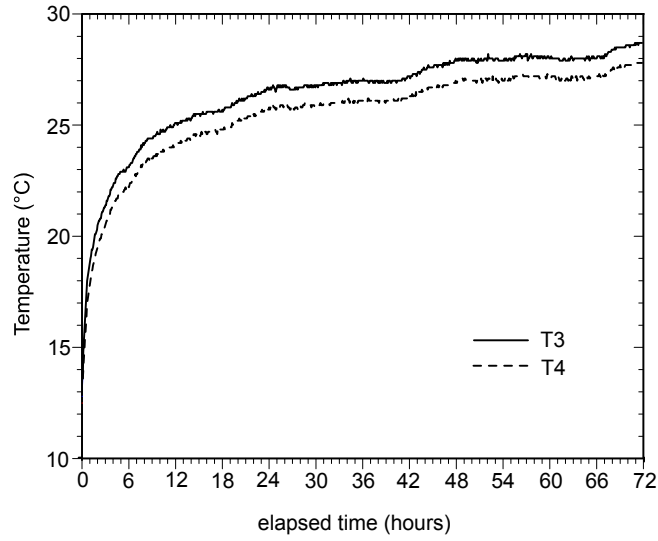


Figure 17: Measured temperature curve of UBeG test in Mol

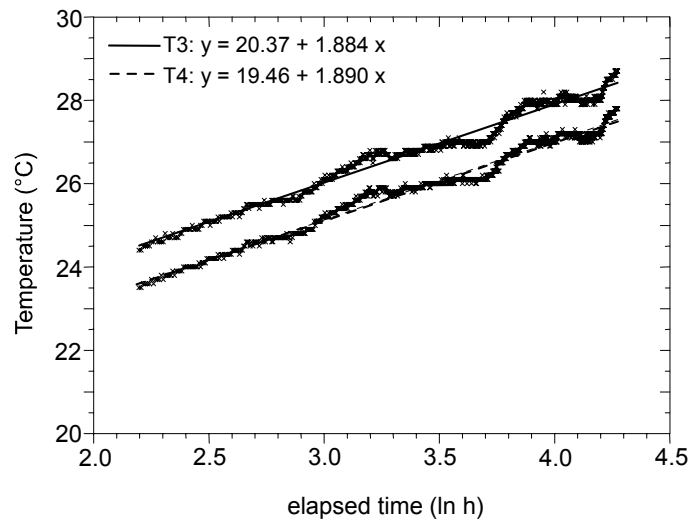


Figure 18: Measured temperatures on logarithmic time scale and regression lines for data in Figure 17.

The thermal borehole resistance R_b is calculated for several time-temperature pairs, from 12 h to 71 h. The representative value is $R_b = 0.13 \text{ K/(W/m)}$

The results of the various tests (Table 3) show a thermal conductivity of the ground around 2.5 W/m/K (1.4 Btu/hr-ft). It was expected that all results for the ground thermal conductivity should give near the same answer, because the geological profile is the same for each borehole. Only the Groenholland/Bentonite test deviates somewhat; further investigation is needed to determine the cause of the anomaly. The Groenholland tests were also analysed using a parameter estimation procedure. The results are shown in Table 4. While some

Table 3: Results of comparison of Thermal Response Test in Mol, evaluation with line-source method

Grouting:	Groenholland	UBeG	LTW
Mol-sand	$\lambda = 2.47 \text{ W/m/K}$ $r_b = 0.06 \text{ K/(W/m)}$	-	$\lambda = 2.47 \text{ W/m/K}$ $r_b = 0.05 \text{ K/(W/m)}$
Graded sand	$\lambda = 2.40 \text{ W/m/K}$ $r_b = 0.1 \text{ K/(W/m)}$	-	$\lambda = 2.51 \text{ W/m/K}$ $r_b = ?$
Bentonite	$\lambda = 1.86 \text{ W/m/K}$ $r_b = 0.08 \text{ K/(W/m)}$	$\lambda = 2.49 \text{ W/m/K}$ $r_b = 0.13 \text{ K/(W/m)}$	-

deviation is shown for the Bentonite test, the results agree much better using the parameter estimation procedure.

Table 4: Results of comparison of Thermal Response Test in Mol, evaluation of Groenholland data with 2-D parameter estimation model

	Mol-sand	Graded sand	Bentonite
Ground	$\lambda = 2.51 \text{ W/m/K}$	$\lambda = 2.42 \text{ W/m/K}$	$\lambda = 2.20 \text{ W/m/K}$

7. CONCLUSIONS

7.1 General conclusions

Since the introduction of mobile thermal response tests in Sweden and the U.S.A. in 1995, the method has developed and spread rapidly in North America and Europe. With the exception of the Dutch system, all of the systems rely on imposing a heat injection into the ground, which is intended to be held constant by providing a constant power supply to an electric resistance heater element. The Dutch system can impose either heat injection or a heat extraction, and the power output is controlled by maintaining a constant ΔT across the ground. Also the AETNA rig has this option.

A variety of data analysis models have been developed. Various applications of the line source approach are used because of its simplicity and speed. The line source theory is the most commonly used model for evaluation of the response test data in all countries, and is dominant in Europe. The use of the cylinder source model for thermal response tests is only reported in the U.S.A, although the theory is used for design of BHE systems in both U.S.A. and Canada. Numerical models coupled with parameter-estimation techniques have been used in the U.S.A.

The issue of the duration of the test period is still discussed, and further studies are needed. The most scientifically rigorous work indicates that, with current test methods and analysis procedures, approximately 50 hours of measurements are needed to obtain an accurate estimate of the thermal conductivity. However, economic aspects of the test duration must be considered for commercial thermal response tests -- a shorter test may be “good enough” if reasonably constant heat injection can be imposed. In this case, the result may be conservative.

Thermal response tests have so far been used primarily for *in situ* determination of design data for BHE systems, but also for evaluation of grout material, heat exchanger types and groundwater effects. The method is also suitable for verification of design when the BTES system has been constructed.

7.2 Further research

This review of the state of the art elucidated some areas where further research and clarification are required. Future research is recommended in the following areas:

- Experimental methods and analysis procedures should be developed to allow shorter tests. This should improve commercial acceptance of the technology. Current limitations which increase the required test length and possible solutions include:
 - Particularly when the line-source analysis procedure is used to analyse results, any deviations from a constant heat rejection/extraction pulse cause difficulties in analysing the results. Deviations are commonly caused by fluctuations in the heat input supplied by the electric resistance heater and heat transfer from the apparatus to the environment that fluctuates with weather conditions. Possible approaches to insure more uniform heat rejection/extraction pulses include:
 - Use of higher quality power supplies or well-controlled heat injection/extraction.

- Reduction of heat leakage and influence of solar radiation by better thermal insulation of the equipment.
- For boreholes with significant amounts of low-conductivity grout between the U-tube and borehole wall, the thermal response in the early hours depends much more on the grout rather than the surrounding ground. Any installation procedure that reduces the resistance of the borehole will allow the thermal response to more quickly approach the line-source response for the surrounding ground. Hence, the line-source analysis procedure will be feasible at an earlier time and allow shorter tests. One approach would be to use spacer clips and/or thermally-enhanced grout. (In an analogous manner, the same approach should allow parameter-estimation procedures to more quickly differentiate between the effects of the grout and the ground on the thermal response, allowing shorter tests.
- Current recommendations for tests on the order of 50 hours or more are based on a range of different geological conditions, test apparatus with varying power quality, etc. The development of analysis procedures which can be run in real-time and also used to determine when the test results are conclusive would allow some tests to be run for significantly shorter periods. A preliminary investigation of this carried out by Jain (1999) showed that required test lengths, for some cases, could be as short as ten hours, when an online parameter estimation method was run with an heuristic convergence algorithm. It might also be possible to apply a simpler criterion based on the quality (uniformity) of the heat rejection/extraction pulse.
- Alternatively, test apparatus might be developed which do not require test personnel on site. This might allow longer tests to be more acceptable. Based on the Dutch approach, this might involve systems enclosed in large (theft-resistant) containers with telemetry and large, high-quality, reliable, well-maintained diesel generators, where stable net supplied electricity is not available.
- Validations to date have been made primarily by comparisons to cored samples. Ultimately, the best confirmation of the method's validity will probably involve comparison of data from long-term operation with predictions made based on a thermal response test. As suitable measured data are extremely rare, future work is necessary to collect such data. (At the least, such data should be continuously and accurately measured from the beginning of the system operation.). More comparisons between response tests and drill core data may be of interest for studies of special geological situations and of groundwater influence.
- There are some phenomena that can have a significant effect on test results, but have only been given preliminary consideration. These areas in which further research would be useful include:
 - The minimum required elapsed time after drilling and grouting before a thermal response test should be started is not well understood. Further work to establish guidelines would be useful.
 - The analysis procedures all assume that there is no groundwater flow. Practical guidance and analysis procedures (coupled conductive models) should be developed also for situations where significant groundwater flow occurs.
 - The issue of groundwater influence is of interest both for the estimation of the ground thermal conductivity and for the borehole thermal resistance. Since the convective effects of groundwater are temperature dependent, it may be necessary

to study the effect of heating versus cooling mode during the response test when measuring a groundwater filled borehole.

- Study the effect of superimposed sinusoidal power fluctuations (e.g. variation of ambient temperature) and stepwise thermal load (effect of convection, effect of stops etc), as well as evaluation of decline period in borehole following thermal load period may give information about the variation of thermal resistance and effective thermal conductivity for water filled boreholes.
- Many of the systems built to date have been more-or-less experimental in nature – designed and fabricated by researchers and/or constructed without the benefit of any previous operational experience. Consequently, the systems have not always been as reliable and robust as might be desired. Additional efforts to develop more reliable and robust equipment for performing thermal response test are needed.
- Another potential application of thermal response testing is verification of the design and installation. If applied to a ground heat exchanger that has been installed, it may be possible to determine whether or not the ground heat exchanger will perform as planned. In order to realize this application, it will be necessary to include the effects of horizontal connecting pipes in the analysis procedure.

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Appendix 1 Summary of Experimental Apparati State of the Art December 2001

Reporting Country	Canada	Germany ¹	Netherlands	Norway	Sweden	Switzerland ²	Turkey	United Kingdom	U.S.A. ³
References	Cruickshanks, et al. (2000)	Sanner (2001)	Witte, et al. (2001)	Helgesen (2002)	Gehlin and Hellström (2000)	Eugster (2002)	Paksoy (2000)	Curtis (2001)	Austin, et al. (2000)
Configuration	Trailer	Trailer	Container	Trailer	Trailer	mobile	Trailer	Cart, 2-wheel	Trailer
Heat Injection (kW)	3.2	1-6	0.05-4.5	3-12	3-11	3-9	3-12	3-6	0-4.5
Heat Extraction(kW)	--	--	0.05-4.5	--	--	--	--	--	--
Power Control	None	Manual, six levels	Continuously variable with controlled ΔT	Manual, four levels	Manual, three levels	semi-manual, three levels	Manual, four levels	Manual, two levels.	Manual, continuously variable rate.
Flow Rate (L/s)	0.75 (est.)	0.28	0.14-0.83	0.5-1.0	0.5-1.0	variable	0.5-1.0	0.25-1	0.2 (typical)
Circulating Fluid	Water / Prop. Glycol	Water	Water Water/glycol	Water / Prop. Glycol	Water / Prop. Glycol	Water	Water	Water	Water
Temperature sensors	Not reported.	PT100	PT100	Thermocouples	Thermocouples	PT100	Thermocouples	Thermistors	Thermistors
Reported accuracy: temperature sensors	Not reported.	Not reported	± 0.07 K	± 0.2 K	± 0.2 K	0.1	± 0.2 K	± 0.1 K	± 0.1 K
Power sensor	Not reported.	Not reported	Not reported	Watt transducer	Watt transducer	not reported	Watt transducer	kWh meter (pulse output)	Watt transducer
Reported accuracy: power measurement	Not reported.	Not reported	Not reported	$\pm 2\%$	$\pm 2\%$	not reported	$\pm 2\%$	Not reported	$\pm 1.5\%$
Flow sensor	Estimated from ΔP .	Not reported	MagMaster	Volumetric flow meter	none	not reported	Volumetric flow meter	Electromagnetic	Volumetric flow meter
Reported accuracy: flow sensor	Not reported.	Not reported	0.2-0.9 %	$\pm 3\%$	--	not reported	$\pm 3\%$	Not reported	$\pm 2\%$

¹ There are three known test units in Germany; only one (UBeG) is described in this column.

² There are two known test units in Switzerland; only one (EPFL) is described in this column.

³ There are a number of test units in the USA; the one described in this column is the only one for which specifications are published.

Appendix 2. Summary of Measurements State of the Art December 2001

Reporting Country	Canada	Germany	Netherlands	Norway	Sweden	Switzerland	Turkey	United Kingdom	U.S.A.
First year of operation	2000	1999	1999	1998	1996	1998	2000	1999	1995
Number of test rigs	1	3	1	1	1	2	1	1	>10
Total number of tests	2	> Ca. 35 ⁴	Ca. 20 ⁵	Ca. 50	Ca. 35	7	2	Ca. 6	>300
Measured ground types	Hard rock, Slate	Unconsolidated sediments (sand, silt etc.), Sediments (Marl, Shale etc.)	Clay, sand, peat, shale, mudstone, sandstone, chalk	Hard rock, Shale	Hard rock, Shale, Sedimentary	Molasse sediments	Sedimentary	Hard rock, shales, clays, mudstones, coal bearing measures, limestone	Sedimentary, clay, shale
Measured BHE Backfill material	Groundwater	Grout, Sand	Groundwater Bentonite grout, sand, ground material, bentonite/cement grout	Groundwater	Groundwater, Sand	Grout (BHE)	Groundwater	High solids bentonite	Bentonite grout, thermally enhanced grout, pea gravel, sand
Measured BHE types	Single U-tube	Single U-tube, double U-tube Energy piles	Single and double U-tube, concentric	Single U-tube	Single U-tube, double U-tube, concentric	Double U-pipe , Energy piles (EP)	Single U-tube	Single U-pipe with geoclips	Single U-tube, double U-tube.
Typical borehole depth	55-91 m	26-117 m (min. pile 7 m, max 250 m)	30-100 m	120-200 m	100-150 m	150-300 m (BHE) < 30 m (EP)	150 m	50-70 m	60-120 m
Typical borehole diameter	150-164 mm	150-160 mm	50-300 mm	115-140 mm	110-115 mm	150 mm (BHE) ~240 mm (EP)	150-200 mm	125-150 mm	85-150 mm

⁴ UBEG and AETNA ca. 15 tests each from 1999 to 2002

⁵ Tests performed in Netherlands, Belgium and UK

PAPER III

Determining Undisturbed Ground Temperature for Thermal Response Test.

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Determining Undisturbed Ground Temperature for Thermal Response Test

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ABSTRACT

This study treats the determination of undisturbed ground temperature in a borehole for ground heating/cooling and its effect on the accuracy of a thermal response test analysis. Three different ways of estimating temperatures were used in one groundwater-filled borehole in crystalline rock. The first method, temperature logging along the borehole, is assumed to give the correct temperature profile and results in the best estimate of the mean temperature of the ground. A good estimate is also obtained by circulating a heat carrier through the borehole heat exchanger pipes while measuring the flow temperature at a short time interval (10 seconds). The calculated temperature profile is used for deriving a mean temperature of the borehole. Heat is added to the fluid by friction heat caused by the pump work, which results in an overestimation of the borehole temperature. This influence becomes significant after 20 minutes of pumping.

INTRODUCTION

Thermal response test is a method for determining ground thermal properties for ground heat exchangers. Since its introduction in 1995-1996, this in situ method for ground-source heat pump systems has spread to most countries where borehole thermal energy storage (BTES) is used on a larger scale. The method is described in several papers, e.g., Gehlin (1998), Witte et al. (2002), Sanner et al. (2000) in Europe and Austin (1998) and Austin et al. (2000), Shonder and Beck (2000), Kavanaugh and Rafferty (1997), Kavanaugh et al. (2000), Smith and Perry (1999), Cruickshanks (2000) in North America. Most analysis procedures for estimating the ground thermal conductivity from the response test require good estimates of the undisturbed ground temperature at the site. This temper-

ature should be determined before the response test has started. The error in the estimated thermal conductivity is then directly proportional to the error in the undisturbed ground temperature. In some line source evaluation methods the undisturbed ground temperature is eliminated in the analysis procedure. However, a good estimate of the undisturbed ground temperature is necessary for a correct design of the ground heat exchanger.

The undisturbed ground temperature increases with depth due to the geothermal gradient, an effect that cannot be neglected. The geothermal gradient varies over the world and is normally in the range 0.5-3 K per 100 m (0.3°F to 1.6°F per 100 ft). Eskilson (1987) shows that for BTES applications, it is not necessary to consider the temperature variation along the borehole. The mean temperature along the borehole is a good approximation of a homogeneous undisturbed ground temperature around the borehole.

There are mainly two ways used to determine the undisturbed ground temperature before a thermal response test. Both methods require that the borehole be at thermal equilibrium with the surrounding ground. One commonly used method is circulating the heat carrier fluid of the borehole heat exchanger through the borehole for about half an hour before the heater is switched on for the test. The collected temperature data are used to estimate the average borehole temperature. However, even though no heat is injected by the heater during this period, there will always be some heat gain to the system from the pump work.

Another method is lowering a thermocouple down the water-filled U-tube before the measurement has started. The temperature is measured every few meters along the U-pipe and the readings are used to calculate an arithmetic mean borehole temperature.

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TABLE 1
Data for the Test Borehole at
Luleå University of Technology

Drilled depth	60 m (197 ft)
Groundwater level during test	2 m (6.5 ft)
Active borehole length	58 m (190 ft)
Borehole diameter	152 mm (6 in.)
Ground type	Hard rock (gneiss/granite)
Borehole filling	Groundwater
Collector type	Single U-tube PE DN 32 PN6
Heat carrier fluid	Water/glycol mixture

The importance of determining the undisturbed ground temperature, and various ways of doing it, has previously been discussed by, e.g., Kavanaugh et al. (2000), who also presents measurements. Kavanaugh recommends activating the pump and recording the minimum temperature as a good estimate of the initial ground temperature.

The Borehole

The experiments were conducted in a well-documented borehole (Nordell 1985, 1986, 1994) at Luleå University of Technology. The borehole is drilled in hard crystalline rock to a depth of 60 m (197 ft) and fitted with a single water/glycol mixture filled U-tube. The borehole is groundwater filled and not grouted, which is the normal case in Sweden. A summary of borehole data is found in Table 1.

The borehole is one of 120 boreholes in an old high-temperature borehole storage. The 10 × 12 borehole heat storage was shut down in 1990, after six years of operation, and the ground is still thermally disturbed by the heat storage. The normal annual mean ground surface temperature in the area is 3.5°C (38.3°F), but even ten years after the closing down of the heat storage, the peripheral boreholes are still measuring around 13°C (55.4°F).

The test borehole is number 4 out of 12 in the outermost borehole row on one side of the store, and this and other holes have been used for several thermal response tests since 1996 (Gehlin 1998).

The Response Test Equipment

The response test device used in this experiment was constructed at Luleå University of Technology in 1995-1996 (Eklöf and Gehlin 1996; Gehlin and Nordell 1997). It is set up on a small covered trailer and consists of an in-line electric resistance heater, instrumentation, and an 85-liter (22.5-gallon) tank used for purging and as an expansion tank. The tank also contains fluid for the initial filling of the pipe system.

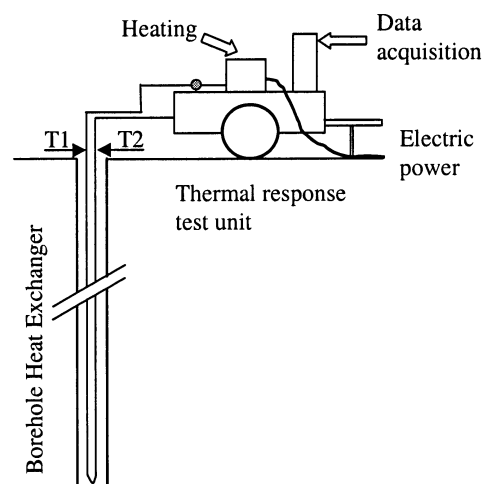


Figure 1 Thermal response test setup.

A 1.75 kW (5970 Btu/h) pump circulates the heat carrier fluid through the borehole. The heater has step-wise adjustable power rates in the range of 3-12 kW (10,200-40,950 Btu/h). Fluid temperatures are measured by thermocouples at the inlet and outlet of the borehole. The fluid temperatures, ambient air temperature, air temperature inside trailer, and power rate are recorded at an optional preset time interval. A more thorough description of the response test apparatus is given in Gehlin (1998).

When running the test, the response test facility is placed as close as possible to the test borehole and is connected to the fluid-filled borehole pipes. The connection pipes are filled with fluid from the purge tank (air separator) and the test loop (i.e., the collector pipes and the response test device) is purged. Exposed parts between the borehole and the response test apparatus are well insulated. The purge tank (air separator) is connected to the pipe system to collect air bubbles but the fluid is not flowing through the tank. Once the pipe system is full, no fluid is added to the pipe system from the tank; in fact, a small inflow into the tank is caused by the volume expansion of heated fluid. The test procedure is fully automated as soon as the test has started. The principle of a thermal response test setup is seen in Figure 1.

MEASUREMENTS

Method 1—Temperature Logging Along the Borehole

A temperature sensor (PT104) at the end of a 70 m (230 ft) cable (about 5 mm [0.2 in.] diameter) was lowered down the groundwater-filled borehole. The cable was connected to a universal instrument, set for PT104, on which the temperature logging was read manually. Lead weights were attached to the end of the cable to pull the sensor and cable down the borehole. Meter values were marked along the cable, starting with 0 m (0 ft) at the sensor and ending with 70 m (230 ft) near the

connection to the universal instrument. The borehole was in thermal equilibrium with its surroundings when the logging started.

Temperatures were read every meter for the uppermost 10 meters (33 ft) of the borehole and every second meter below that level all the way down to the bottom of the borehole. The resulting temperature profile along the borehole is shown in

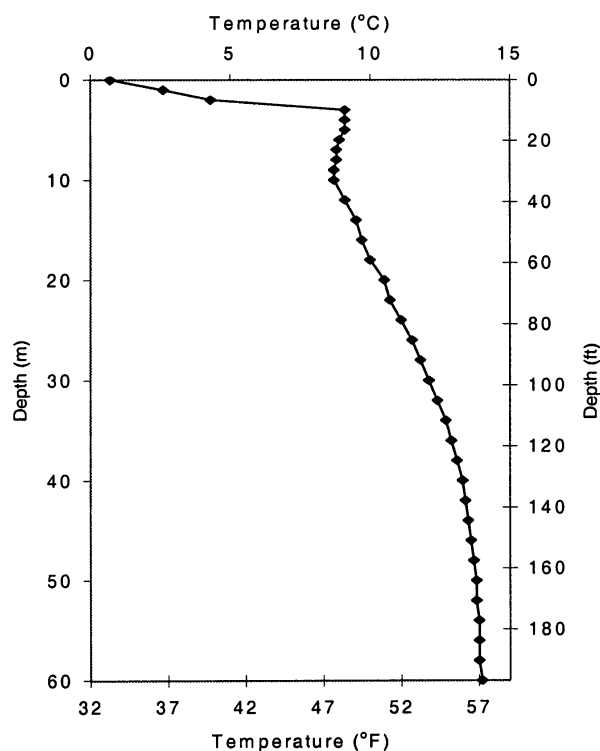


Figure 2 Temperature profile along the test borehole.

Figure 2. An arithmetic mean temperature of 11.8°C (53.2°F) was calculated from the groundwater table and down to the bottom of the borehole. The water table was, at this time of the year (October 2001), 2 m (6 ft) below ground surface (see Table 1) and the ambient air temperature was 0°C (32°F). Only the active part of the borehole, i.e., below the groundwater table (standing column) or below the top of the grout, is included in the mean temperature estimation. This active part of the ground heat exchanger accounts for the essential part of the heat transfer. The upper part of the borehole does not reflect the ground temperature but is disturbed by ambient conditions (air temperature, wind, and rain).

Method 2—Flow Temperature Measurements at 10-second Interval

After the manual temperature logging was completed, the borehole collector pipes were connected to the thermal response test device. The data logger was set to record the inlet and outlet temperatures every 10 seconds during the experiment. The electric resistance heater was off during the test. The heat carrier in the collector U-tube was allowed to circulate for 77 minutes, and the initial 10 minutes of circulation gave a temperature profile of the fluid flow in the collector pipes, as seen in Figure 3. The temperature measurements were analyzed assuming plug flow and no delay in temperature recording, which means that measurements taken at certain times correspond to certain depths. The plug flow assumption is reasonable in small diameter pipes and the temperature recordings are reliable, as small temperature sensors immersed in the fluid were used.

The recorded temperatures show the influence of the fluid in the above ground piping, which had come to equilibrium with the environment. It is seen as initial temperature downward spikes in Figure 6. At the time when the experiment was

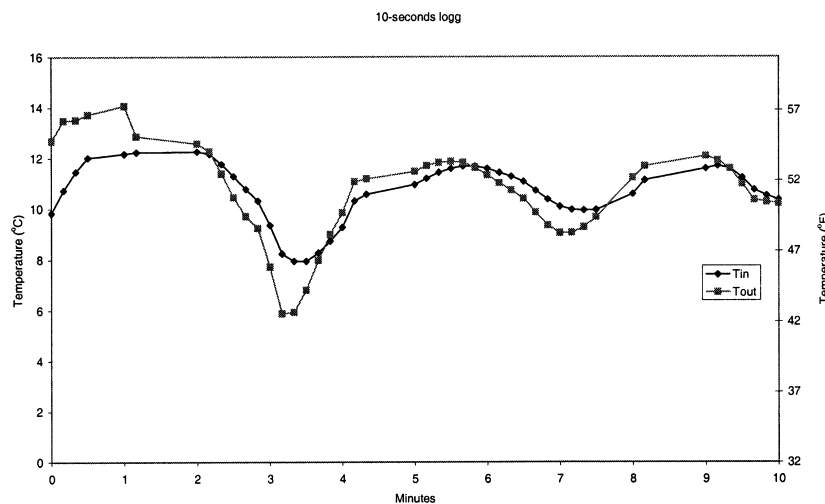


Figure 3 Collector pipe plug-flow temperatures logged at 10-second time interval.

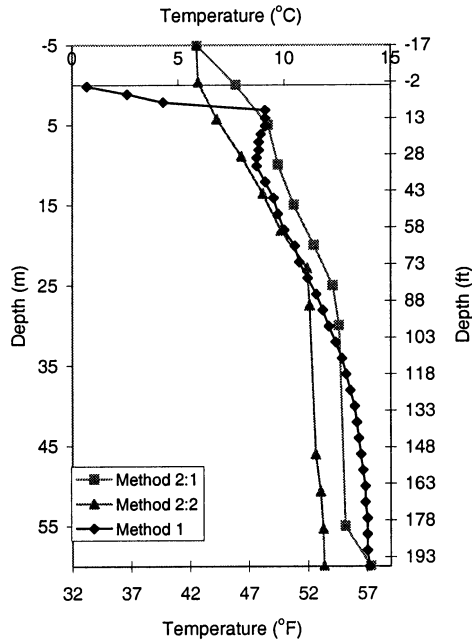


Figure 4 Borehole temperature profiles determined by method 1 and method 2.

conducted, the ambient air temperature was about 0°C (32°F) and there was a slight snowfall. Thus, the ambient air was cooling the heat carrier. A comparison of the manual temperature log and the temperature profiles from the first cycle (up and down) is shown in Figure 4. Arithmetic mean temperatures were calculated for the first cycle—one for the up-flow and one for the down-flow. The first profile gives a mean temperature of 11.7°C (53.1°F), and the second profile gives 10.3°C (50.5°F). Thus, the cooling effect of the ambient conditions is clearly seen in the latter.

Method 3—Flow Temperature After Period of Circulation

The heat carrier fluid was circulated for 77 minutes. After approximately 15 minutes, the temperature fluctuations along the borehole even out. A plot of all temperature profiles from the first 15 minutes of circulation is seen in Figure 5. Each line represents a temperature profile along the borehole at different times of the test. The profiles converge at the mean borehole temperature of 11.8°C (53.2°F). The fluid velocity was estimated from the time between peak temperatures (see Figure 6) and the known flow distance through the pipe system.

As seen in Figure 6, the fluid temperature increases with time. Plug flow is assumed through the pipe system though some mixing of colder and warmer water occurs. This effect does not influence the estimation of undisturbed ground temperature. After 30 minutes, the fluid temperature is 12.2°C (54°F) and after 60 minutes, it reads 13.8°C (56.8°F). The increase of the mean fluid temperature is caused by the heat gain from the 1.75 kW (5970 Btu/h) circulation pump.

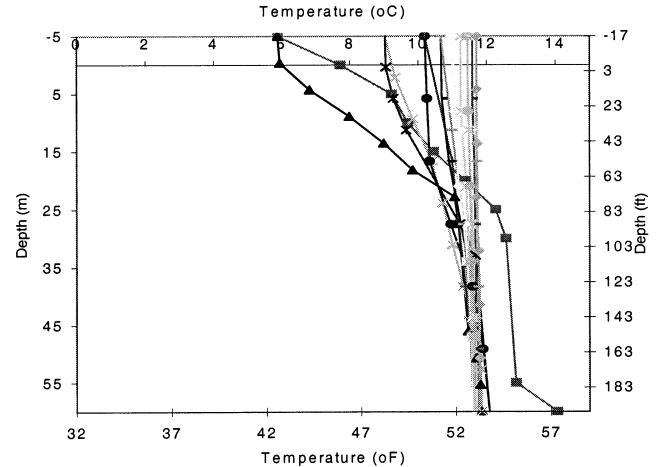


Figure 5 Fluid temperatures during the initial 15 minutes.

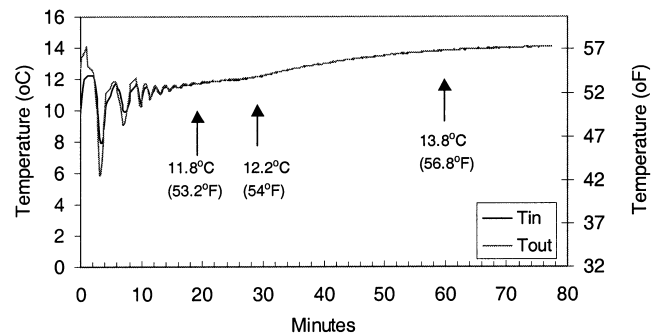


Figure 6 Ten-second interval temperature loggings in the borehole.

RESULTS AND DISCUSSION

The resulting estimations of the undisturbed ground temperature around the test borehole with the three different methods are summarized in Table 2.

The undisturbed ground temperature calculated from the manual log and the temperature calculated from the recordings from the first few minutes of circulation in the pipes show an agreement within 0.1°C (0.2°F). After about 15 minutes (velocity 1 m/s [3.3 ft/s]), the temperature fluctuations in the pipe ceased. The temperature readings of the fluid after 20, 30, and 60 minutes showed that the value at 20 minutes of circulation agreed well with the manual log, whereas the heat gain from the circulation pump to the fluid overestimates the undisturbed temperature by 0.4°C (0.7°F) after 30 minutes. After 60 minutes, the overestimation is 2°C (3.6°F).

In this test, a 60 m (197 ft) borehole and a 1.75 kW (5970 Btu/h) circulation pump were used. The temperature disturbance occurring from the circulation pump is proportional to the specific power load on the measured borehole; thus, a

TABLE 2
Summary of Mean Borehole Temperatures Estimated with the Different Methods in the Study

Method	Resulting Temperature Estimation
Method 1—Temperature logging along the borehole	11.8°C (53.2°F)
Method 2—Flow temperature measurements at 10-second interval (1st pulse)	11.7°C (53.1°F)
Method 2—Flow temperature measurements at 10-second interval (2nd pulse)	10.3°C (50.5°F)
Method 3—Flow temperature after 20 minutes of circulation	11.8°C (53.2°F)
Method 3—Flow temperature after 30 minutes of circulation	12.2°C (54°F)
Method 3—Flow temperature after 60 minutes of circulation	13.8°C (56.8°F)

smaller pump or deeper borehole would result in a less disturbed temperature.

At the time of the measurement, the temperature of ambient air was considerably lower than the ground temperature, and although the connection pipes and coupling of the test device were insulated, some cooling of the circulation circuit occurred. In the case of warmer weather or solar radiation during the response test, the circuit will be warmed. The disturbance from the ambient conditions will be smaller for deeper boreholes and with better insulation of exposed parts of the test device.

The undisturbed ground temperature profile from the test borehole is, in this specific case, slightly rounded. Normally the ground temperature will increase more or less linearly with depth below a few meters depth, above which the seasonal variation of the ground surface temperature will characterize the temperature profile. The reason for the rounded shape of the test borehole temperature profile is the heat (or temperature) distribution in the old heat store. The law of diffusion gives that the warmest temperatures in the heat storage volume will be found in the center. This nonlinear temperature distribution along the borehole does not interfere with Eskilson's (1987) approximation of a homogenous ground temperature.

The temperature estimation recommended by Kavanaugh et al. (2000), to use the recorded minimum flow temperature, is not supported by measurements performed. This recommendation would give a strongly underestimated temperature in this case (see Figure 6).

CONCLUSION

Temperature logging of the borehole is assumed to give the correct undisturbed ground temperature profile. Short interval fluid temperature logging gives an estimation that is close to the undisturbed temperature. In this case, with a relatively large circulation pump and a shallow borehole, it cannot be recommended to use the temperature reading after 30 minutes of fluid circulation as an estimation of the undisturbed ground temperature. A maximum of 20 minutes of circulation is the limit for a reasonable estimation of the ground temperature from one reading, in this case. In a deeper borehole, the disturbance from the circulation pump would be smaller, and

it would take a longer time for the temperature fluctuations in the pipe to cease.

A high ambient air temperature could affect the ground temperature estimation, i.e., shorten the measurement time within which reliable temperatures are obtained. A possible approach would be to use the intercept temperature as the undisturbed ground temperature. This would need further investigation.

ACKNOWLEDGMENTS

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PAPER IV

Comparison of four models for Thermal Response Test Evaluation.

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Comparison of Four Models for Thermal Response Test Evaluation

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ABSTRACT

Four two-variable parameter estimation models for evaluation of thermal response test data are compared when applied on the same temperature response data. Two models are based on line-source theory, the third model is a cylinder-source-based solution, and the fourth is a numerical one-dimensional finite difference model. The data sets contain measured temperature response, heat load, and undisturbed ground temperature from three thermal response tests, together with physical data of the tested borehole heat exchangers (BHE). The models estimate ground thermal conductivity and thermal resistance of the BHE and are compared regarding test length and data interval used. For the three defined data sets, the line source approximation model shows the closest agreement with the measured temperature response. The cylinder source and numerical models show sensitivity to the inclusion of early data. A recommended minimum response test duration of 50 hours is concluded from the model comparison.

INTRODUCTION

During a thermal response test, a defined thermal load is applied to a borehole heat exchanger and the temperature development of the inlet and outlet temperatures are measured over time. This temperature response allows extrapolation of the thermal behavior in future time. One possible conceptual model for the interpretation is to assume the ground to be a conductive medium and to determine the apparent thermal conductivity and other thermal parameters of this medium. The test may be conducted using a transportable device that is brought onsite to the borehole.

Since its introduction in 1995-1996, this in-situ method has spread to most countries where boreholes in the ground are used as a heat source/sink on a larger scale. The method serves primarily to assess the ground thermal conductivity and performance of different borehole heat exchanger designs, which are important for optimal design and quality control. The method is described in several papers, e.g., Gehlin (1998), Austin (1998), Austin et al. (2000), Shonder and Beck (2000), and Kavanaugh et al. (2000). The principle of a thermal response test setup is outlined in Figure 1.

The borehole temperature response is the temperature development over time of the heat carrier fluid circulating through the borehole heat exchanger when a known heating or cooling load is imposed. By evaluating the increasing fluid

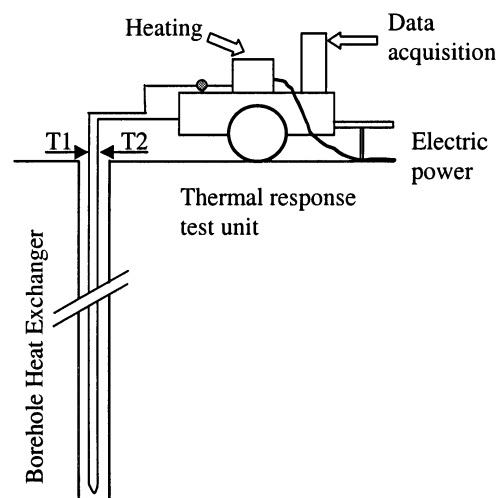


Figure 1 Thermal response test setup.

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temperature versus time, information about the thermal properties in and around the borehole is obtained. A low thermal conductivity is, e.g., indicated by a more rapid temperature response. The response also gives information about the temperature difference between the heat carrier fluid and the surrounding ground caused by the heat transfer, i.e., the thermal resistance of the borehole heat exchanger.

Several analytical and numerical methods are used for the evaluation of response test temperature data. The different models require somewhat different sets of input data. Various analytical methods for evaluation of borehole response test data are discussed below.

Evaluation Methods

A number of methods have been applied over the years for the simulation of borehole heat exchanger performance. Both analytical and numerical models have been used and reported in several papers, reports, and books. Here, the focus is on models for the evaluation of thermal response test data for determining ground thermal conductivity and evaluation of the efficiency of the borehole heat exchanger.

The thermal response test method is based on the so-called single probe method for determining the thermal conductivity of solid materials in a laboratory environment (Stålhané and Pyk 1931). Initial analyses were based on the line-source approximation, which does not consider the thermal properties of the probe material. In 1954, Blackwell presented an analytical solution including both the probe material and a possible contact resistance at the probe surface. In principle, this method makes it possible to shorten the measurement periods, especially for large probe diameters. Attempts to determine both thermal conductivity and diffusivity simultaneously by taking the contact resistance into account were not successful (Blackwell 1954; Beck et al. 1956). The determination of the thermal diffusivity was found to be very sensitive to the contact resistance. Sundberg (1988) developed a detailed FEM model of the probe in order to shorten the measurement period. He found that both thermal conductivity and diffusivity were heavily influenced during the initial time period by small changes in the probe properties.

Analytical models, such as the line-source and cylinder-source theories, require several simplifying assumptions regarding the geometry of the borehole and heat exchanger pipes. For the purpose of the thermal response test evaluation, the heat flow to or from the borehole may be represented as an infinitely long heat source or sink in the ground with negligible influence of heat flows in a direction along the borehole axis. In the ground outside the borehole it is common practice to assume that the thermal process depends only on the radial distance from the borehole axis. The one- or two-dimensional heat flow process from the circulating fluid to the borehole wall is assumed to be represented by a thermal resistance that characterizes the temperature loss between heat carrier fluid and borehole wall. Some models also include the thermal mass of the materials in the borehole.

Ingersoll and Plass (1948) applied the line-source model to the design of ground loop heat exchangers. Mogensen (1983) proposed to use a borehole similar to the probe to estimate the ground thermal conductivity from an experimental field test. This method is now commonly used for thermal response test evaluation in Europe.

The cylinder source approach models the ground loop heat exchanger as a cylinder by introducing an equivalent diameter to represent the two pipes of a single U-pipe heat exchanger as a single coaxial pipe. Carslaw and Jaeger (1959) developed analytical solutions with varying boundary conditions for regions bounded by cylinder geometry. Deerman and Kavanaugh (1991) and Kavanaugh and Rafferty (1997) describe the use of the cylinder-source model in designing ground loop heat exchangers. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground loop heat exchanger. Based on a short-term in-situ test, the measured effective thermal resistance of the ground of a daily heat pulse is fitted to a value computed from a dimensionless cylinder-source function by varying the thermal conductivity and diffusivity of the ground.

Numerical models can be designed to handle detailed representations of the borehole geometry and thermal properties of the fluid, pipe, borehole filling, and ground, as well as varying heat transfer rates. The more extensive set of required input data often make these models more difficult and time-consuming to use than the analytical methods, which sometimes may be implemented as simple spreadsheet applications.

Berberich et al. (1994) describe a response test type of measurement in groundwater-filled ducts in water-saturated claystone where temperature sensors were placed along the borehole wall. The measured data were analyzed with both an analytical line-source model and a numerical two-dimensional finite difference model using parameter estimation with ground thermal conductivity and volumetric heat capacity as variables. The numerical model calculates the heat flows in both the vertical and the radial directions for a borehole of finite length. The results from the numerical analyses resulted in 5% lower thermal conductivity values than the analytical results. Berberich et al. (1994) attribute this difference to end effects of the finite-length borehole, i.e., increased heat transfer near the top and bottom of the borehole.

Shonder and Beck (1999) developed a parameter-estimation-based method, which is used in combination with a one-dimensional numerical model. This model is similar to a cylinder-source representation in that it represents the two pipes of the U-tube as a single cylinder. However, it adds two more features—a thin film that adds a resistance without heat capacity and a layer of grout, which may have a thermal conductivity and heat capacity different from the surrounding soil. This model accommodates time-varying heat input.

A transient two-dimensional numerical finite volume model in polar coordinates for response test evaluation is

TABLE 1
Summary of Required Input to the Four Analysis Models

Input Data	Model 1 Line Source E1	Model 2 Line Source Approx.	Model 3 Cylinder Source	Model 4 FDM Numerical
Effective borehole depth	X	X	X	X
Borehole diameter	X	X	X	X
Undisturbed ground temperature	X	X	X	X
Injected power	X	X	X	X
Volumetric heat capacity of the ground	X	X	X	X
Volumetric heat capacity of the heat carrier	–	–	X	X
Volumetric heat capacity of the borehole filling	–	–	X	X
Pipe diameter	–	–	X	X
Pipe wall thickness	–	–	X	X
Pipe thermal conductivity	–	–	–	X

reported in Austin (1998) and Austin et al. (2000). The geometry of the circular U-tube pipes is approximated by “pie-sectors,” over which a constant flux is assumed. The convection resistance due to the heat transfer fluid flow inside the U-tubes is accounted for by using fluid properties through an adjustment on the conductivity of the pipe wall material. A thorough description of the numerical model is found in Yavuzturk et al. (1999). The model has since been improved by introducing a boundary-fitted grid system that is more flexible and better represents the U-tube pipe geometry (Spitler et al. 2000). The model is compared with the line-source and cylinder-source models in Austin (1998).

Smith (1999) and Witte et al. (2002) compare results from a response test, analyzed with the line-source model and the numerical model described by Spitler et al. (2000). The results from the two analytical methods fall within 4% difference in the estimates.

Kavanaugh et al. (2000) provide an extensive comparison between conductivity estimation with several analytical and numerical evaluation models from 65 thermal response tests in North America. The different models worked well under certain conditions and no obvious “best” analysis procedure could be distinguished.

MODEL COMPARISON

Four evaluation models were compared when used for analysis of the same three temperature response data sets. The three analytical models and the numerical model used are described below. A summary of the required input variables for the four models is presented in Table 1.

In all models, the following three assumptions are made:

1. Heat transport in the ground is purely conductive.
2. There is radial symmetry around the borehole axis.
3. Heat conduction in the direction along the borehole axis is negligible.

The first assumption regarding heat transport in the ground taking place only by heat conduction is a common approach in most published evaluation models. However, the influence of convective heat transport by groundwater movement can be large. Groundwater movement may occur by regional groundwater flow and by natural convection induced by the thermal disturbance caused by heat transfer at the borehole heat exchanger. Disturbances from drilling adjacent boreholes in the vicinity have also been observed. The influence by regional groundwater flow has been addressed by Chiasson et al. (2000), Claesson and Hellström (2000), and Witte (2001). In a groundwater-filled borehole, there may be both a “small-scale” natural convection between the pipe and the borehole wall (Hellström and Kjellsson 2000), as well as a large-scale natural convection cell involving the borehole as conduit for vertical water movement and the surrounding ground. Presence of groundwater flow in the borehole has, in several Swedish and Norwegian tests, resulted in an effective thermal conductivity that is considerably higher than during stagnant conditions (Gehlin 1998; Skarphagen and Stene 1999). The parameter estimates may then depend on the test conditions, such as the resulting magnitude of the temperature change of the borehole water. It is important to establish the nature and magnitude of the groundwater flow in order to extrapolate the thermal response of a 50-hour test to much longer periods (years). This is an issue that needs further research.

In this study, it is also assumed that the heat transfer rate is constant, although the numerical models can handle varying heat transfer rates without problems.

Line Source Approximation

Model 1 is based on the line-source theory. The continuous line source, as described by Carslaw and Jaeger (1959, p. 261), presumes a constant heat flux from a line along the vertical axis of the borehole in an infinite solid. The fluid temper-

ature is evaluated by taking the line-source temperature at the borehole radius ($r = r_b$) and adding the effect of the thermal resistance R_b between the fluid and the borehole wall.

$$T(t) = T_{ug} + \frac{Q}{4\pi\lambda_{ground} \cdot H} \cdot E1\left(\frac{r_b^2}{4 \cdot a_{ground} \cdot t}\right) + \frac{Q}{H} \cdot R_b \quad (1)$$

where

$$E1(x) = \int_x^\infty \frac{e^{-u}}{u} du \quad (2)$$

$$a_{ground} = \frac{\lambda_{ground}}{c_{ground}} \quad (3)$$

For small values of x , as is normally the case for thermal response tests on ground heat exchangers, a serial development may be used as an approximation. In this model, the following approximation of the exponential integral was used (Abramowitz and Stegun 1964):

$$E1 \approx -\gamma - \ln x + A \cdot x - B \cdot x^2 + D \cdot x^3 - E \cdot x^4 + F \cdot x^5 \quad (4)$$

where

$$\begin{aligned} A &= 0.99999193 & B &= 0.24991055 & D &= 0.05519968 \\ E &= 0.00976004 & F &= 0.00107857 & \gamma &= 0.5772... \end{aligned}$$

It should be noted that the line-source solution includes a kind of thermal capacity in the borehole, namely, the thermal capacity of a borehole completely filled with ground material.

Simplified Line Source Approximation

Model 2 is a further simplification of the line-source approximation, as used by Mogensen (1983), Eskilson (1987), and Hellström (1991). It includes the thermal resistance between the fluid and the borehole wall and is valid when the thermal process within the borehole is near steady-state condition.

$$\begin{aligned} E1(x) &\approx \ln \frac{1}{x} - \gamma & \text{for} & \quad \frac{a_{ground} \cdot t}{r_b^2} \geq 5 \\ \gamma &= 0.5772... & a_{ground} &= \frac{\lambda_{ground}}{c_{ground}} \end{aligned} \quad (5)$$

This gives, for the above assumptions,

$$T(t) = T_{ug} + \frac{Q}{4\pi\lambda_{ground} \cdot H} \cdot \left[\ln \left(\frac{4 \cdot a_{ground}}{r_b^2} \cdot t \right) - \gamma \right] + \frac{Q}{H} \cdot R_b \quad (6)$$

Model 3—Probe Method

Model 3 is a cylinder-source analytical model. Carslaw and Jaeger (1959, p. 345) presented a “probe” method of determining thermal conductivity where a cylinder of a perfect

conductor with finite thermal mass is surrounded by an infinite conductive medium. For large values of the time or a small radius, the temperature of the conductor becomes

$$\begin{aligned} T(t) &= T_{ug} + \frac{Q}{4\pi\lambda_{ground} \cdot H} \cdot \\ &\left(2h + \ln \frac{4\tau}{C} - \frac{4h - \alpha_1}{2\alpha_1\tau} + \frac{\alpha_1 - 2}{2\alpha_1\tau} \cdot \ln \frac{4\tau}{C} + \dots \right) \end{aligned} \quad (7)$$

where

$$h = 2\pi \cdot \lambda_{ground} \cdot R_b \quad \alpha_1 = \frac{2 \cdot \pi \cdot r_b^2 \cdot c_{ground}}{c_{cyl}} \quad \tau = \frac{a_{ground} \cdot t}{r_b^2} \quad (8)$$

$$a_{ground} = \frac{\lambda_{ground}}{c_{ground}} \quad C = e^\gamma \quad \gamma = 0.5772... \text{ (Euler's constant)}$$

The borehole heat exchanger is approximated as a cylinder filled with a backfill material of a certain volumetric heat capacity. The borehole cylinder heat capacity is calculated by assuming the U-tube pipes as one concentric pipe with an equal radius as follows:

$$c_{cyl} = c_{fl} \cdot \pi \cdot r_{fl}^2 + c_{fill} \cdot \pi \cdot (r_b^2 - r_{fl}^2) \quad (9)$$

where

$$r_{fl} = \sqrt{2 \cdot r_{p-i}^2}$$

Numerical Method

Model 4 is an explicit one-dimensional finite difference (FDM) numerical model. The numerical grid consists of 18 cells in the radial direction from the center of the borehole. The first cell represents the volume and thermal mass of the heat carrier fluid, the second cell represents the filling material, and the remaining cells are used for the surrounding ground. The grid size in the surrounding ground starts with three 0.004 m cells and then expands outward. The outer radius of the physical domain is roughly at 13 m, which is outside of the zone of thermal influence during the duration of a thermal response test. The time step is on the order of five to ten seconds.

The borehole heat exchanger is a single U-pipe that is approximated by a coaxial pipe filled with heat carrier fluid and surrounded by the borehole filling material. The thermal process between the heat carrier fluid and the borehole wall is accounted for as a borehole thermal resistance. The borehole thermal resistance is divided into two components—a thermal resistance between the fluid and the borehole filling material and a thermal resistance between the borehole filling material and the borehole wall.

$$R_b = R_{bhf} + \frac{R_{pipe}}{2} \quad (10)$$

where

$$R_{pipe} = \frac{\ln\left(\frac{r_{p-o}}{r_{p-i}}\right)}{2\pi\lambda_{pipe}}$$

The thermal state in the borehole filling is represented by one average temperature. The thermal resistance of the borehole filling material is further divided into two parts—one for the heat flow between the outer surface of the flow channel pipes and the borehole filling temperature and one between this temperature and the borehole wall.

$$R_{bhf-bhw} = 0.33 \cdot R_{bhf} \quad R_{fl-bhf} = (1 - 0.33) \cdot R_{bhf} \quad (11)$$

The value 0.33 is based on a calculation of the thermal resistance between the fluid temperature and the mean temperature of the filling material at steady-state conditions for a representative case using an exact analytical method (Bennet et al. 1987). The heat conductance between the fluid and the borehole filling is then

$$U_{fl-bhf} = \frac{1}{\frac{R_{pipe}}{2} + R_{fl-bhf}}, \quad (12)$$

and the heat conductance between the borehole filling and the borehole wall is

$$U_{bhf-bhw} = \frac{1}{\frac{\ln\frac{r_m}{r}}{2\pi \cdot \lambda} + R_{bhf-bhw}}. \quad (13)$$

The radial heat conductance between two adjacent cells in the ground is

$$U_{ground} = \frac{2\pi\lambda}{\ln\frac{r_m}{r_m - \Delta r}}. \quad (14)$$

The specific heat flow is calculated from the heat conductance and the temperature difference between two points at different radial distance from the borehole center, and the change in temperature over time depends on the change in specific heat flow over time and the specific heat capacity.

Parameter Estimation Procedure

Parameter estimation involves minimizing the differences between an experiment and an analytical or numerical model by adjusting model input. Some input data are fixed, whereas others are allowed to vary. In this parameter estimation procedure, two variables—ground thermal conductivity (λ_g) and borehole thermal resistance (R_b)—have been varied. By systematically varying these two variables, the minimum difference between the experimental and modeled values is found, which indicates the best estimate of the two variables.

The optimization procedure is performed with a nonlinear optimization technique called Nelder-Mead Downhill Simplex (Press et al. 1986), and the objective function for the optimization is the sum of squares of the errors between the experimental and theoretical results.

INPUT DATA SETS

Data sets from three thermal response tests conducted at different locations were used for the simulations (Table 2). All three boreholes were fitted with single U-pipe heat exchangers; however, pipe materials and dimensions vary. In this paper, hourly temperature recordings are presented for all three data sets; however, temperature recordings were made every two minutes for data set A and every ten minutes for data set B and C during the response tests.

Data set A is collected from a response test conducted in Oklahoma (Austin 1998). The grouted borehole was drilled in sedimentary bedrock. The power supply was fluctuating during the measurement but, in this analysis, the mean injection power was used.

Data set B comes from a Norwegian measurement of a groundwater-filled borehole drilled in slate. The power injection was stable during the response test. The test was conducted by a test device (Skarphagen and Stene 1999) of the same construction as the Swedish apparatus (Gehlin 1998).

Data set C is from a Swedish borehole drilled in a cave 240 m (787 ft) below sea level, which meant that the borehole was filled with saline groundwater. The hole was sealed at the top to prevent overflow due to the high water table. The surrounding rock was granitic, and the air temperature in the cave was constantly 15°C (57.4°F) during the measurement. The heat exchanger was made of aluminum pipes to resist the pressure in the borehole. The electric power supply was stable during the measurement. Gehlin (1998) describes the response test device. It should be noted that it is quite likely that the thermal process in and around the borehole is influenced by groundwater flow, since the geohydrological conditions are disturbed by the presence of the tunnel.

The error of the assumed value of the ground heat capacity is small. The estimation of the undisturbed ground temperature is a more delicate matter. Gehlin and Nordell (2002) compare three different methods to estimate the undisturbed ground temperature—manual temperature logging, calculating the temperature profile from ten-second interval temperature recording during initial heat carrier fluid circulation, and using the recorded temperature at a certain time after starting the pump. The two first methods give the best estimations. Kavanaugh et al. (2000) also briefly discusses undisturbed ground temperature estimation methods and presents some data. The error in the thermal conductivity is directly proportional to the error in the estimated undisturbed ground temperature. An accurate estimation of this temperature is particularly important for small temperature changes over the response test period, as the relative error becomes large.

TABLE 2
Evaluated Data Sets

	Notation	Data Set A	Data Set B	Data Set C
Effective borehole depth, m (ft)	H	74.7 (245)	178.5 (586)	132.6 (435)
Borehole diameter, m (in.)	$D = 2r_b$	0.108 (4.25)	0.140 (5.5)	0.096 (3.78)
Rock type		Sedimentary	Slate	Igneous rock
Volumetric heat capacity of the ground, $\text{J/m}^3\text{-K}$ (Btu/ft ³ -F)	c_g	2000000 (30)	2400000 (35.8)	2200000 (32.8)
Borehole filling material		Grout	Groundwater	Groundwater (saline)
*Volumetric heat capacity of borehole filling, $\text{J/m}^3\text{-K}$ (Btu/ft ³ -F)	c_{fill}	3484000 (52)	4182000 (62.4)	4182000 (62.4) [†]
Heat exchanger type		Single U-pipe	Single U-pipe	Single U-pipe
Heat exchanger material		Polyethylene	Polyethylene	Aluminum
Pipe diameter, m (in.)	$D_{po} = 2r_{po}$	0.0334 (1.315)	0.032 (1.26)	0.033 (1.3)
Pipe wall thickness, m (in.)	t_w	0.003 (0.12)	0.003 (0.12)	0.0065 (0.26)
Pipe thermal conductivity, W/m K (Btu/ft-h-f)	λ_p	0.391 (0.226)	0.42 (0.243)	168 (97)
Heat carrier fluid		Water	Water	Water
Volumetric heat capacity of heat carrier fluid $\text{J/m}^3\text{-K}$ (Btu/ft ³ -F)	c_w	4182000 (62.4)	4182000 (62.4)	4182000 (62.4)
‡Undisturbed ground temp., °C (°F)	T_{ug}	12.4 (54.3)	7.6 (45.7)	14.1 (57.4)
Power injection (mean), W (Btu/h)	Q	2595 (8855)	9510 (32450)	6253 (21336)
Test period, h		50	69	89
Comments				Measured in a cave with constant air temperature 15°C (59°F)

* Estimated value.

† Salinity ca 7‰ gives a 1.4% lower heat capacity than that of pure water. This difference has negligible impact on the simulations.

‡ Measured undisturbed borehole average temperature.

RESULTS AND DISCUSSION

Comparing Models

In this section, the four evaluation models are compared with regard to model behavior. Independent thermal conductivity measurements were not available for the three test sites, so our comparison does not define the most “correct” evaluation model but compares model characteristics.

In Figure 2, the thermal conductivity is compared for all three data sets, analyzed with the two different line-source models. The end data point is fixed at the very last measured data point (hours 50, 69, and 89 for data sets A, B, and C, respectively), and with the simulation start point varying from hour 1 to hours 45 (A), 60 (B), and 75 (C). Thus, the first point for data set A in Figure 2 is the conductivity estimation from the data interval between hour 1 and hour 50, and the last data point is the estimation for the data interval between hour 45 and hour 50. The leftmost values are most stable, which implies that a longer data interval improves the conductivity estimation. When the data interval is shorter than 30 hours from the end points, the estimated conductivity starts to become unstable due to increasing sensitivity to single data

points. Results from the two versions of the line-source theory show no significant difference between model 1 and model 2. The deviation is less than 1%, with the maximum deviation during the first hours of the test. Since model 2, the approximated version of the line-source model, is most commonly used in the analysis of thermal response test data, hereafter model 2 represents the line-source theory.

The two analytical and the numerical models are compared in Figures 3 to 5. Thermal conductivity (Figure 3) and thermal resistance (Figure 4) for data sets A, B, and C were determined for increasing the length of the data interval. The start point is fixed at hour 10; i.e., the first nine hours of measurement data are excluded from the analysis. This choice is based on conclusions from Figure 8. The first point in the figures is the estimation for the data interval between hour 10 and hour 15. The last point is the estimation for the data interval between hour 10 and hour 50 (A), hour 69 (B), and hour 89 (C). This type of sensitivity test has also been discussed in Austin (1998) and Witte et al. (2002). The average temperature deviation between measured temperature and temperature calculated using the estimated thermal conductivity and thermal resistance is plotted in Figure 5.

The results from the line-source model and the numerical model are very similar. The average deviation between these models is of the magnitude 1% to 5%, whereas the estimate from the cylinder-source model is found to be around 10% to 15% higher than for the other models. This may be explained as follows. The temperature response of the cylinder source exhibits a slower initial increase due to the thermal mass of the materials inside the borehole wall. As time increases, and the

borehole thermal mass gradually becomes less important, the temperature curve will rise more steeply to approach the level of the line-source model. Given the same thermal conductivity, the slope of the cylinder-source response is steeper than that of the line source. In order to match the slope of the measured response, the thermal conductivity of the cylinder source must be larger than for the line source. This typically also requires that the borehole resistance estimated by the

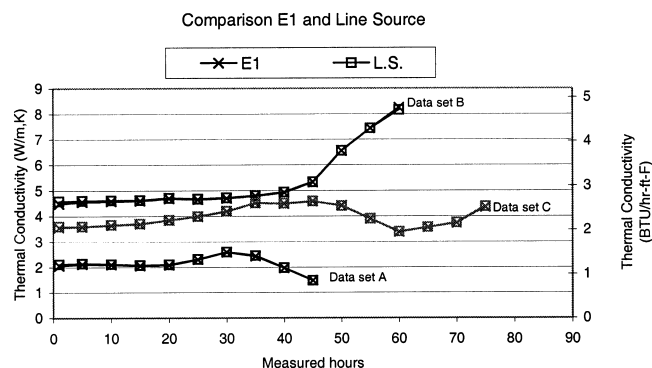


Figure 2 Results from simulation with the line-source approximation (L.S.) and the E1 solution (E1), for data sets A, B, and C. First data point is the conductivity estimated from the interval between hour one and hour 50(A), 69(B), and 89(C). The leftmost values are most stable, which implies that a longer data interval improves the estimation. The plot shows that there is no significant difference between results from the two line-source models.

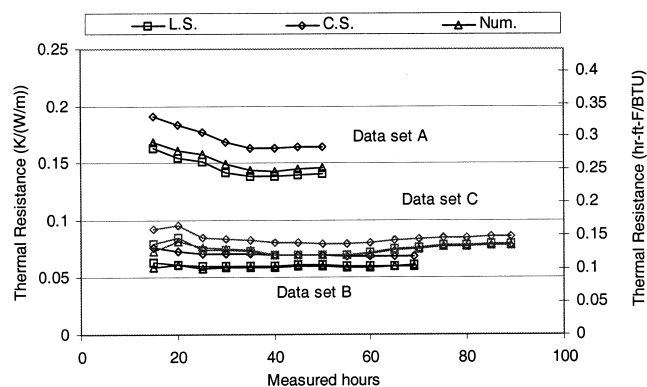


Figure 4 Borehole thermal resistance for data sets A, B, and C, parameter estimated with the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.). The leftmost data points show the thermal resistance estimation from the data interval between hour 10 and hour 15.

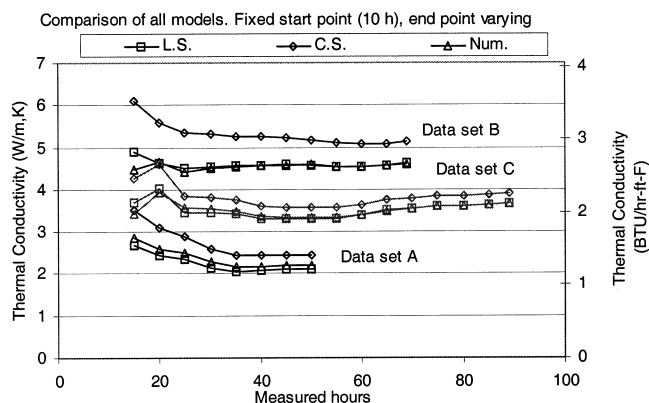


Figure 3 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.). The leftmost data points show the conductivity estimation from the data interval between hour 10 and hour 15. Stability increases with increasing length of data interval.

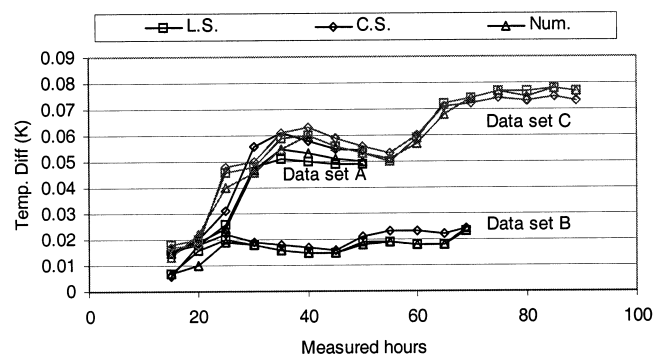


Figure 5 Average temperature difference between measured and simulated data for data sets A, B, and C, calculated from the estimated λ and R_b in Figures 3 and 4. Line-source approximation (L.S.), cylinder-source solution (C.S.), and numerical model (Num.).

TABLE 3
Best-Fit Parameter Estimations for the Three Data Sets and the Three Analysis Models

Model	Data Set A—min at 50 h			Data Set B—min at 45 h			Data Set C—min at 55h		
	λ	R_b	ΔT	λ	R_b	ΔT	λ	R_b	ΔT
	W/m K (Btu/ft-h-F)	K/(W/m) (F/[Btu/h-ft])	K	W/m K (Btu/ft-h-F)	K/(W/m) (F/[Btu/h-ft])	K	W/m K (Btu/ft-h-F)	K/(W/m) (F/[Btu/h-ft])	K
Line source	2.12 (1.22)	0.141 (0.244)	0.049	4.59 (2.65)	0.061 (0.106)	0.015	3.31 (1.91)	0.070 (0.121)	0.050
Cylinder source	2.45 (1.42)	0.164 (0.284)	0.054	5.23 (3.02)	0.070 (0.121)	0.016	3.57 (2.06)	0.079 (0.137)	0.053
Numerical	2.20 (1.27)	0.146 (0.253)	0.050	4.57 (2.640)	0.060 (0.104)	0.015	3.34 (1.93)	0.070 (0.121)	0.051

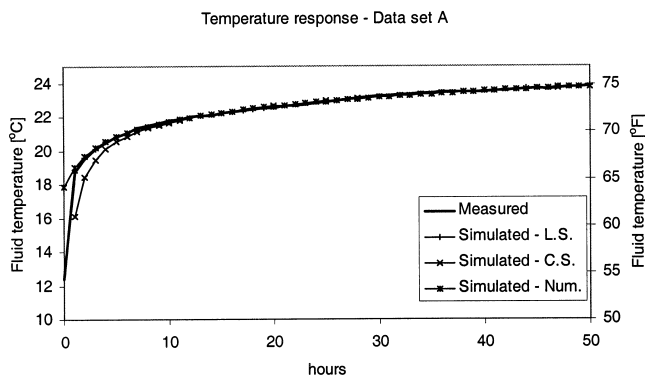


Figure 6 Experimental data for data set A compared to best-fit response for the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.).

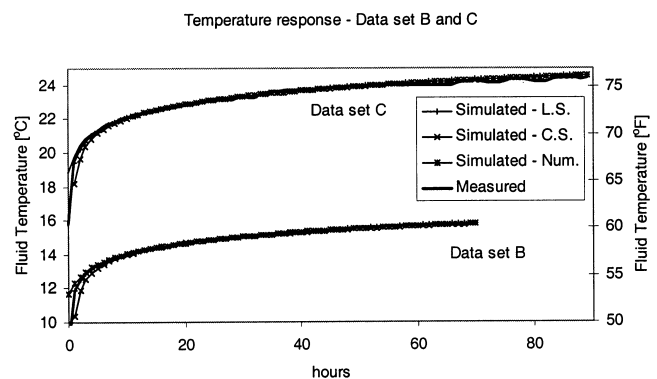


Figure 7 Experimental data for data sets B and C compared to best-fit response for the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.).

cylinder source be larger, so that the total thermal resistance of the ground and the borehole is appropriate. The deviation between the models decreases with longer measurement time.

The smallest average temperature difference between measured and simulated temperatures is found for the conductivity and thermal resistance estimated from the data interval between hour 10 and hours 50 (A), 45 (B), and 55 (C). The resulting ground thermal conductivity and borehole thermal resistance are found in Table 3 for each of the three models. Best-fit simulated temperatures for the three models are presented together with the measured temperatures in Figures 6 and 7.

Data Sets

It is common practice to disregard the measured data during a certain initial time. This is done to avoid the complexity of the transient heat transfer process in the borehole and to use a period when the ground thermal properties have a relatively larger influence on the thermal response. Kavanaugh et al. (2000) point at several reasons for disturbance of the initial temperature response, such as disturbance from the drilling

procedure, injection of drilling mud, and grouting. The effect of the early measurement data and test length is illustrated in Figure 8. The thermal conductivity is plotted for all three data sets, and three models, when the end data point is fixed at the very last data point (hours 50, 69, and 89 for data sets A, B, and C, respectively) and with the simulation start point varying from hour 1 to hours 40 (A), 60 (B), and 80 (C). The thermal conductivity becomes stable for data series starting at 10–15 h and becomes unstable again when the data series become too short (<30 h). The line-source solution gives results that are least sensitive to the inclusion of early values, whereas the numerical model tends to result in a lower estimate and the cylinder-source model a higher estimate of the thermal conductivity when early data are included.

The issue of required response test duration has been discussed in several papers (e.g., Austin et al. 2000; Smith 1999). In Figure 9, the thermal conductivity estimated with the line-source model is plotted for the three data sets and various test lengths. Five curves with start data point at hour 1, 5, 10, 15, and 20, respectively (see legend in Figure 9), are plotted using increasing data intervals. Figures 10 and 11 show the

same graphs plotted for the cylinder-source model and the numerical model, respectively. As discussed earlier, the line-source model gives results most similar to measured data when early data points are included. However, the plots converge around the estimates for ten initial hours excluded and become relatively stable when including at least 40 h measurement. In literature recommendations of required response, test durations vary from 12-14 h (Smith 1999) to 48 h (Spilker 1998), 50 h (Austin et al. 2000), and 50-60 h (Gehlin 1998).

A possible—but not recommended—variety of choosing analysis data interval is to use a “data window” along the measurement series. However, this method is sensitive to small disturbances in the temperature data, as illustrated in

Comparison of model results. First data point varying, last datapoint fixed.

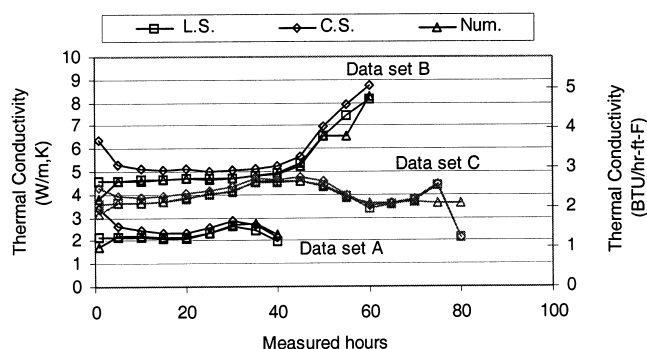


Figure 8 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.). The last data point is fixed, and first data point is varied.

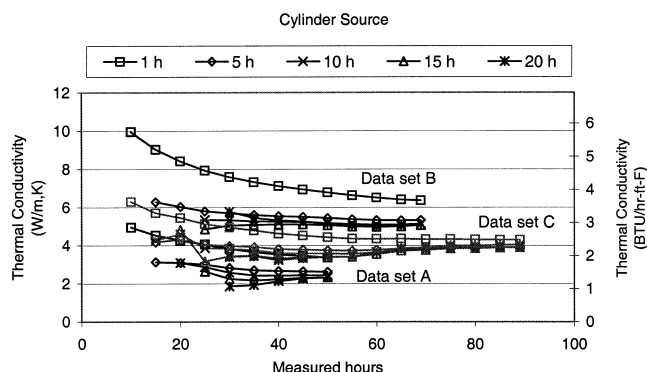


Figure 10 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the cylinder-source solution. The first data point in the data interval used for the estimation is fixed at the hour shown in the legend, and the end point in the interval is shown on the x-axis.

Figure 12, where a data window of 25 h is used. The figure shows the resulting thermal conductivity for a 25-hour window starting at different hours along the measurement, estimated for all three data sets and three analysis models. The first points in the figure show the thermal conductivity for the data-window 1-25 h. Especially for data set C, where small temperature fluctuations of the order 0.2°C (0.36°F) appear in the late part of the measurement, the difficulties with this data-window method become evident. The sensitivity is also discussed in Austin (1998), where a floating three-hour period is used with the line-source model. The shorter the data window, the more sensitive the evaluation.

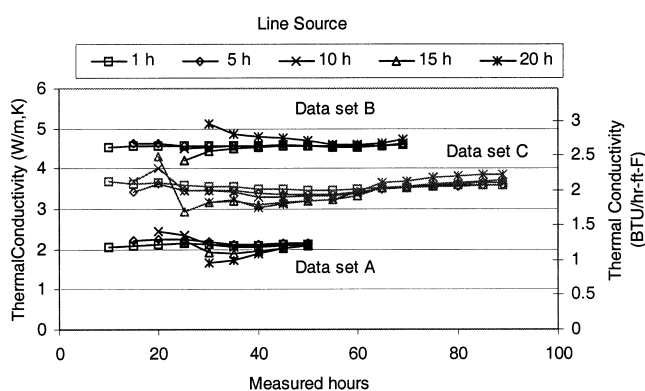


Figure 9 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the line-source approximation. The first data point in the data interval used for the estimation is fixed at the hour shown in the legend, and the end point in the interval is shown on the x-axis.

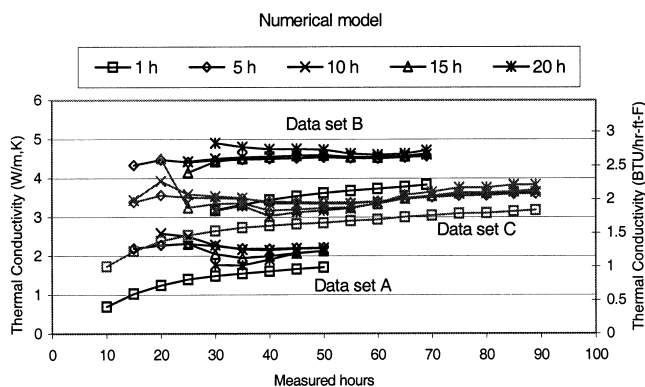


Figure 11 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the numerical model. The first data point in the data interval used for the estimation is fixed at the hour shown in the legend, and the end point in the interval is shown on the x-axis.

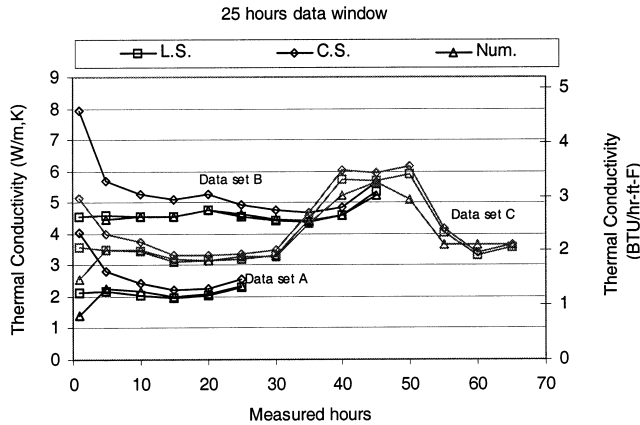


Figure 12 Ground thermal conductivity for data sets A, B, and C, parameter estimated with the line-source approximation (L.S.), the cylinder-source solution (C.S.), and the numerical model (Num.). A sliding 25-hour data window is used.

CONCLUSIONS

Four different evaluation models were compared in analyzing thermal response tests conducted at three test sites. Three analytical models were used, of which two were based on the line-source theory and one on the cylinder-source theory. The fourth model was a one-dimensional finite difference numerical model. All four models used a two-variable parameter estimation technique, using ground thermal conductivity and borehole thermal resistance as variables to find the best fit to measured data. The four models were used to analyze varying portions of the measurements with regard to model behavior rather than “true value” estimation. The following conclusions were drawn from the model comparison using the three defined data sets (Table 2) and assuming pure conductive conditions:

- The E1-line source and the simplified line source give results with negligible difference.
- Thermal conductivity estimated with the cylinder-source model gives 10% to 15% higher values than corresponding estimation with the other models. This may be explained by the cylinder source giving a slower initial increase due to the thermal mass of the materials inside the borehole. This effect becomes less important as time increases, and to compensate for this steeper response in the match with the measured response, the thermal conductivity and thermal resistance will both be larger than for the line-source estimation.
- The line-source theory and the one-dimensional FDM numerical model result in estimations of the ground thermal conductivities with a difference less than 4%.
- The deviation in results between the models is larger for short measurement series, and decreases with longer measurements.

- Of the compared models, the line-source representation agrees best with the first hours of the measured data. The cylinder-source representation deviates most from the early measured temperatures.
- The line-source model agrees best with the measured data when ten hours or less of the initial data are excluded, whereas the representation by the cylinder source and numerical models diverges when too much initial data is included. Excluding the first 10-15 h appears to be optimal for the cylinder source, while exclusion of the initial 5-10 h gives best results for the numerical model. Thus, excluding the first ten hours of data will give good estimates regardless of which of the three models is used for evaluation.
- At least 50 h of measurement is recommended. If less than 30 h are used, the convergence of the best fit becomes poor. The conclusion is that if ten hours initial data are excluded and a minimum of 30 h data from the final hour is needed, then the measurement must continue for > 40 h.
- Using a sliding data window (in this case 25 h data) gives uncertain results and is not recommended. The evaluation results are more affected by temperature fluctuations late in the measurement.
- The line-source model shows closest agreement with measured temperatures for all three data sets. As used in this paper, the line-source model is the fastest and simplest model. The numerical model is most time consuming and tends to overestimate the borehole temperature during the initial test hours. However, the numerical model is better suited for situations with variable heat injection.

The validity of short-term evaluation results from a response test used on long-term operation of a borehole heat exchanger needs further study, e.g., by using the response test estimates from the different evaluation models and comparing the long-term response using different design tools. Several factors that may affect the short-term response of a borehole may have declining influence as time increases, e.g., natural convection inside and outside the borehole, which is most significant when the temperature gradients are high during the initial borehole operation. This issue needs to be studied further.

NOMENCLATURE

- a = diffusivity = $\frac{\lambda}{c}$, m^2/s (ft^2/s)
- C = e^γ
- c = volumetric heat capacity, $\text{J}/\text{m}^3 \cdot \text{K}$ ($\text{Btu}/\text{ft}^3 \cdot ^\circ\text{F}$)
- c_{cyl} = cylinder heat capacity per m borehole, $\text{J}/\text{m} \cdot \text{K}$ ($\text{Btu}/\text{ft} \cdot ^\circ\text{F}$)
- $E1$ = the exponential integral
- H = effective borehole depth, m (ft)
- h = $2\pi \cdot \lambda_{ground} \cdot R_b$

Q	=	injected heat power rate, W (Btu/h)
q	=	heat flux, W/m (Btu/ft-h)
R	=	thermal resistance, K/(W/m) (°F/[Btu/ft-h])
r	=	radius, m (in.)
T	=	temperature, °C (°F)
t	=	time, s
U	=	heat conductance, K/(W/m) (°F/[Btu/ft-h])
x	=	$\frac{r_b^2}{4 \cdot a_{ground} \cdot t}$
α_1	=	$\frac{2 \cdot \pi \cdot r_b^2 \cdot c_{ground}}{c_{cyl}}, \text{ m}^2 (\text{ft}^2)$
γ	=	Euler's constant = 0.5772...
λ	=	thermal conductivity, W/m-K (Btu/ft-h-F)
τ	=	$\frac{a_{ground} \cdot t}{r_b^2}$

Subscripts

b	=	borehole
bhf	=	borehole filling
bhw	=	borehole wall
ug	=	undisturbed ground
$fill$	=	filling
fl	=	fluid
m	=	mean
p_i	=	pipe (inner)
p_o	=	pipe (outer)

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PAPER V

**Influence on Thermal Response Test by Vertical Fractures in Hard
Rock**

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INFLUENCE ON THERMAL RESPONSE TEST BY GROUNDWATER FLOW IN VERTICAL FRACTURES IN HARD ROCK

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ABSTRACT

In this paper different approaches to groundwater flow and its effect in the vicinity of a borehole ground heat exchanger are discussed. The common assumption that groundwater flow in hard rock may be modelled as a homogeneous flow in a medium with an effective porosity is confronted and models for heat transfer due to groundwater flow in fractures and fracture zones are presented especially from a thermal response test point of view. The results indicate that groundwater flow in fractures even at relatively low specific flow rates may cause significantly enhanced heat transfer, although a continuum approach with the same basic assumptions would suggest otherwise.

INTRODUCTION

The influence of groundwater flow on the performance of borehole heat exchangers has been a topic of discussion. Field observations indicate that groundwater influences the borehole performance by increasing the heat transport significantly (Gehlin 1998, Sanner et al. 2000, Chiasson et al. 2000, Helgesen 2001, Witte 2001). Some theoretical studies have been published on the subject. Eskilson (1987), Claesson & Hellström (2000), Chiasson et al (2000) present models for the influence of regional groundwater flow based on the assumption that the natural groundwater movement is reasonably homogeneously spread over the ground volume. This applies well on a homogeneous and porous ground material. Eskilson and Claesson & Hellström use the line source theory for modelling the groundwater effect on a single vertical borehole. They conclude that under normal conditions, the influence of regional groundwater flow is negligible. Chiasson et al. use a two-dimensional finite element groundwater flow and mass/heat transport model and come to the conclusion that it is only in geologic materials with high hydraulic conductivity (sand, gravel) and in rocks with

secondary porosities (fractures and solution channels in e.g. karst limestone), that groundwater flow has a significant effect on the borehole performance. Simulations of the effect on thermal response tests give artificially high thermal conductivity values. Witte (2001) performed a thermal response test where groundwater flow was induced by pumping in an extraction well located 5 m from the thermal well. Clear indications of enhanced heat transfer due to the induced groundwater flow were observed.

Thermal response test is a method to determine effective ground thermal conductivity in-situ borehole ground heat exchangers and is used in most countries where ground source heat systems are used on a larger scale (Gehlin 1998, Kavanaugh 2000, Shonder and Beck 2000, Austin et al. 2000, Witte 2001). The principle of the test is a constant heat pulse injected into the borehole heat exchanger by heating a fluid that is pumped through the heat exchanger pipes, while inlet and outlet temperature is measured and recorded. The test typically takes 50 hours to perform.

The influence of single or multiple fractures and fracture zones on the performance of the ground heat exchanger has not been thoroughly studied, and may explain field observations where groundwater effects have resulted in artificially high ground thermal conductivity estimations.

GROUNDWATER FLOW IN FRACTURED ROCK

Groundwater flow rate is proportional to the hydraulic conductivity, K , and the hydraulic gradient, I , in the ground. The hydraulic gradient is usually of the same order or smaller than the ground surface slope (Andersson S., et al, 1981). It is calculated as the change in hydraulic head as we move along the ground surface. Common hydraulic gradients are 0.01-0.001 m/m or less (Åberg & Johansson, 1988).

In fractured crystalline rock, the interconnected fractures are the main passages for groundwater flow, and the solid rock may be considered practically impermeable. Two main approaches – continuum and discrete - are used when dealing with groundwater flow in fractured rock.

The continuum approach assumes the fractured rock mass to be hydraulically equivalent to a porous medium. The equivalent porous medium model (EPM) is also known as the equivalent continuum model. It is a conceptually simple and commonly used approach in estimating flow and transport in fractured media as it avoids characterization of fractures. The advantage of this approach is the applicability of Darcy's law. Much research has shown that flow in a large enough volume of fractured medium can be reasonably well represented by

flow through a porous medium, i.e. by an equivalent continuum model. This will be true when (Singhal and Gupta, 1999):

- fracture density is high
- apertures are constant rather than distributed
- orientations are distributed rather than constant
- larger sample sizes are tested
- interest is mainly in volumetric flow, such as for groundwater supplies.

The equivalent hydraulic conductivity, K , of a fractured rock mass regarded with the EPM is defined by Darcy's law:

$$v_{\text{darcy}} = K \cdot \frac{dh}{dx} = K \cdot I \quad (1)$$

where v_{darcy} is the darcy velocity in ms^{-1} , and I is the hydraulic gradient defined as the change in hydrostatic pressure as we move along the x -direction. Darcy's law is only valid for laminar flow in porous media. Groundwater flow in porous media has a Reynolds number usually in the range 1-10. Flow in fractures may vary between laminar and turbulent depending on the structure of the fracture along the flow path. For a fracture, the equivalent diameter in the Reynolds equation may be replaced by the hydraulic diameter (D_h) which for a very long planar fracture is equal to twice its aperture, $D_h = 2 \cdot t_f$ and Re is given by (Singhal and Gupta, 1999):

$$Re = \frac{v_w \cdot 2t_f}{\nu} \quad (2)$$

where v_w is the ground water flow velocity (ms^{-1}), t_f is the fracture aperture (m) and ν is the kinematic viscosity of water (m^2s^{-1}).

Fracture aperture is the perpendicular distance between the adjacent rock walls of a fracture, and may vary from very tight to wide. Commonly, subsurface rock masses have small apertures. Table 1 gives aperture ranges as usually classified in rock mechanics (Singhal and Gupta (1999)).

Table 1.
Aperture classification by size after (Barton, 1973)

<i>Aperture (mm)</i>	<i>Term</i>
< 0.1	Very tight
0.1 – 0.25	Tight
0.25 – 0.50	Partly open
0.50 – 2.50	Open
2.50 – 10.0	Moderately wide
> 10.0	Wide

The equivalent hydraulic conductivity in normally fractured igneous rock is in the range 10^{-5} to 10^{-9} ms^{-1} , and varies with depth from 10^{-5} - 10^{-6} ms^{-1} near the surface to 10^{-8} - 10^{-9} ms^{-1} down to 100-150 m depth (Andersson S., et al, 1981). Snow (1968) showed that the permeability decreases with depth in fractured rocks, usually attributed to reduction in fracture aperture and fracture spacing due to increasing pressure.

If conditions for a continuum approach do not exist, the flow must be described in relation to individual fractures or fracture sets (discrete). Network models use fracture characteristics and heterogeneity of rock mass based on field data. Two-dimensional and three-dimensional models have been developed, but the application of these theoretical models has been limited. The disadvantages of the discrete modelling are that statistical information about fracture characteristics may be difficult to obtain. The models are complex and there is no guarantee that a model reproducing the apparent geometric properties of a fracture network will capture its essential flow or transport features (Singhal and Gupta, 1999).

According to Singhal and Gupta (1999), fractures may be identified into two broad types - systematic (planar and more regular in distribution) and non-systematic (irregular and curved). Systematic fractures may further be classified genetically into shear fractures, dilation fractures and hybrid fractures, of which dilation fractures tend to be most open. Natural fractures vary widely as far as planerity and surface geometry is concerned. Bedding plane fractures in fine-grained sedimentary rocks like shale may be relatively smooth and parallel, but in crystalline rock such as granites, fracture surfaces are usually rough and the aperture varies. Knutsson & Morfeldt (1993) described the fracture characteristics of the most common Scandinavian rock types. Granites usually show regular fractures in three planes; two steep or vertical nearly perpendicular fracture planes and one more or less horizontal plane. Fractures are usually coherent and long. Fractures in gneisses are normally less regular and coherent than in granites. Horizontal fractures are not as common in gneiss as in granites.

SKB (1992) presents a simplified model for fracture zones and fractures in undisturbed granitic rock (Table 2). The model is based on extensive mapping, compiling and statistical modelling of rock structures of all ranges in crystalline rock in Sweden, and theoretical and experimental studies of fracture development. The classification is rather arbitrary and the limits are vague.

Table 2.
Fracture spacing and hydraulic conductivity (after SKB, 1992)

<i>Fracture class</i>	<i>Typical spacing</i> <i>(m)</i>	<i>Typical hydraulic conductivity</i> <i>(m³/s,m²)</i>
1 st order	3000	10 ⁻⁶
2 nd order	500	10 ⁻⁷
3 rd order	50	10 ⁻⁸
4 th order	5	10 ⁻¹¹
5 th order	0.5	0

The SKB classification in Table 2 suggests that within a horizontal distance of 3000 m there is statistically one first order fracture present that has the capacity of draining all groundwater that equals the flow through a porous medium of the equivalent hydraulic conductivity of 10⁻⁶ ms⁻¹. Since the area drained is 3000 m² counted per meter depth, this means that this first order fracture may drain a flow rate of 3 litres per second. Every 500 m there will be a second order fracture that may drain 0.05 litres per second etc. The lower ordered fractures are fed by the higher order fractures in a network. The actual groundwater flow rate is dependent also on the hydraulic gradient in the area.

In fractured rocks, a distinction can be made between hydraulic conductivity of fracture, K_f and of intergranular (matrix) material, K_m . The latter is typically much smaller than the first. The relationship between hydraulic conductivity of a single plane fracture with aperture t is given by:

$$K_f = \frac{\rho \cdot g}{\mu} \cdot \frac{t_f^2}{12} \quad (3)$$

where ρ is density of fluid (kgm⁻³), g is the gravitational acceleration (ms⁻²), μ is the dynamic viscosity (kgs⁻¹m⁻¹) and t_f is the fracture aperture (m). The equivalent hydraulic conductivity of a rock mass with one parallel set of fractures is expressed by:

$$K_s = \frac{t_f}{s} \cdot K_f + K_m = \frac{\rho \cdot g}{\mu \cdot s} \cdot \frac{t_f^3}{12} + K_m \quad (4)$$

where s is fracture spacing (m). As K_m is usually very low except when the rock matrix is porous and/or fractures are filled with impervious material, this part may be neglected:

$$K_s = \frac{\rho \cdot g}{\mu \cdot s} \cdot \frac{t_f^3}{12} \quad (5)$$

Figure 1 gives the hydraulic conductivity values of fractures with different apertures and frequencies. It can be seen that one fracture per metre with an aperture of 0.1 mm gives rock hydraulic conductivity of about 10^{-6} ms^{-1} , which is comparable with that of porous sandstone. With a 1 mm aperture and the same spacing, the hydraulic conductivity will be 10^{-3} ms^{-1} , similar to that of loose clean sand.

The equivalence between hydraulic conductivity in fractured rock and that of porous material is depicted in Figure 2. As an example, the flow from a 10 m wide cross-section of a porous medium with a hydraulic conductivity of 10^{-4} ms^{-1} could be the same as from one single fracture with an aperture of about 1 mm. This demonstrates the large amount of flow which can be expected even from very fine fractures.

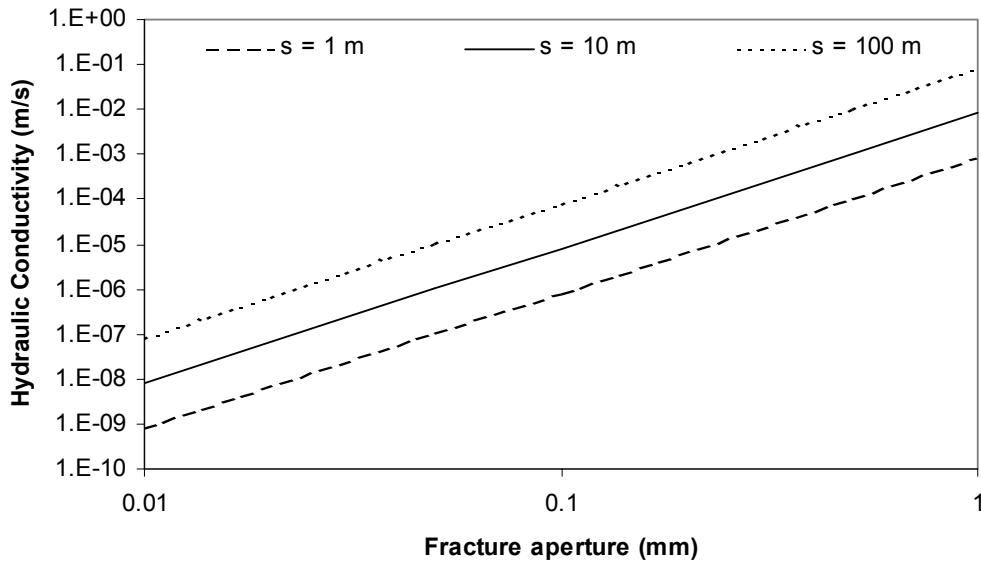


Figure 1. Variation in hydraulic conductivity with fracture spacing and conducting aperture. (After Singhal and Gupta, 1999).

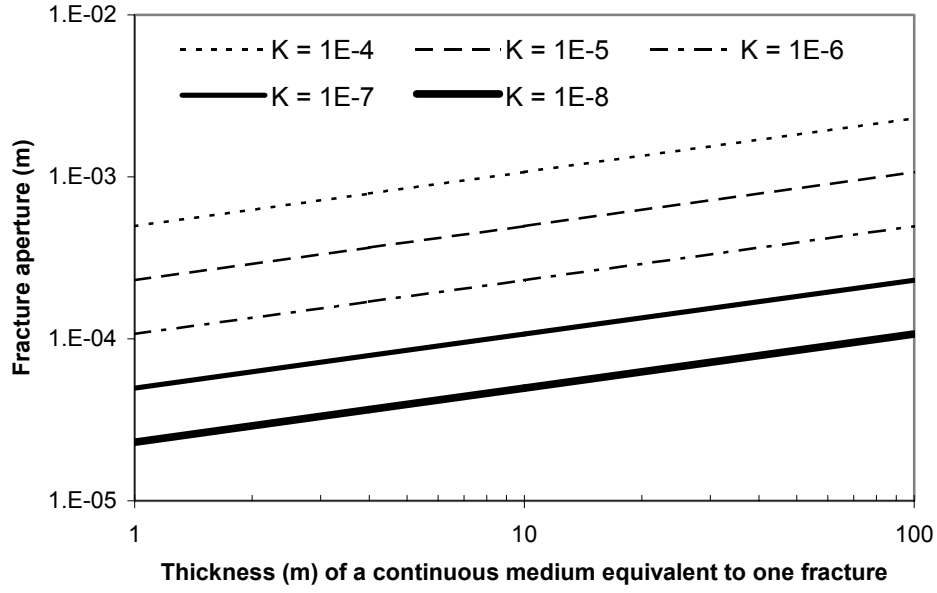


Figure 2. Comparison between the hydraulic conductivity of the porous medium and that of the fractured medium as a function of aperture. (After Singhal and Gupta, 1999).

The fracture permeability in hard rock is affected by a number of factors such as stress, temperature, roughness, fracture geometry, aperture, and intersection. Cementation, filling and weathering of fractures are factors that affect the permeability. Natural fractures have a certain roughness, however this roughness is difficult to measure, which makes the practical use of a roughness factor small. The fracture is commonly treated as two parallel planes with a certain aperture. The parallel plate model uses the so-called cubic law, which is valid for laminar flow between two parallel plates with smooth surfaces. The cubic law expresses the volumetric flow per meter as function of fracture aperture:

$$q_w = K_s \cdot I = \frac{\rho \cdot g}{\mu \cdot l} \cdot \frac{t_f^3}{12} \cdot I \quad (6)$$

The flow velocity of groundwater is dependent on the rock porosity. Primary porosity is the inherent character of a rock which is developed during formation, whereas secondary porosity is developed subsequently due to various geological processes, e.g. fracturing, weathering and solution activity. In unconsolidated rocks, primary porosity is of importance but in hard rocks secondary porosity is of greater significance. Singhal and Gupta (1999) give representative values of porosity as 0-5 % for dense crystalline rock and 5-10 % for fractured crystalline rock. Weathered crystalline rock has a porosity of as much as 20-40 %. Naturally occurring ranges of values of hydraulic and thermal properties of some soils and rocks are listed in Table 3.

Table 3

Typical Values of Hydraulic and Thermal Properties of Soils and Rocks (after Chiasson et al., 2000)

Medium	Hydraulic Properties		Thermal Properties	
	Hydraulic conductivity (K) [m/s]	Porosity (n) [-]	Thermal conductivity (λ) [W/m-K]	Volumetric heat capacity (c_v) [J/m ³ -K]
Gravel (dry)	$3 \cdot 10^{-4}$ - $3 \cdot 10^{-2}$	0.24 – 0.38	0.70 – 0.90	$1.4 \cdot 10^6$
Coarse sand (dry)	$9 \cdot 10^{-7}$ - $6 \cdot 10^{-3}$	0.31 – 0.46	0.70 – 0.90	$1.4 \cdot 10^6$
Fine sand (dry)	$2 \cdot 10^{-7}$ - $2 \cdot 10^{-4}$	0.26 – 0.53	0.70 – 0.90	$1.4 \cdot 10^6$
Silt	10^{-9} - $2 \cdot 10^{-5}$	0.34 – 0.61	1.20 - 2.40	$2.4 \cdot 10^6$ - $3.3 \cdot 10^6$
Clay	10^{-11} - $4.7 \cdot 10^{-9}$	0.34 – 0.60	0.85 - 1.10	$3 \cdot 10^6$ - $3.6 \cdot 10^6$
Limestone	10^{-9} - $6 \cdot 10^{-6}$	0 – 0.20	1.50 - 3.30	$2.13 \cdot 10^6$ - $5.5 \cdot 10^6$
Karst limestone	10^{-6} - 10^{-2}	0.05 – 0.50	2.50 – 4.30	$2.13 \cdot 10^6$ - $5.5 \cdot 10^6$
Sandstone	$3 \cdot 10^{-10}$ - $6 \cdot 10^{-6}$	0.05 – 0.30	2.30 – 6.50	$2.13 \cdot 10^6$ - $5 \cdot 10^6$
Shale	10^{-13} - $2 \cdot 10^{-9}$	0 – 0.10	1.50 - 3.500	$2.38 \cdot 10^6$ - $5.5 \cdot 10^6$
Fractured igneous and metamorphic rock	$8 \cdot 10^{-9}$ - $3 \cdot 10^{-4}$	0 – 0.10	2.50 – 6.60	$2.2 \cdot 10^6$
Unfractured igneous and metamorphic rock	$3 \cdot 10^{-13}$ - $2 \cdot 10^{-10}$	0 – 0.05	2.50 – 6.60	$2.2 \cdot 10^6$

GROUNDWATER FLOW MODELLING

Three models for groundwater flow around a ground heat exchanger in fractured rock are discussed. The first model regards the fractured rock volume as a homogeneous medium equal to a porous medium with a certain (small) porosity. The groundwater flow is evenly spread over the rock volume and water flows through the pore openings between the mineral grains. The second model assumes the rock to be completely impermeable, and all groundwater flows through a fracture zone of a certain width and at a certain distance from the borehole. The fracture zone is modelled as a zone with a homogeneous porosity equal to that of karst limestone. The distance from borehole to fracture zone is varied. The third model regards the ground as completely impermeable, but with one plane vertical fracture (slot) at varying distance from the borehole. All groundwater passes through this fracture, which has no width in the model, and no own mass or heat capacity but that of the flowing groundwater. Heat transfer coefficients at the two fracture walls are used for the heat flow between rock and groundwater. The three models are outlined in Figure 3.

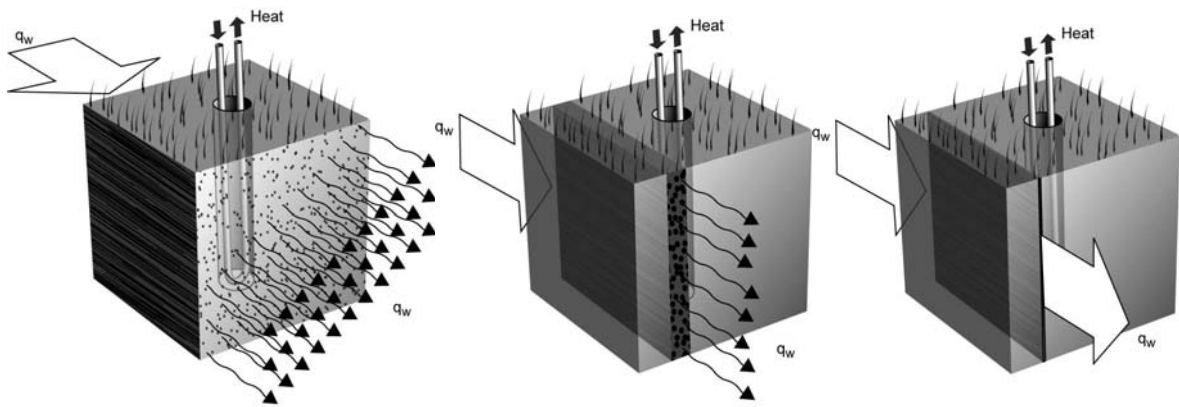


Figure 3. (Left) Model A: Homogeneous flow around a borehole surrounded by a porous medium. (Middle) Model B: Homogeneous groundwater flow in a porous zone near a borehole in an impermeable medium. (Right) Model C: Groundwater flow in a fracture near a borehole in an impermeable medium.

All models are based on the same two-dimensional numerical finite difference representation of the borehole and its surroundings. A water-filled single u-pipe ground heat exchanger is represented by four square grids with a thermal capacity of water and a borehole thermal resistance. An equivalent borehole diameter is calculated. Constant initial temperature is assumed for the surrounding ground.

Equivalent Porous Medium Model

This model illustrates heat transport around a borehole surrounded by a porous medium with a constant homogeneous groundwater flow, hence this is the EPM approach. The temperature in the ground is satisfied by the heat conduction with an added term to account for the convective heat flow due to the specific groundwater flow q_w in the x-direction.

$$\frac{\rho c}{\lambda} \cdot \frac{\partial T}{\partial t} = \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} - \frac{\rho_w c_w q_w}{\lambda} \cdot \frac{\partial T}{\partial x} \quad (7)$$

The darcy velocity, v_{darcy} , is calculated from Darcy's law, and the flow velocity, v_w , is the specific flow that passes through the pores between the grains:

$$v_{darcy} = K_{eq} \cdot I \quad [ms^{-1}]$$

(8)

$$v_w = \frac{v_{darcy}}{n_{eq}} \quad [ms^{-1}] \quad (9)$$

K_{eq} is the equivalent hydraulic conductivity, I is the hydraulic gradient and n_{eq} is the equivalent porosity of the rock volume. The incoming groundwater has the same temperature as the undisturbed ground and flows from left to right, only in the x-direction. No vertical water flow is assumed.

For model A, the heat flow is conductive in the porous medium. Convective transport is calculated for each time step as below

$$T_{i,t} = T_{i-1,t} \cdot \frac{dx}{v_w \cdot dt} + T_{i,t-dt} \cdot \left(1 - \frac{dx}{v_w \cdot dt}\right) \quad (10)$$

Where T is temperature ($^{\circ}C$), dx is the grid size in the x-direction (m), dt is the time step (s), and v_w is the groundwater velocity in ms^{-1} .

Porous Zone Model

Model B computes the heat transport around a borehole surrounded with an impermeable medium and with a nearby porous zone where groundwater flows. Only conductive heat transport occurs in the impermeable medium while both convective and conductive heat flows occur within the porous zone. No vertical heat flow is assumed. The specific groundwater flow is the same as for the above model, but since groundwater flow merely occurs in the porous zone, the thermal velocity in the flow zone will be higher. The porous zone has a porosity n_z .

No thermal resistance between the impermeable medium and the porous zone is assumed, and the in-flowing groundwater has the same temperature as the undisturbed ground. Heat capacity in the porous zone is that of water. The width of the porous zone is one grid width, and the velocity is

$$v_z = \frac{v_{\text{darcy}} \cdot 1 \cdot 1}{b_z \cdot 1 \cdot n_z} = \frac{v_{\text{darcy}}}{b_z \cdot n_z} \quad [\text{ms}^{-1}] \quad (11)$$

where v_{darcy} is the darcy velocity, b_z is the width of the porous zone (m), and n_z is the equivalent porosity of the porous zone. The convective transport is calculated as in model A, but for the porous zone only.

Single Fracture Model

The discrete model for heat transport around a borehole with one single fracture at various distances from the borehole, assumes the fracture as having negligible width. The fracture is located between two grid cells and stretches in the x-direction with water flowing from left to right. The specific groundwater flow is the same as before, however the surrounding ground medium is impermeable and the groundwater flow occurs within the fracture, thus the thermal velocity will be even greater.

The temperature in the ground by conduction is satisfied by

$$\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} = \frac{\rho c}{\lambda} \cdot \frac{\partial T}{\partial t} \quad (12)$$

We will calculate the steady-state temperature distribution in the fracture when the fluid is exposed to a constant temperature T_1 on one side of the fracture and a constant temperature T_2 on the other side. The heat transfer between the fluid and the surrounding temperatures takes place via a heat transfer coefficient α_1 (to T_1) and α_2 (to T_2). The heat transfer coefficients have the unit ($\text{Wm}^{-2}\text{K}^{-1}$). The temperature in the flow direction is denoted $T(x)$. The steady state heat balance for the fluid becomes:

$$-c_w \cdot v_f \cdot \frac{\partial T}{\partial x} = \alpha_1 \cdot (T - T_1) + \alpha_2 \cdot (T - T_2) \quad (13)$$

The solution becomes:

$$T(x) = \frac{a}{b} \cdot (1 - e^{-bx}) + T_{\text{in}} \cdot e^{-bx} \quad (14)$$

where the fraction a/b can be interpreted as the equilibrium temperature in the fracture in absence of water flow (or the limiting value):

$$\frac{a}{b} = \frac{\alpha_1 T_1 + \alpha_2 T_2}{\alpha_1 + \alpha_2} = T_\infty \quad (15)$$

The solution then takes the following simple form:

$$T(x) = T_\infty + (T_{in} - T_\infty) \cdot e^{-bx} \quad b = \frac{\alpha_1 + \alpha_2}{c_w \cdot v_f} \quad (16)$$

In-flowing groundwater from the left has the same temperature as the undisturbed ground and the temperature of the fracture is calculated in the x-direction. Flow velocity in the fracture is calculated from:

$$v_f = \frac{v_{darcy} \cdot 1 \cdot 1}{t_f \cdot 1} = \frac{v_{darcy}}{t_f} \quad (17)$$

where v_f is flow velocity in the fracture (ms^{-1}), v_{darcy} is the darcy velocity (ms^{-1}) and is the same as for all models, B is the width of the rock matrix (m) and t_f is the fracture aperture (m), calculated from Equation 5.

Model Input

In all cases of modelling, the same ground volume is used, and the same specific groundwater flow rate, hence also the same equivalent hydraulic conductivity for the complete rock volume. When modelling the ground as a continuum, the equivalent ground porosity of $n_{eq} = 0.05$ is chosen to represent the rock mass. For the case of a porous zone in an impermeable rock volume, the equivalent porosity of $n_z = 0.25$ is used, as to regard the porous zone as a fracture zone, similar to karst limestone. Table 4 lists the data for the borehole and

TABLE 4
Data for the borehole models

Borehole depth	H	100 m
Borehole diameter ¹	$D = 2r_b$	0.1128 m
Hydraulic gradient	I	0.01 m/m
Density of water	ρ_w	1000 kg/m ³
Volumetric heat capacity of water	c_w	4180000 J/m ³ -K
Dynamic viscosity of water	μ	10 ⁻³ kg/s-m ²
Undisturbed ground temperature	T_{ug}	8°C
Ground thermal conductivity	λ_g	3.5 W/m-K
Ground volumetric heat capacity	c_g	2200000 J/m ³ -K
Borehole thermal resistance	R_b	0.07 K/(W/m)
Injected heat	$p = P/H$	40 W/m
Total simulation time	t_{tot}	100 h
Grid size	$dx = dy$	0.05 m

¹ Equivalent diameter for a borehole modelled by four quadratic grids with the side 0.05 m. $D = 2\sqrt{\frac{dx \cdot dy}{\pi}}$

surrounding ground, used for all modelling cases.

Values of the effective hydraulic conductivity are in the range 10^{-4} – 10^{-9} ms^{-1} . A comparison of groundwater velocity for the case of a continuum, a porous zone and a fracture for the chosen range of hydraulic conductivity is shown in Table 5. The corresponding fracture width is calculated with Equation 5.

TABLE 5
Flow velocity and fracture aperture as a function of effective hydraulic conductivity

K_{eff} [$\text{m}^3/\text{s}, \text{m}^2$]	q_w [$\text{m}^3/\text{s}, \text{m}^2$]	Continuum	Porous zone	Fracture	
		v_w [m/year]	v_z [m/year]	v_f [m/year]	t_f [mm]
10^{-9}	10^{-11}	0.0063	0.075	61	0.015
10^{-8}	10^{-10}	0.063	0.75	285	0.03
10^{-7}	10^{-9}	0.63	7.5	1300	0.07
10^{-6}	10^{-8}	6.3	75	6100	0.15
10^{-5}	10^{-7}	63	750	28500	0.33
10^{-4}	10^{-6}	630	7500	130000	0.72

RESULTS AND DISCUSSION

In Figure 4 the temperature fields around the borehole after 100 hours are calculated with the three flow models and the case of a specific flow rate of 10^{-6} ms^{-1} . These models are compared with the case of only conductive heat transfer. The bilaterally symmetric temperature pattern around the borehole affected only by conduction is transformed into a considerably cooler borehole with a laterally symmetric temperature field for the case of a continuum with a specific flow rate. The heat transport transverse the flow direction is very small whereas the heat is transported in a narrow streak downstream.

The porous zone causes a highly unsymmetrical temperature field where little heat is transferred to the opposite side of the flow zone, and a considerable amount of heat follows the flow in the porous zone. The effect of the convective heat transport is not as effective as the continuum, but yet causes a significantly lower borehole temperature than for the pure conductive case.

Although narrow and at a distance of 0.05 m from the borehole wall, the high flow velocity in the fracture causes a legible distortion of the temperature field around the borehole. The temperature field is no longer centred round the borehole and hardly any heat is transferred past the fracture. The borehole temperature is lower than for the case of a porous zone at the same distance, but not as low as for the case of a continuum.

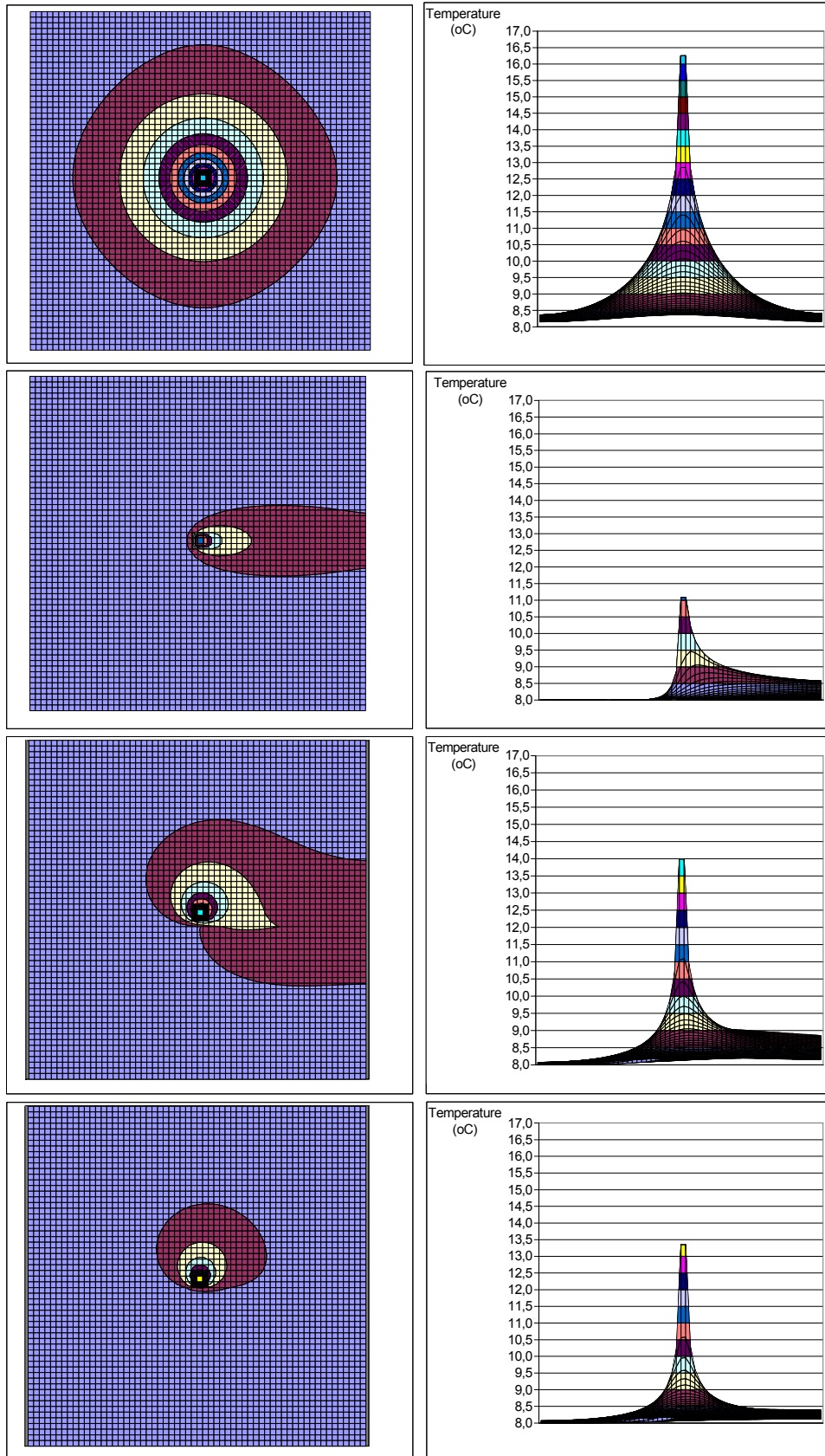


Figure 4: Temperature field around the borehole after 100 hours and $K_{eff} = 10^{-4} \text{ ms}^{-1}$. (From top to bottom) A) Only conduction, B) Continuum, C) Porous zone at 0.05 m distance from borehole wall, D) Fracture at 0.05 m distance from borehole wall

The specific flow rate for which the temperature fields are plotted is high, however the temperature field patterns are the same although on a smaller scale for lower flow rates.

Figure 5 depicts the temperature development over time for the three models at specific flow rates of 10^{-6} ms^{-1} and 10^{-7} ms^{-1} compared to the case with pure conduction. The borehole temperature development is strongly inhibited for all three flow models at the higher specific flow rate. There is a distinct bend in the initial temperature development after which the further development becomes more or less horizontal. The convective effect is considerably smaller for a specific flow rate of 10^{-7} ms^{-1} , and the initial bend on the curve does not occur to the same extent at this flow rate, except for the fracture flow case. It is noteworthy that the effectiveness among the three flow models alters when the flow rate changes. For the higher flow rate, the continuum is outstandingly most effective, followed by the fracture flow and the porous zone. However, as the flow rate becomes a ten-fold lower, the fracture is now the more effective flow case, followed by the continuum and the porous zone.

The break point for the fracture flow becoming more effective than the continuum, appears at a flow rate of about $5 \cdot 10^{-7} \text{ ms}^{-1}$, as can be seen in Figure 6.

The ratio between the effective thermal conductivity and the actual thermal conductivity (i.e. a kind of Nusselt number) versus specific flow rate is plotted in Figure 6. The three models show little or no effect at flow rates less than 10^{-8} ms^{-1} , however the fracture flow starts to cause additional heat transport already at a flow rate of $2.5 \cdot 10^{-8} \text{ ms}^{-1}$ and is the most effective flow model up to flow rates of about $5 \cdot 10^{-7} \text{ ms}^{-1}$. After that, the continuum model becomes decidedly more effective. At specific flow rate $2.5 \cdot 10^{-8} \text{ ms}^{-1}$, the fracture flow model causes a heat transport corresponding to an effective thermal conductivity that is 6% higher than the purely conductive case. This may seem a small effect, but for a rock with a thermal conductivity of $3.5 \text{ Wm}^{-1}\text{K}^{-1}$, this would correspond to an effective thermal conductivity of $3.7 \text{ Wm}^{-1}\text{K}^{-1}$.

The continuum and the porous zone model follow each other up to flow rates of 10^{-7} ms^{-1} , after which the continuum model overtakes the porous zone model. The continuum model shows a more exponential behaviour, whereas the porous zone and the fracture flow models are less steep and have a similar behaviour. At higher flow rates than $2.5 \cdot 10^{-7} \text{ ms}^{-1}$ the fracture flow effectiveness is however a factor 2.5 larger than that for the porous zone model.

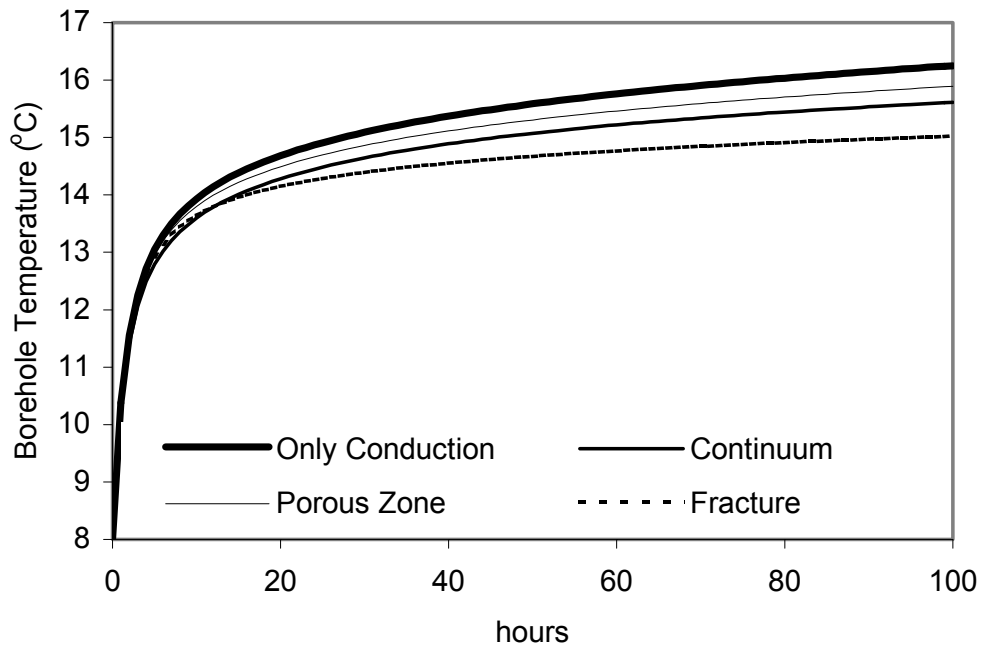
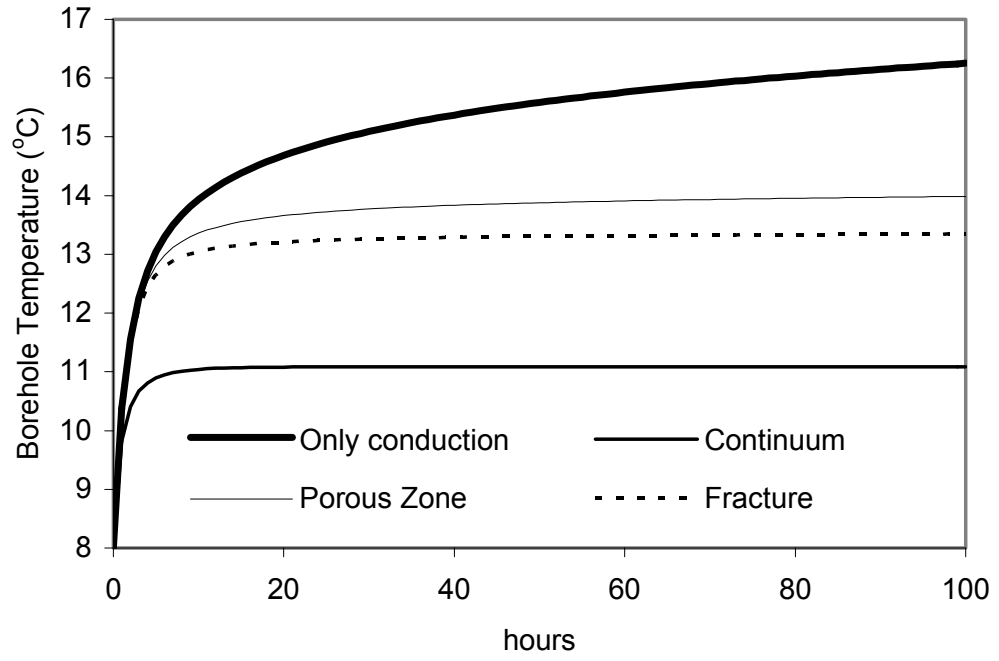


Figure 5. Temperature response in borehole for a continuum, a porous zone and a fracture, compared to the case of no convection, for the case of specific flow rates of 10^{-6} ms^{-1} (upper) and 10^{-7} ms^{-1} (lower).

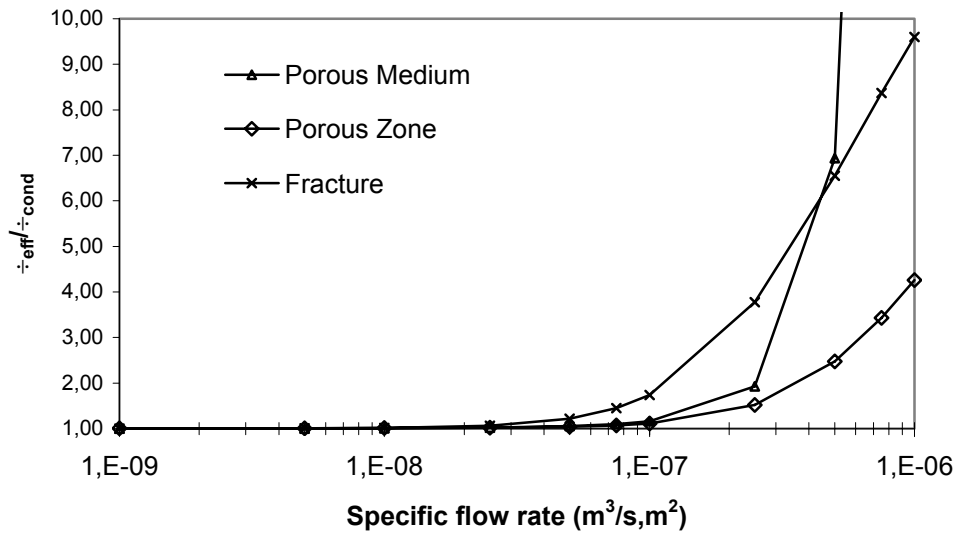


Figure 6. The ratio between effective thermal conductivity and real thermal conductivity plotted versus specific flow rate for the case of a continuum, a porous zone at the distance 0.05 m from the borehole wall, and a fracture at the distance 0.05 m from the borehole wall.

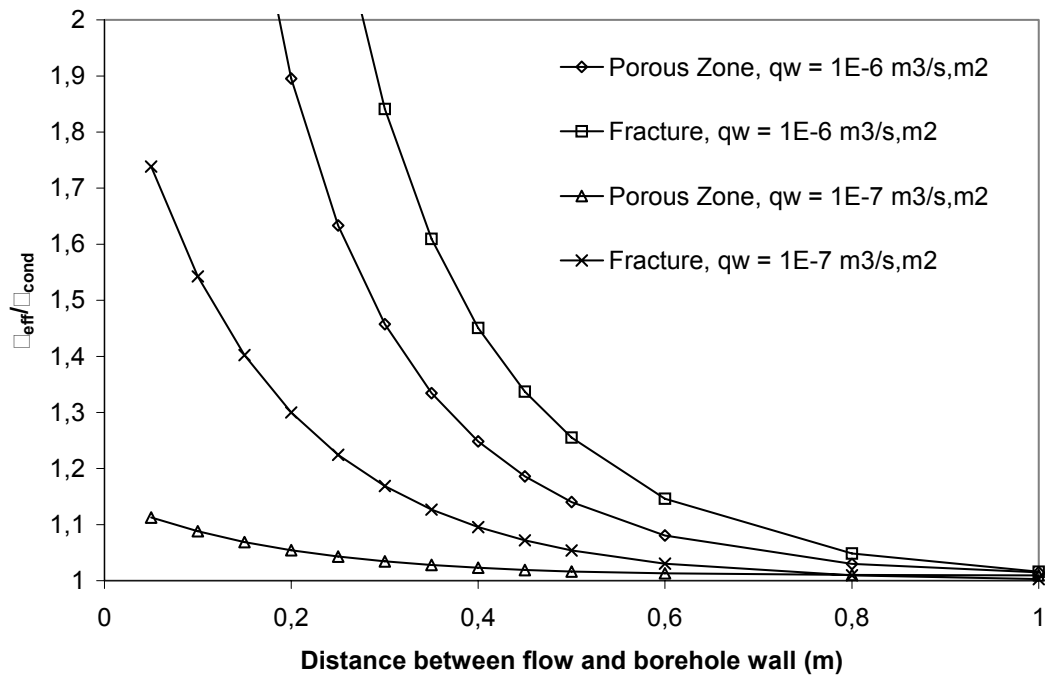


Figure 7. The ratio between effective thermal conductivity and real thermal conductivity plotted versus distance between borehole wall and the flow channel.

Figure 7 shows the effect of the distance between fracture or porous zone and the borehole. As expected, the effect of the flow in the fracture or porous zone decreases with the distance from the borehole. The porous zone causes a 10% higher effective thermal conductivity still at a distance of 0.1 m for a flow rate of 10^{-7} ms^{-1} and at 0.6 m for 10^{-6} ms^{-1} flow rate. The corresponding distances for the fracture are 0.4 m and 0.75 m respectively.

The findings from the model simulations may be applied on two real cases from thermal response tests performed in Norway (Skarphagen, 2001). One test result from groundwater rich shale in a steep hill gave an effective thermal conductivity of $10 \text{ Wm}^{-1}\text{K}^{-1}$, and a similar test at another location gave an effective thermal conductivity of $25 \text{ Wm}^{-1}\text{K}^{-1}$. A typical thermal conductivity values for shale is $2.5 \text{ Wm}^{-1}\text{K}^{-1}$. Figure 6 then implies required specific flow rates of $2.5 \cdot 10^{-7} \text{ ms}^{-1}$ and 10^{-6} ms^{-1} respectively, in a fracture at 0.05 m distance from the borehole. A hydraulic gradient of 0.01 would mean equivalent hydraulic conductivities of $2.5 \cdot 10^{-5} \text{ ms}^{-1}$ and 10^{-4} ms^{-1} for the two cases. In these steep places the gradient may very well be larger than 0.01.

The case of the fracture cutting directly through the borehole has not been simulated. This situation causes complicated flow patterns and convective transport when the groundwater in the fracture enters the borehole and is retarded by the larger water volume in the borehole. The case of fractures cutting through the borehole in various ways is a topic that raises several interesting questions, and should be investigated. In this paper the fracture or porous zone has been modelled as vertical and long, but in nature fractures are more likely to cut diagonally or sometimes horizontally through the borehole.

In the case of a fracture cutting through the borehole at some depth, it is likely that the fracture corresponds with undisturbed groundwater at some distance from the borehole. Since water expands at heating, the water table in the borehole will be higher than in its surroundings during a thermal response test. The water table in the borehole will be decanted at the borehole top, and therefore keep the same level as the surroundings. Colder (more dense) groundwater may then flow into the borehole and cause a vertical groundwater flow along the borehole, induced by the temperature difference between heated borehole and the undisturbed groundwater. This thermosiphon effect may cause considerable heat transport from a borehole, and should be investigated further. This effect is not likely to be significant for grouted boreholes.

The phenomenon of heat losses due to convective transport in rock fractures was analysed in 1994 by Claesson et al., for the case of a rock cavern heat store in Lyckeby. The heat store

had heat losses that were 50% higher than expected, which was explained by thermally driven convection around the cavern.

Natural fractures are not easy to map or picture, though we may be rather sure that they rarely appear so planar, smooth and regular as manmade models assume. The interest in developing more advanced discrete fracture models for the modelling of heat transport effects on borehole ground heat exchangers is limited. Developing models for using drilling data on groundwater flow and fracture zones to estimate the potential groundwater influence on the ground heat exchanger would be of more practical use. Statistical fracture frequency such as in Table 2 may also bring some light to what may be expected.

The long-term influence of groundwater effects is another topic that needs further studies. The course of a thermal response test is to be considered a short term operation, but the estimation of effective thermal conductivity from such a test may not necessarily be valid for the long-term operation of the ground heat exchanger. Hydraulic gradients may vary over seasons, which must be considered. The temperature gradient between the borehole and the fracture flow will decrease with time as the ground is gradually heated. This effect also requires more studies.

In the case of cold injection in the borehole (i.e. heat extraction) the heat transport behaviour will be reversed, as long as the cooling not causes freezing of the flow path.

CONCLUSIONS

In this paper three different models for estimating the heat transfer effect of groundwater flow have been compared and related to the case of no groundwater flow. The simulations and comparisons result in the following findings:

- The three flow models cause significantly different temperature field patterns around the borehole and all three cause lower borehole temperatures
- A continuum approach gives no effect at specific flow rates below $5 \cdot 10^{-8} \text{ ms}^{-1}$ and small effect of the same magnitude as for the porous zone approach up to flow rates of 10^{-7} ms^{-1} . At specific flow rates larger than $5 \cdot 10^{-7} \text{ ms}^{-1}$, the continuum approach gives very large effects on the effective thermal conductivity.
- The fracture flow model results in higher effective thermal conductivity than the continuum and porous zone models in the interval $2.5 \cdot 10^{-8} \text{ ms}^{-1}$ to $5 \cdot 10^{-7} \text{ ms}^{-1}$. This illustrates the efficiency of the high flow velocity in the fracture and the large temperature gradient between the borehole and the fracture flow.

- The effect of the flow in the fracture or porous zone decreases with the distance from the borehole, but even at distances of half a meter or more the porous zone or fracture may result in significantly enhanced heat transfer.
- Even a relatively narrow fracture close to a borehole may result in higher effective thermal conductivity, although estimations made with a continuum approach may indicate otherwise.

The authors request further studies of the possibility to develop models for estimating and investigating the influence of groundwater from drilling data and hydraulic testing. Modelling of the thermal effect of groundwater flow in non-vertical fractures and fractures corresponding through the borehole would be useful to investigate a possible thermosiphon effect due to the expansion of heated borehole water. The long term effects of fracture flow near a ground heat exchanger, and the influence off varying groundwater flow over the year should be investigated.

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PAPER VI

Influence on Thermal Response Test by Thermosiphon Effect

Submitted to Renewable Energy, 2002

INFLUENCE ON THERMAL RESPONSE TEST BY THERMOSIPHON EFFECT

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ABSTRACT

The issue of natural and forced groundwater movements, and its effect on the performance of ground heat exchangers is of great importance for the design and sizing of borehole thermal energy systems (BTES). In Scandinavia groundwater filled boreholes in hard rock are commonly used. In such boreholes one or more intersecting fractures provide a path for groundwater flow between the borehole and the surrounding rock. An enhanced heat transport then occurs due to the induced convective water flow, driven by the volumetric expansion of heated water. Warm groundwater leaves through fractures in the upper part of the borehole while groundwater of ambient temperature enters the borehole through fractures at larger depths. This temperature driven flow is referred to as thermosiphon, and may cause considerable increase in the heat transport from groundwater filled boreholes. The thermosiphon effect is connected to thermal response tests, where the effective ground thermal conductivity is enhanced by this convective transport. Strong thermosiphon effects have frequently been observed in field measurements. The character of this effect is similar to that of artesian flow through boreholes.

INTRODUCTION

Effects of groundwater movements and natural convection in and around borehole heat exchangers for Borehole Thermal Energy Storage (BTES) are of importance when designing such systems. In North America the borehole heat exchangers are mostly filled with grout, to seal the borehole and prevent contamination from the ground surface, or sand to enhance thermal contact. In Scandinavia borehole heat exchangers are commonly groundwater filled. Groundwater filled boreholes and to some extent also sand filled boreholes allow for a vertical groundwater flow through the borehole.

Groundwater flow may occur as regional flow of groundwater due to a natural groundwater gradient, or induced by pumping in the nearby region. This causes a horizontal flow past the borehole. Normal natural groundwater gradients are on the order of 0.01 m/m or less and the corresponding flow velocity is normally in the order of tens of meters per year or considerably less.

Drilling through zones that are not in hydrostatic equilibrium may cause artesian groundwater flow through boreholes. This vertical groundwater flow may take place also through sand filled boreholes and may damage the backfill (Sanner et al. 2000).

There is also the possibility of a thermally induced groundwater flow due to the volumetric expansion of heated water. In relatively porous media convection cells may form.

Regional groundwater flow is commonly analysed by assuming homogeneous groundwater flow through an approximated porous borehole surrounding. This approach has been discussed in several papers over the years. Eskilson (1987), Claesson and Hellström (2000), Chiasson et al. (2000), Witte (2001), all relate to horizontal groundwater flow through a homogeneous porous medium. Gehlin and Hellström (2002) showed that groundwater flow in a single fracture in hard rock may have a large influence on the heat transport around the borehole heat exchanger.

The aim of this paper is a qualitative study of the influence of a temperature induced fracture flow during a thermal response test. An idealised situation is treated; one fracture providing the borehole with groundwater at ambient ground temperature while heated borehole water leaves at the upper part of the hole. This flow is a result of induced natural groundwater convection along the entire borehole length. The phenomenon was analysed in 1994 by Claesson et al., for the case of a rock cavern heat store in Lyckeby, Sweden, where the heat losses were 50% higher than expected. The losses were explained by unintended convection around the cavern. In this paper, the same theory is applied on a groundwater filled borehole heat exchanger in crystalline rock.

A small laboratory study was carried out where the siphon effect in two corresponding vertical cylinders was measured as a water flow rate related to injected heat. A simulation model for thermosiphon effect in a borehole heat exchanger during a thermal response test is presented. The model may explain field experiment data from thermal response tests (Gehlin and Spitler, 2002) where discrepancies from expected ground thermal conductivity values were obtained. Such observations have been made at locations in Norway (Helgesen et al., 2001) and in Germany (Mands et al., 2001). Thermosiphon effects may also offer an explanation to observed differences in thermal response between heat injection and extraction.

LABORATORY STUDY

A small-scale laboratory model of a thermosiphon was constructed at Luleå University of Technology in 1998. The model consisted of two 500 mm high and 70 mm diameter transparent plastic cylinders interconnected with a short 7 mm diameter plastic pipe at the bottom of the cylinders (Figure 1). The upper parts of the two cylinders were brimmed at the same level. One cylinder simulated the borehole and was heated with an immersion heater with variable power level. The outflow from the “borehole” cylinder was weighed on an electronic balance. The other cylinder, simulating the undisturbed groundwater table, was kept at constant temperature and water level throughout the measurements.

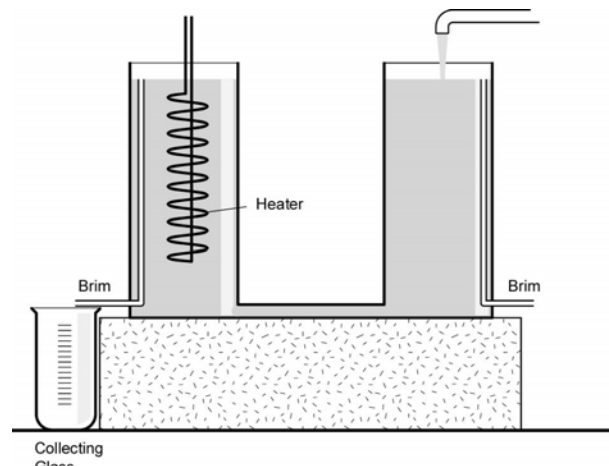


Figure 1. Laboratory model of thermosiphon

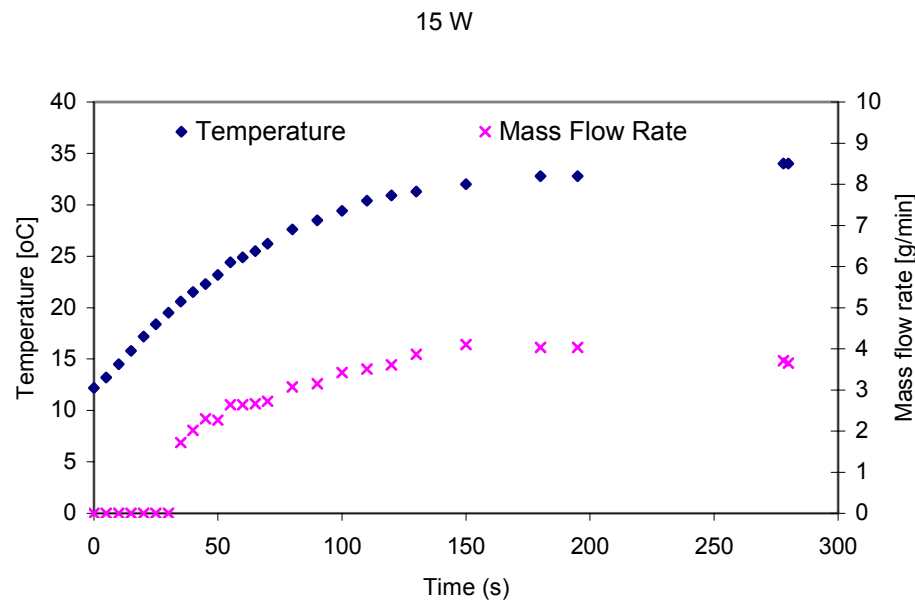


Figure 2. Measured water temperature and flow rate versus time.

Five power injection levels were used for the measurements; 15 W, 95 W, 190 W, 280 W and 300 W. The outflowing mass of water and its temperature were recorded with short time intervals until temperature and flow rate stabilised. Figure 2 shows temperature and mass flow rate over time for the measurement at 15 W heat input, which stabilised at 34°C and 3.6 g/min. In Figure 3, the steady-state mass flow rate is plotted versus heat injection. The mass flow rate shows a near linear relation to injected power rate.

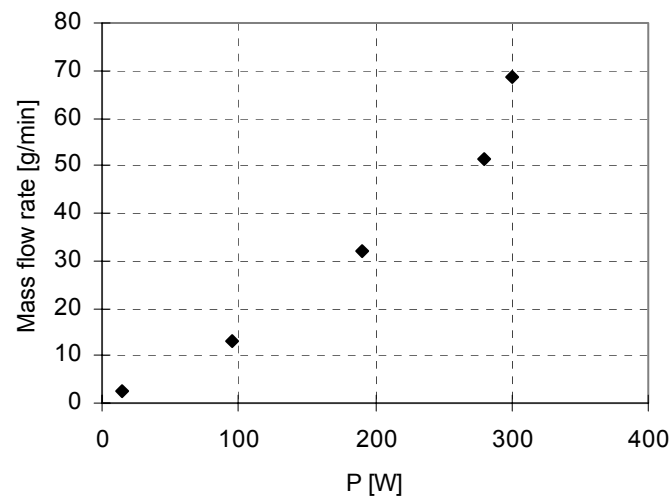


Figure 3. Measured flow rate versus injected heat load

The experiment was conducted in a small size set-up, which means that effects of surface tension, evaporation, volume of heater, no total mixing, friction, and heat losses to surroundings are likely to have some effect on the results. The laboratory experiment is therefore rather of a qualitative than a quantitative value, that demonstrates the thermosiphon effect but not the magnitude. Encouraged by the indications from the laboratory experiment, a numerical simulation model for thermosiphon effect in a full-scale ground heat exchanger borehole in hard rock was developed in order to quantify its influence on the ground heat exchanger efficiency.

SIPHON MODEL SIMULATION

A two-dimensional axi-symmetrical heat conduction model was developed to simulate the thermosiphon effect in a borehole heat exchanger. The borehole heat exchanger is assumed to have properties similar to a single U-pipe. The model takes into account conductive heat flow in the surrounding ground and convective flow in the borehole water. The effect of axial heat conduction is found to be negligible. Figure 4 shows the principle of the thermosiphon for a groundwater filled borehole in hard fractured rock.

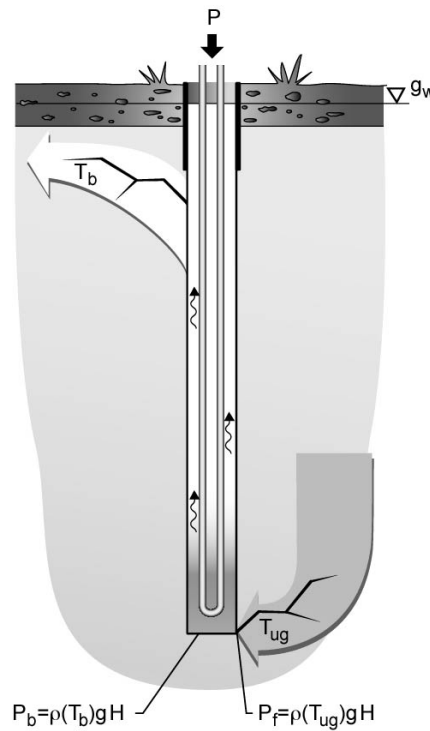


Figure 4. The principle of a thermosiphon induced by the pressure difference between heated water in a groundwater filled borehole and groundwater at undisturbed temperature. The heated and less dense water at the temperature T_b is leaving the borehole at the top while groundwater at the temperature T_{ug} is entering the hole at the bottom.

Model description

The simulation model is an explicit two-dimensional finite difference (FDM) numerical model. The numerical grid consists of 15 cells with expanding size in the radial direction from the center of the borehole and constant grid size in the vertical direction. The first cell represents the borehole. The remaining cells represent the surrounding ground. The outer radius of the physical domain is 4 m, which is outside the zone of thermal influence during the duration of a thermal response test (100 hours).

The borehole heat exchanger is a single U-pipe with a borehole thermal resistance, R_b between the heat carrier fluid and the borehole wall. Half of this resistance is assumed to be between the borehole water and the borehole wall. The heat conductance U_b between the heat carrier fluid and the borehole wall is

$$U_b = \frac{1}{R_b} \cdot \Delta z \quad (1)$$

where Δz is the grid spacing in the axial direction.

The radial heat conductance between two adjacent cells in the ground, U_{ground} , is

$$U_{ground} = \frac{2\pi\lambda_{ground}}{\ln \frac{r_m}{r_m - \Delta r}} \cdot \Delta z \quad (2)$$

where ground thermal conductivity is denoted λ_{ground} and r_m and Δr are radial distance to grid centre and radial distance between grid centres respectively.

The specific heat flow is calculated from the heat conductance and the temperature difference between two points at different radial distance from the borehole centre. The change in temperature over time depends on the change in specific heat flow over time, and the specific heat capacity.

Undisturbed ground temperature, T_{ug} , is allowed to increase with depth, z , due to a thermal gradient, dT/dz . Undisturbed temperature at ground surface is T_0 :

$$T_{ug}(z) = T_0 + \frac{dT}{dz} \cdot z \quad (3)$$

The siphon effect is driven by the pressure difference between the borehole water and the undisturbed groundwater table, caused by the density decrease of heated water. The maximum available pressure difference Δp is given by:

$$\Delta p = p_0 - p_b \quad (4)$$

$$\text{where } p_0 = g \cdot \int_0^z \rho(T(z, t = 0)) dz \quad (5)$$

$$\text{and } p_b = g \cdot \int_0^z \rho(T_b(z, t)) dz \quad (6)$$

Hydraulic pressure in undisturbed ground is denoted p_0 , g is the gravitational constant and $\rho(T)$ is the temperature dependent density of water. $T_b(z, t)$ is the transient borehole water temperature varying with depth. Head loss due to friction in the borehole is calculated as:

$$dp = \xi \cdot \frac{\rho(\overline{T_b}) \cdot H \cdot v_f^2}{2 \cdot D_h} \quad (7)$$

where ξ is the hydraulic friction factor, H is the total borehole depth and v_f is the flow velocity of water. The hydraulic diameter, D_h , calculated from borehole radius r_b and pipe radius r_{pipe} is:

$$D_h = 2r_b - 2\sqrt{2} \cdot r_{pipe} \quad (8)$$

For laminar flow, the friction factor becomes:

$$\xi = \frac{64}{Re} \quad (9)$$

Reynolds number is:

$$Re = \frac{v_f \cdot \rho(\overline{T_b}) \cdot D_h}{\mu(\overline{T_b})} \quad (10)$$

Flow velocity (Hagen-Poiseuille) for laminar flow is expressed as:

$$v_f = \frac{dp \cdot D_h^2}{32 \cdot \mu(\overline{T_b}) \cdot H} \quad (11)$$

The temperature dependent dynamic viscosity is denoted μ . Friction factor in the borehole in the transitional and fully developed turbulent flow is calculated according to Colebrook & White (VDI, 1988):

$$\frac{1}{\sqrt{\xi}} = -2 \cdot \log \left(\frac{2.51}{Re \cdot \sqrt{\xi}} + \frac{\left(\frac{k_s}{D_h} \right)}{3.71} \right) \quad (12)$$

The term k_s is the roughness factor of the borehole wall surface.

Volumetric flow q_w through the borehole is determined from the flow velocity and the hydraulic area, A_h :

$$q_w = v_f \cdot A_h \quad \text{where} \quad A_h = \pi \cdot (r_b^2 - 2 \cdot r_{\text{pipe}}^2) \quad (13)$$

Temperature dependency of water density and dynamic viscosity is accounted for according to Franks (1972).

Convective heat transport $q_{\text{heat_conv}}$ occurs as an axial heat flow

$$q_{\text{heat_conv}} = q_w \cdot \rho \cdot c_w \cdot T_b(z, t) \quad (14)$$

where c_w is the specific heat of water.

Thermal response was calculated for several heat transfer cases.

1. Response with pure conductive heat transport.
2. No flow resistance except that in the borehole, and free availability of groundwater at undisturbed ground temperature.
3. Three different models (A, B and C) adding various restrictions to the inlet and outlet flow of the borehole.

The convective models assume a fracture at the bottom of the borehole, corresponding to undisturbed groundwater table, and fractures allowing heated water to leave at the top of the borehole.

Model A adds an inlet flow resistance in the fracture at the bottom of the borehole. The inlet flow resistance is given by a steady-state hydraulic flow resistance between the borehole and an outer radius r_{ug} . The fracture has a hydraulic conductivity K . A hydraulic skin factor ζ , is added at the borehole wall. The pressure difference between undisturbed groundwater conditions and the borehole then becomes:

$$\Delta p = \xi \cdot \frac{\rho(T_b) \cdot H \cdot v_f^2}{2 \cdot D_h} + v_f \cdot A_h \cdot \left[\frac{\ln\left(\frac{r_{ug}}{r_b}\right) + \zeta}{2\pi \cdot \frac{K}{\rho(T_b) \cdot g} \cdot H} \right] \quad (15)$$

Model B is based on model A, but the convective heat transfer from fluid to borehole water is set proportional to the difference between the average fluid temperature T_f and the borehole water temperature T_b varying with depth. The proportionality factor PF is:

$$\left\{ \begin{array}{l} PF = \frac{\overline{P}}{\overline{T_f} - \overline{T_b}} \\ \overline{T_f} - \overline{T_b} = \frac{P}{H} \cdot \frac{R_b}{2} \end{array} \right. \Rightarrow PF = \frac{2}{R_b} \quad (16)$$

The heat transfer then becomes

$$q(z) = PF \cdot (\overline{T_n} - T_b(z)) \quad (17)$$

Model C is based on model A, but adds an outlet flow resistance to the fractures at the borehole top. The outlet flow resistance is the same as the inlet flow, thus the flow resistance contribution from the fractures becomes twice as large.

Model input

As input to the models, a groundwater filled, 0.115 m diameter borehole drilled in hard rock to the depth of 100 m was used. The diameter for the concentric plastic pipe was chosen to 0.040 m. Input data is summarised in Table 1.

TABLE 1
Data for the borehole model

Borehole depth	H	100 m
Borehole diameter	$D = 2r_b$	0.115 m
Pipe diameter	$D_p = 2r_{pipe}$	0.040 m
Ground thermal gradient	dT/dz	0.012 K/m
Undisturbed ground surface temperature	T_0	8°C
Ground thermal conductivity	λ_g	3.5 W/m-K
Ground volumetric heat capacity	c_g	2200000 J/m ³ -K
Groundwater volumetric heat capacity	c_w	4182000 J/m ³ -K
Borehole thermal resistance	R_b	0.10 K/(W/m)
Steady-state radius	R_{ug}	36 m*
Skin factor	ζ	9.2*
Injected heating power rate	$q = P/H$	50 W/m
Total simulation time	t_{tot}	100 h

* Based on pump test by Ericsson (1985)

Hydraulic conductivity, K , was varied in the interval 10^{-6} - $5 \cdot 10^{-5}$ m/s and for model C and the case of $K = 10^{-6}$ m/s heat input rate was varied in steps of 25 W/m, from 25 W/m to 100 W/m.

Simulation results

Simulating thermosiphon effect during a 100 hours thermal response test in a single groundwater filled borehole without flow restrictions resulted in an effective thermal

conductivity of almost 400 W/m,K and a volumetric flow rate near 1.5 l/s through the borehole. Flow conditions in the borehole were turbulent. After 100 hours the Reynolds number was over 3500. Although the assumption of no flow resistance at inlet and outlet is unrealistic, the temperature response had characteristics of a borehole with artesian groundwater conditions, with a near horizontal temperature development, indicating infinite effective thermal conductivity, if evaluated according to standard procedure assuming pure conductive heat transfer. The temperature profile along the borehole is linearly decreasing with depth, which is the opposite situation from pure conductive conditions, when the temperature increases linearly with depth (see Figure 7).

Introduction of a fracture flow resistance in model A, B and C considerably reduced the volumetric flow rate and heat transport. In these three models, flow conditions were well in the laminar zone. Table 2 summarises the driving pressure difference between borehole and undisturbed groundwater, volumetric flow rate, Reynolds number the ratio between power rate transported from the borehole by the siphon effect, and the total injected heating power rate at 100 hours simulation.

TABLE 2
Summary of pressure, flow and heat transport conditions for model A, B and C after 100 hours.

Hydraulic conductivity [m/s]	Δp			q_w			Re			$P_{\text{siphon}}/P_{\text{total}}$		
	[Pa]			[l/s]			[-]			[%]		
	A	B	C	A	B	C	A	B	C	A	B	C
$5 \cdot 10^{-5}$	693	761	889	0.314	0.345	0.204	824	915	552	60	56	49
$2.5 \cdot 10^{-5}$	889	970	1111	0.204	0.223	0.129	552	609	359	49	44	36
10^{-5}	1183	1245	1386	0.110	0.115	0.064	309	328	187	31	28	19
$5 \cdot 10^{-6}$	1386	1414	1528	0.064	0.066	0.036	187	191	105	19	17	11
$2.5 \cdot 10^{-6}$	1528	1534	1610	0.036	0.036	0.019	105	106	56	13	10	5
10^{-6}	1627	1626	1663	0.015	0.015	0.008	45	45	23	4	4	2

Thermal response is clearly affected by the thermosiphon effect for all model cases. The temperature response for model C for some different values of hydraulic conductivity is seen in Figure 5. The uppermost response curve is that for pure conductive conditions, and below are the responses for decreasing flow resistance (i.e. increasing hydraulic conductivity) with the case of no flow resistance as the lowest response. The effective thermal conductivity is evaluated from the slope of the temperature response for 100 hours and for 50 hours measurement. The latter is the recommended minimum measurement duration for a thermal response test. The ratio of effective thermal conductivity (λ_{eff}) and ground thermal

conductivity (λ_{cond}) for model A, B and C is plotted in Figure 6 as a function of hydraulic conductivity for 100 hours response. The ratio is lowest for model C, which is the most realistic case. However, even for low hydraulic conductivities (i.e. high flow resistance), the thermosiphon effect increases the effective thermal conductivity with several percent. The same graph for 50 hours response has the same character, but the ratios are lower. The difference increases linearly from 2% at $K = 10^{-6}$ m/s to 9% at $K = 5 \cdot 10^{-5}$ m/s.

The thermosiphon effect is proportional to the injected heating power rate, as seen in Figure 8, where the results from model C and the case of a hydraulic conductivity of 10^{-6} m/s are plotted. The effect causes a 4% increased effective thermal conductivity even for a low heat load of 25 W/m, and for each extra 25 W/m, the ratio increases with approximately 0.04 for 100 hours response. As can be seen in Figure 8, the estimates for 50 hours response result in about 0.02 units lower ratios. The thermosiphon effect increases with increasing borehole temperature.

Table 3 shows the driving pressure difference between borehole and undisturbed groundwater, volumetric flow rate, Reynolds number and the ration between power rate transported from the borehole by the siphon effect, and the total injected heating power rate for model C and $K = 10^{-6}$ m/s and at increasing power injection load. The table shows values for 100 hours responses. The proportionality is linear except for the power rate transported from the borehole, which shows slight exponential behaviour.

TABLE 3
Summary of pressure, flow and heat transport conditions for model C at $K = 10^{-6}$ m/s and increasing heating power injection after 100 h.

Injected power rate [W/m]	Δp [Pa]	q_w [l/s]	Re [-]	P_{siphon}/P_{total} [%]
25	842	0.0038	11	0.1
50	1663	0.0077	23	2
75	2463	0.0115	38	3.5
100	3475	0.0163	60	5

Borehole temperature profiles for model A, B and C at decreasing hydraulic conductivity from left to right are shown in Figure 7, along with the profiles for pure conductive conditions and for unlimited thermosiphon flow. The profiles for model C at $K = 10^{-6}$ m/s and increasing injected power rate from left to right are also shown in the figure. The bend at the bottom of the borehole, reaching further up along the borehole as the hydraulic conductivity and the injected heating power rate increase is interesting and suggests a possibility for field detection of the thermosiphon effect.

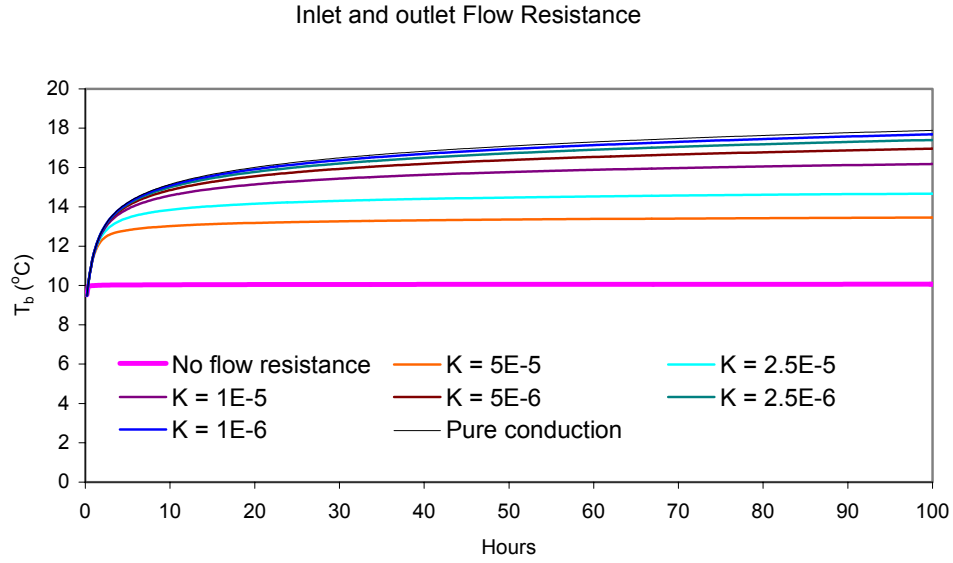


Figure 5. Temperature response for the case of pure conduction (uppermost), decreasing flow resistance at inlet and outlet, and no flow resistance (lowermost).

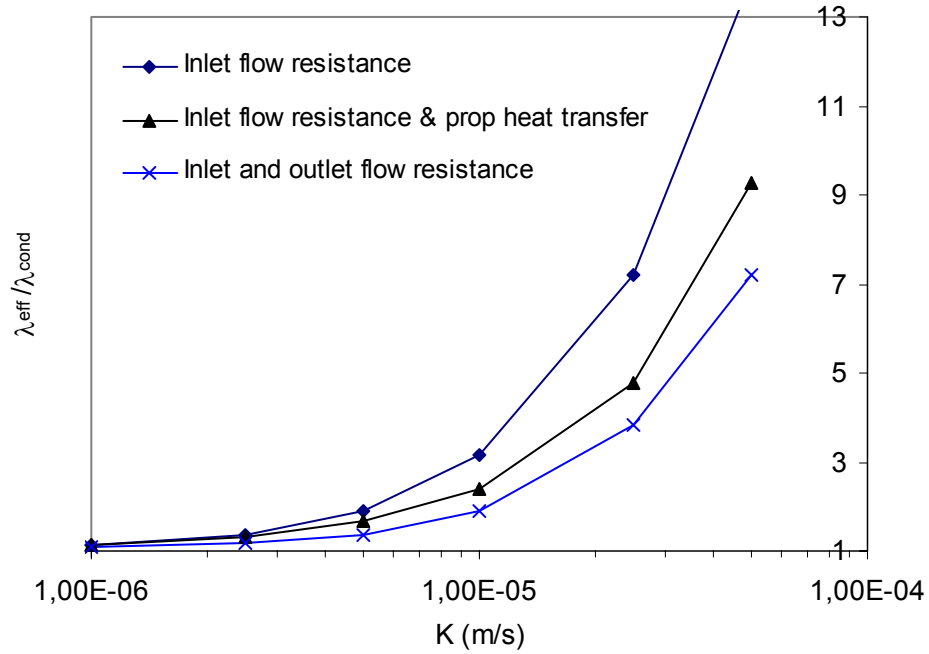


Figure 6. Effective thermal conductivity ratio as a function of flow resistance for model A, B and C, for 100 hours response.

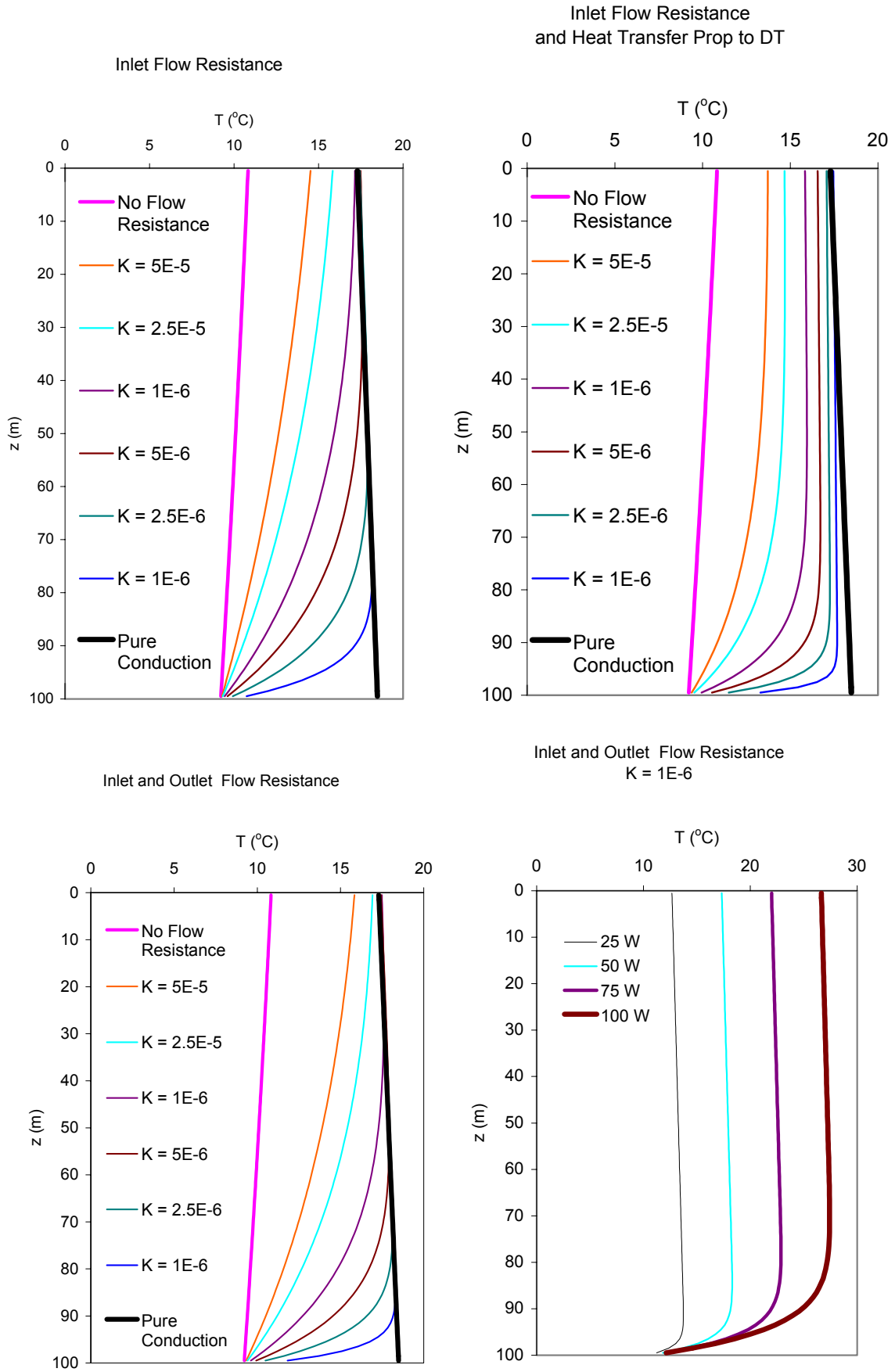


Figure 7. Borehole temperature profiles for model A (upper left), B (upper right) and C (lower left) at various flow resistance. Lower right; Borehole temperature profiles for model C at $K = 10^{-6}$ m/s and various injected power rates. 100 hours response.

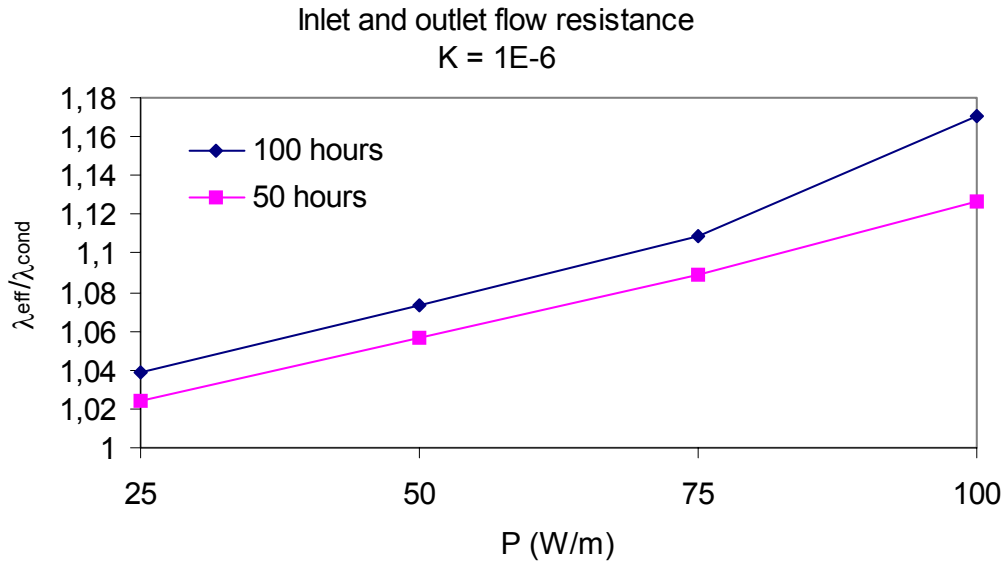


Figure 8. Effective thermal conductivity ratio as a function of injected power rate for model C and hydraulic conductivity $K = 10^{-6}$ m/s.

DISCUSSION

Although results from the simulations with unlimited thermosiphon flow through the borehole are a bit unrealistic, they still show two important things. One is that the thermosiphon phenomenon may have a large impact on the convective heat transport in heated groundwater filled boreholes for the assumed hydraulic conductivities. The other is that the effect is governed by flow resistance in the fractures.

Model A with flow resistance only in the inlet fracture gives a simplified picture but brings down the flow condition to a more realistic level. Outflow from the borehole hardly happens without any resistance; thus model A is likely to over-estimate the thermosiphon effect.

Model B includes a temperature dependent heat transfer rate along the borehole. It is the temperature difference between the fluid in the heat exchanger pipe, and the borehole water that causes this heat transfer. The assumption of an even average fluid temperature in the pipe, along the borehole is a reasonable simplification. During a thermal response test the temperature difference between borehole top and bottom on the order of one degree Kelvin, whereas the borehole water temperature at thermosiphon condition may vary with several degrees.

Model C includes a flow resistance at the outlet fracture at the top of the borehole, assuming its magnitude to be of the same order as the resistance in the inlet fracture at the bottom of the borehole. Common practice is to case the uppermost few meters of the borehole,

sealing the casing into the hard rock with concrete. This is done to prevent collapse of the soil layer above the hard rock and contamination of borehole water by leakage of surface water. Thus borehole water must either pour out of the borehole above the casing, which is unlikely, or escape through fractures in the rock below the casing. Such fractures almost always exist. Water outlet through these fractures takes place with some flow resistance.

It is clear that model A over-estimates the thermosiphon effect in the borehole by neglecting outflow resistance. The approach of model B where the heat transfer rate along the borehole is temperature dependent is interesting. However since the effect of the fracture flow resistance is considerably larger than the effect of flow resistance in the borehole, model C with flow resistance both at inlet and outlet is more realistic (compare the temperature profiles in Figure 7).

In the models used, flow resistance is expressed as a hydraulic conductivity combined with a skin factor. Normal hydraulic conductivity of fractured rock is in the interval 10^{-8} - 10^{-4} m/s (Chiasson et al 2000). In the simulations hydraulic conductivity has been varied between 10^{-6} - $5 \cdot 10^{-5}$ m/s, which is to be considered medium fractured rock. The skin factor was chosen as 9.2, based on a hydraulic pumping test in fractured hard rock in connection with a borehole heat exchanger experiment in Studsvik, Sweden (Ericsson 1985).

Thermosiphon effects may occur for groundwater filled boreholes with injected heat, as during a thermal response test. However it is important to consider that the thermal response test is a relatively short test (i.e. the order of days), usually performed on a single borehole, and with heat injection. The driving pressure difference between borehole water and undisturbed groundwater will not be as large for the case of heat extraction. This is due to the small thermal volume expansion at temperatures around $+4^{\circ}\text{C}$. The effect will not occur for frozen boreholes. If an experiment proceeds for a long time with heat injection, the temperature field around the borehole expands, thus increasing the temperature in the formation outside the outlet fracture. The increased temperature will, according to Equation 15, decrease the viscosity, which also decreases the fracture flow resistance. This would result in increased flow through the fracture. However, if the hydrostatic pressure difference decreases due to decreased temperature gradient, the flow will instead decrease. Multiple boreholes at short distance may cause difficulties for the water to leave the borehole area, thus decreasing the thermosiphon effect. This problem is complex and therefore needs further studies.

In this study we have used the simplest geometry with a borehole intersected by two fractures, one in the bottom and one in the top. Boreholes are likely to be intersected by

several fractures at various levels thus complicating the thermal process and its analysis. Thermosiphon flow occurs also for boreholes drilled in porous ground material such as sedimentary rock. Groundwater flow then takes place as a flow between the pores or in zones with higher permeability. Witte (2001) discusses enhanced effective thermal conductivity determined from thermal response tests in sedimentary ground. A thermal response test was performed with heat extraction instead of injection. The effective thermal conductivity obtained from the heat extraction response test was lower than the result from a response test on the same borehole but with heat injection. The effect was discussed in terms of groundwater flow. Further studies are needed on the behaviour of thermosiphon flow in porous ground.

Gehlin (1998) demonstrated the effect of backfilling to prevent vertical groundwater flow. Thermal response tests were conducted on a groundwater filled borehole that was later backfilled with sand. The effective thermal conductivity decreased from 3.6 W/m,K to 3.45 W/m,K after backfilling. In grouted boreholes thermosiphon effects are prevented by the sealing.

Several observations of enhanced effective thermal conductivity at thermal response tests have been reported and related to groundwater effects. Sanner et al. (2000) and Mands et al. (2001) describe two thermal response tests in boreholes with artesian ground water flow, where the estimated effective thermal conductivity from the temperature response was extremely high. Several Norwegian response tests have measured extreme effective thermal conductivities in water rich shale rich (Helgesen, 2001). These cases report thermal conductivities measuring 300-600% the expected values. It is likely that the hydraulic conductivity of these shales is relatively high, thus providing good conditions for large thermosiphon flow.

The thermosiphon simulation models presented here include several simplifying assumptions. The models do not take into account any heating of the inlet water from the bottom fracture caused by the moving thermal front from the borehole. The models all assume the inlet fracture to be located at the very bottom of the borehole, which is not always the situation. The further up that the inlet fracture connects to the borehole, the smaller the thermosiphon effect due to the smaller driving hydrostatic pressure difference. The roughness, i.e. the flow resistance factor in the borehole, may need some experimental verification. When dealing with fractures in hard rock, there is always an uncertainty factor. Any general model for fracture flow in a borehole must make crude approximations and assumptions about fracture geometry and fracture characteristics.

CONCLUSIONS

This qualitative study of the influence of a temperature induced fracture flow during a thermal response test has treated a situation with one fracture providing the borehole with groundwater of an undisturbed ground temperature while heated borehole water leaves at the upper part of the borehole. This thermosiphon flow enhancing the convective heat transfer from a heated groundwater filled borehole in hard rock may take place if certain fracture conditions exist in the ground heat exchanger. If such fracture conditions exist, a thermal response test would induce a thermosiphon flow due to the temperature difference between the borehole and its surroundings. The enhancement of the effective thermal conductivity of the borehole heat exchanger depends on injected power rate and flow resistance in fractures. The fracture flow resistance may be quantified in terms of hydraulic conductivity.

When designing a ground heat exchanger system where a thermal response test has indicated thermosiphon effects, it is important to relate the result to how the borehole system will be operated. Multiple borehole systems are not likely to be affected by thermosiphon flow to the same extent as a single borehole during a thermal response test. In multiple borehole systems with short distance between the boreholes, the formation between the boreholes will be thermally disturbed, thus decreasing the potential pressure gradient between borehole water and surrounding groundwater table.

Thermosiphon flow is also not occurring in the same way for heat extraction systems due to the lower thermal volumetric expansion at low temperatures, and the prevention of vertical groundwater movements in a frozen borehole.

The effective thermal conductivity evaluated from a thermal response test by standard procedure is sensitive to the duration of the measurement. A shorter measurement interval results in a lower effective thermal conductivity estimation.

Comparing results from thermal response tests conducted on the same borehole with heat injection and heat extraction respectively, or with more than one power level may provide information about the potential for thermosiphon effects in the borehole. It may also differentiate thermosiphon effect from the effect of artesian borehole flow, since the latter would not be affected by changes in power injection. The temperature profile along the borehole may also provide information about this interesting phenomenon.

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