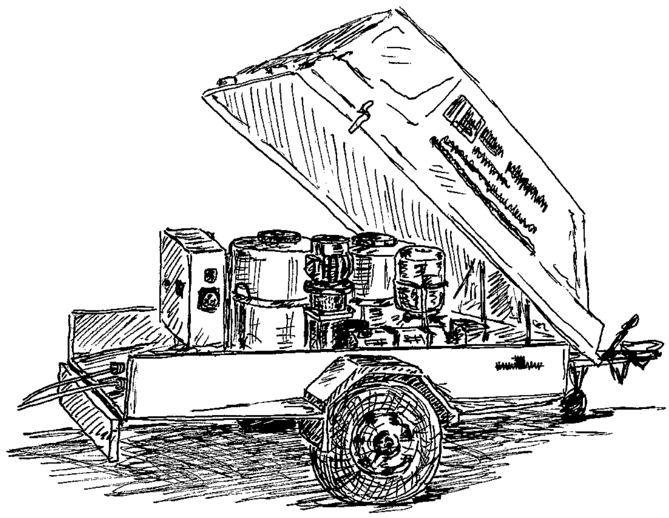
MASTER'S THESIS 1996:198 E

ISSN 0349 – 6023
ISRN: HLU – TH – EX - - 1996/198 – E - - SE

TED

A Mobile Equipment for Thermal Response Test

Testing and Evaluation



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THANKS

This Master Thesis is part of our education of the Civil Engineering program at the division of Water Resources Engineering, department of Environmental Planning and Design, Luleå University of Technology, Sweden. To work with this thesis has been a very stimulating challenge, not the least because of all those wonderful people we have met during the process. Without these people this thesis would never have been done, and therefore we will take the opportunity to show them our gratitude for all that they have done for us.

First of all we would like to give our special salute for professor Bo Nordell, our dear tutor on the subject. He has been the best tutor one could ever wish for, showing great patience with us and catching enthusiasm to our work. We will also give our special thanks to:

- ◊ Martin Edman, IdéArktica, and Thorwald Lundkvist, Anima AB, who helped us by constructing TED.
- ◊ Anders Westerlund and Rolf Engström, LuTH, who helped us with all the practical problems we met.
- ◊ Svante Enlund and Thomas Hallerdt at Telia for giving us the opportunity to use TED at their telephone stations in Stockholm and for all the assistance with the tests.
- ◊ Göran Hellström, LTH, for help with the theoretical parts of the study.
- ◊ Frank Cruickshanks, Environment Canada, for letting us present our thesis at the IEA Conference in Dartmouth/Halifax, June 1996.
- ◊ Jenny Salmonsson for generously offering to read the report for correction.
- ◊ Everyone else who has helped us in any possible way, among them Nyåkers bakery for their cookies that kept us in good temper during our work.

At last, but not least, we must thank TED, our mobile equipment for thermal response test, for cooperating with us when he did. Thanks, all of you!

Catarina Eklöf & Signhild Gehlin
LuTH, June 1996

SUMMARY

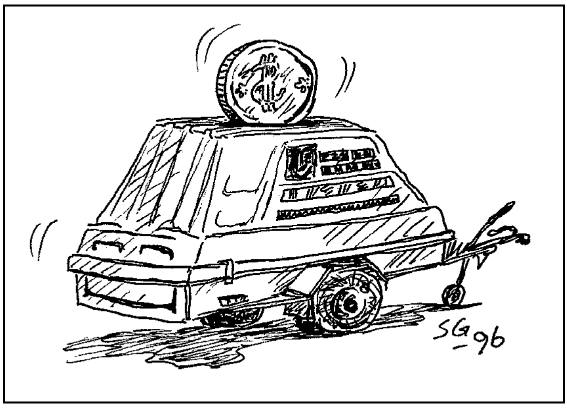
Underground Thermal Energy Storage (UTES) systems have recently been shown an increasing interest. Working groups of national as well as international character have been selected to investigate development potentials for the techniques. An important aspect of the development of UTES is to optimise the systems with regard to the current conditions at each specific location. Today a number of computer simulation programs of good quality for dimensioning of UTES are available, but the use of thermal response test for determining the actual thermal capacity of a UTES in situ, has not yet been granted its legitimate value.

The advantage of a response test is that properties of the installation and local conditions that are difficult to estimate, can be measured, and thus taken into account at the dimensioning process. As the properties of the installation and location quite often have a positive effect on the capacity of the system, money can be saved by determining these properties in an early stage of the construction of the system.

At the request of Division. of Water Resources Engineering, Luleå University of Technology, the company IdéArktica, Övertorneå, Sweden, has constructed a mobile equipment for thermal response test. The equipment, which mainly consists of a pump, a water heater, two temperature sensors for measuring inlet and outlet temperatures and a logger for collecting the temperature data, has in this work been tried with regard to the construction, function and accuracy. It has been tested at two cooling systems for telephone stations in Stockholm, on request from the Swedish Telephone Company, Telia AB.

The results show that the measured power capacity of the two cooling systems correspond, with a good accuracy, to the capacity actually obtained from the systems in use. The results indicate that convection occurs at the locations, which explains why the actual service conditions are better than those suggested by the simulations that were done for the dimensioning of the systems.
Thus the conclusion is that if a response test had been executed at one borehole before the rest of the system was constructed, the number of boreholes required for the system could have been reduced, and the costs for the system would have been less.

As the tests with the mobile response test equipment have given such positive results, development of the test equipment, in order to further improve its reliability and simple construction, is suggested. Today the interest is already large from leading companies in the field to develop the method of using a mobile equipment for thermal response test. The method has also been paid attention to internationally, and the market for response test is now being investigated in a number of countries, among them Germany and Canada.



"TED saves money! Put your money in a Teddybank!"

SAMMANFATTNING

Bergvärmesystem för uppvärmning, kylning och värmelagring har på senare år visats ett ökande intresse. Arbetsgrupper nationellt såväl som internationellt har tillsatts för att undersöka utvecklings-potentialer för tekniken. En viktig del i utvecklingen av bergvärme är att på ett enkelt sätt kunna optimera anläggningarna med avseende på de förhållanden som råder vid respektive anläggningsplats. Redan idag finns ett antal väl fungerande datorbaserade simuleringsprogram för dimensionering av bergvärmesystem. Vad som dock i dagsläget ännu inte kommit att utnyttjas i tillräcklig utsträckning är möjligheten att mer exakt kunna bestämma en anläggnings termiska kapacitet in situ, vilket kan göras med hjälp av ett termiskt responstest. Fördelen med ett sådant test är att egenskaper hos installationen, och lokala förhållanden som i simuleringarna är svåra att uppskatta, kan tas med vid dimensioneringsberäkningarna. Eftersom det är vanligt att egenskaper hos installation och lokal har en positiv effekt på anläggningens termiska kapacitet, kan pengar sparas genom att dessa egenskaper undersökts inför dimensioneringen.

Företaget IdéArktica har på uppdrag av Avdelningen för Vattenteknik, Tekniska Högskolan i Luleå, konstruerat en mobil utrustning för termisk responstest. Utrustningen som i huvudsak består av en pump, en värmare, två temperaturmätare för in- och utloppstemperatur samt en datalogger för insamling av temperatur-data, har genom det här examensarbetet testats med avseende på utformning, funktion och tillförlitlighet.

Utrustningen har testats på borrhål i berg-baserade kylsystem för AXE-växlar, som ägs av Telia AB. De två AXE-stationerna är båda konstruerade i likartad berggrund (granit), den ena i Drevikstrand, söder om Stockholm och den andra i Ängby, norr om Stockholm. Mätningarna visar att den effekt hos de båda kylsystemen som den mobila utrustningen ger, väl överens-stämmer med den effekt som man erhållit under drift. Resultaten indikerar att konvektion förekommer och kan förklara varför de verkliga driftsförhållandena visat sig vara bättre än de som simuleringarna förutsade. Slutsatsen är alltså att om responstest utförts på ett borrhål vid anläggningsplatserna innan hela borrhålssystemen konstruerades, hade anläggningarnas storlek kunnat reduceras och kostnaderna för anläggningarna minskats.

Eftersom försöken med den mobila responstestutrustningen givit så positiva resultat, ges i examensarbetet förslag på hur utrustningen kan vidareutvecklas.

Redan idag finns ett glädjande stort intresse från ledande svenska företag inom närliggande branscher för att utnyttja möjligheterna med termisk responstest. Även internationellt har uppmärksamhet riktats åt metoden, och marknaden för responstest undersöks nu i ett flertal länder världen över, bland annat Kanada och Tyskland.

1. INTRODUCTION

Natural heat systems make it possible to utilise solar energy which is stored passively in air, ground and water. Using a heat pump, this low temperature heat can be extracted for heating purpose.

In 1980 the referendum about nuclear power, which took place in Sweden, resulted in a decision to gradually close all the Swedish nuclear power plants until the year of 2010. As it looks today, this aim will not be fulfilled till then, but still the result of the referendum has increased the interest for development of alternative energy sources and energy saving techniques. Along with raised taxes on fossil fuels and a possible closing of nuclear power plants, energy prices will raise and solar heat and heat storage will see a widened market with an improved economical potential.

There are a great number of Underground Thermal Energy Storage (UTES) systems available today. One way to extract heat from the ground to support a heat pump for domestic heating is to use a deep borehole, preferably in rock with high thermal conductivity. The depth of the borehole may be 40-150 meters. The heat carrier fluid is heated by the rock, while it flows down to the bottom of the borehole in one channel, and back upwards in another channel. The cold borehole extracts heat from the surrounding rock by heat conduction.

When the borehole is used for heating as well as cooling, one may speak of heat storage, i.e. heat is being led through the borehole for cooling and will later be used for heating. There are several different types of UTES storage, but the technique which is said to have the greatest potential for large stores of thermal energy is the so called borehole heat storage. The thermal energy is then stored in the bedrock between the boreholes.

Thermal energy storage in boreholes is now shown an increasing international interest. In Sweden there are about 3000 UTES systems built every year, while USA produces about 40.000 each year. In USA a consortium has been established, Geothermal Heat Pump Consortium (GHPC), with the aim of increasing the number of installations done each year by a factor ten. This would mean that by the year 2001, USA would have 400.000 UTES systems done per year. Also in several other countries, an extensive work is done in this field. (For more information see http://www.ghpc.org/index.html).

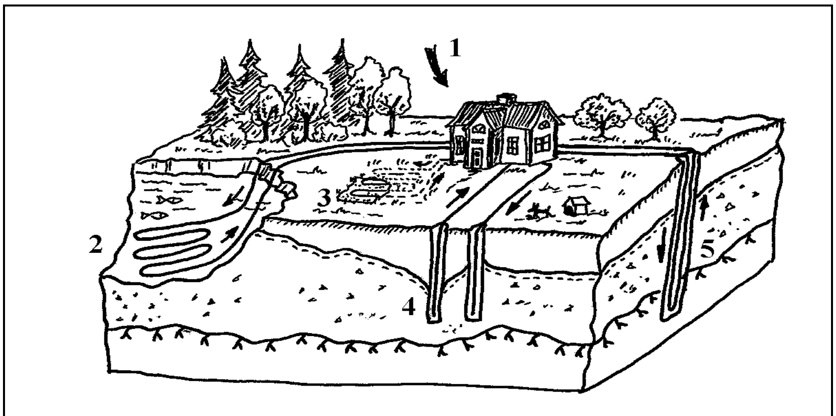


Figure 1.1 This picture shows some common types of natural heat systems: 1. Heat from air, 2. Heat from sea or lake, 3.Heat from ground, 4.Heat from groundwater, 5. Borehole system. (After Nordell, Söderlund 1991)

1.1 BACKGROUND

To make UTES even more economically reasonable it is necessary that the capital cost is not too large. It is therefore of great importance to develop methods for better optimisation of the systems. This can be done by measuring the actual *thermal conductivity* of the bedrock and the *thermal resistance* of the borehole installation before the full scale plant is built. The two parameters mentioned above are both of general interest for the efficiency of the heat store. They can be determined in situ by a *thermal response test*.

During a response test, a heat carrier fluid is circulated through the borehole installation during a few days. While this is done the inlet and outlet temperatures of the heat carrier fluid in the borehole are measured. The test can be done for heat injection as well as for heat extraction, and it is also possible to run the test for one single borehole or for a complete borehole system. An important condition for the test is that the heat injection-/extraction rate is constant and known throughout the test. The thermal conductivity and thermal resistance can then be determined if the mean temperature of the heat carrier fluid is plotted against the logarithmic time.

Thermal response tests have been carried out at several occasions at various borehole heat stores, but as the test requires a pump, temperature measurements, a heater etc., the tests have so far only been performed at full scale plants. There would be a considerable advantage if the response test could be run before the plant is fully installed. With the help of a mobile equipment for thermal response test, this could be done. The thermal conductivity and thermal resistance are then determined in situ for one borehole and the rest of the plant sized thereafter. The economical gains obtained by the use of such a mobile equipment would help to improve the significance of thermal heat systems in rock as an energy saving technique.

1.2 AIM

The aim of this study is to describe, test and further develop a mobile equipment for thermal response test in boreholes.

A preparatory study to this work was done in 1995 as a part of a course in Solar Heat and Heat Storage given by Division of Water Resources Engineering, University of Luleå, Sweden. In that study a mobile equipment for response tests in boreholes was designed [1]. The equipment was later constructed by IdéArktica in Övertorneå, Sweden.

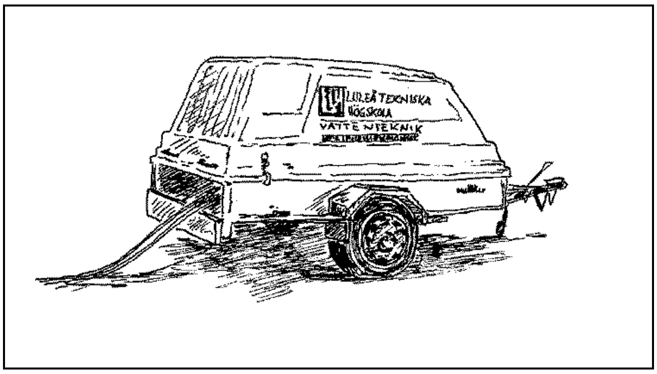


Figure 1.2 TED - the covered trailer contains all that is needed for the measurements.

2. UNDERGROUND THERMAL ENERGY

Underground Thermal Energy Storage systems (UTES) require that suitable rock is available, which is the situation in most parts of Sweden [2]. For low power requirements it may be sufficient with one single borehole, but more often the stores are constructed for large energy requirements, and therefore the boreholes are placed in suitable multiple constellations. In this study we will only discuss detached boreholes.

The UTES system can be operated to utilise the heat from the sun that is passively stored in the bedrock. The temperature in the bedrock is low, and therefore a cold fluid is circulated in the borehole to obtain the necessary temperature difference between the heat carrier fluid and storage medium (rock). In most cases this type of thermal energy systems must be recharged with heat from solar panels, waste heat or similar.
The systems require boreholes of about 100-150 meter of depth [2]. The larger power extracted from the store, the more boreholes are required, but as the boreholes influence each other thermally, one must take into account that a number of closely placed boreholes produce less power than the same number of detached boreholes.

The energy demand over the year normally shows large seasonal changes. In households the power demand in summertime is mainly used for tapwater heating, while the energy demand during the coldest Swedish winter days will be considerably larger due to space heating.
For natural energy systems the lowest energy supply coincide with the periods of the largest energy needs. A way to compensate for this seasonal problem is to balance the energy supply over the year by using some kind of long-term storage, e.g. a duct store. The duct store is very functional. It is general, simple and unexpensive, it has a large volume but does not require large ground surface reservations,.

Geothermal heat and Groundwater heat

While discussing bedrock heat systems, geothermal heat and groundwater heat are sometimes included. Geothermal heat refers to the method of extracting hot water from deep boreholes (500 - 2000 meter) [2].

Groundwater heat utilises wells with the possibility of extracting large groundwater flows. The water is directly pumped to the evaporator chamber of the heat pump where the temperature decreases. The groundwater is then drained to a recipient or is re-injected to the groundwater aquifer.

These two types of UTES systems are not based on the same principals as duct heat, and will not be further discussed in this study.

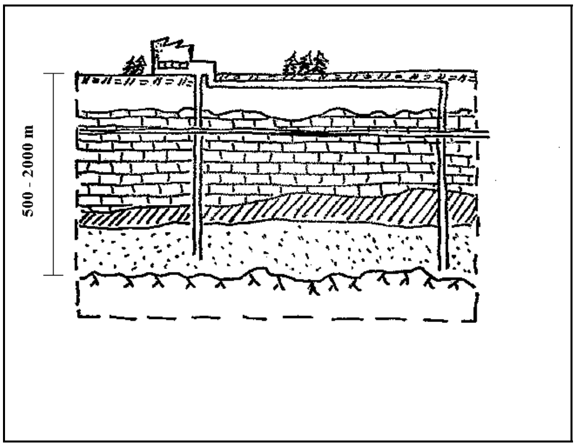


Figure 2.1 Geothermal energy is extracted from very deep boreholes (500-2000 m). (After Nordell, Söderlund 1991).

2.1 TYPES OF BOREHOLE INSTALLATIONS

There is a distinction between *open* and *closed* borehole systems, with regard to the arrangement of the tubes through which the heat carrier fluid flows in the borehole.

In an *open system* the groundwater, which fills the borehole, is extracted from the borehole via a single plastic tube. After cooling/heating the water in a heat pump, the water is reinjected into the well (Figure 2.2 a).
The main advantage of this arrangement is that the heat carrier fluid is in direct contact with the surrounding rock in the borehole. This leads to a good heat transfer between the heat carrier fluid and the surrounding rock. The heat extraction temperature must, however, be above 0°C in order to avoid freezing.

Geohydrological and geochemical conditions are often unfavourable to an open system. By inserting one or more closed U-shaped loops of plastic tubing, a so called *closed system* is obtained. The heat carrier fluid that is circulated through the system is then entirely separated from the surrounding medium (Figure 2.2 b,c and d). This circumstance makes it possible to use other heat carriers than water (e.g. glycol mixtures), so that temperatures below 0°C can be used. The heat transfer is not as good as for the open system though, as the heat transfer from the heat carrier fluid to the surrounding rock takes place via the tube material and the medium which fills the borehole (e.g. groundwater or sand). This means that the closed system will have a greater thermal resistance between the heat carrier fluid and the borehole wall, something that will reduce the capacity of the system. (see section 4.2.5).

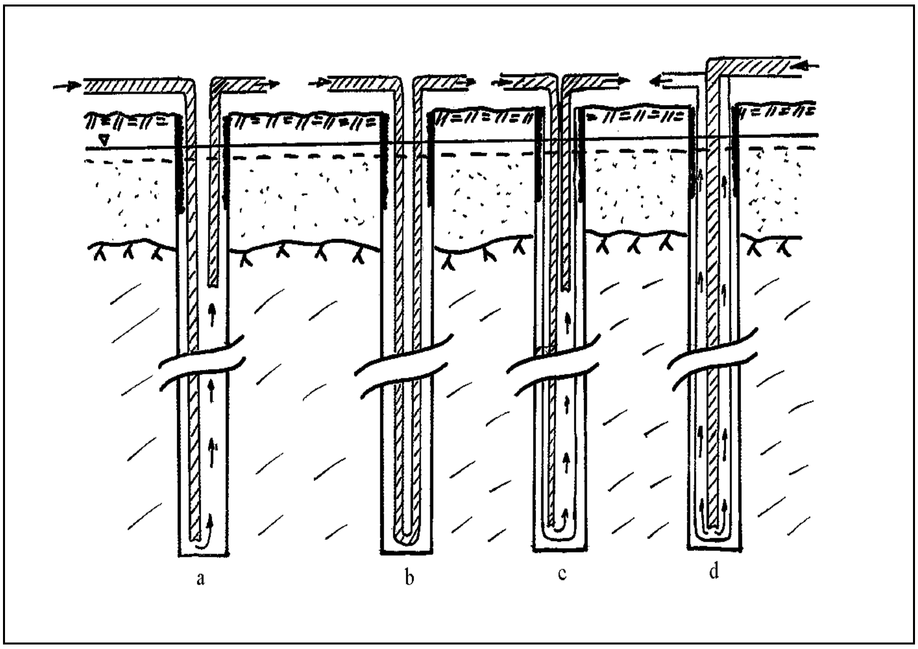


Figure 2.2 Four types of borehole installations. Borehole a is an open installation. b, c and d are all closed installation. b is a common U-loop, c is an open system enveloped by a 'sock', d is called coaxial system.

3. SYMBOLS

Before explaining the theory of the response test, we would like to introduce the symbols and definitions used in this thesis. The symbols defined below are used throughout this work:

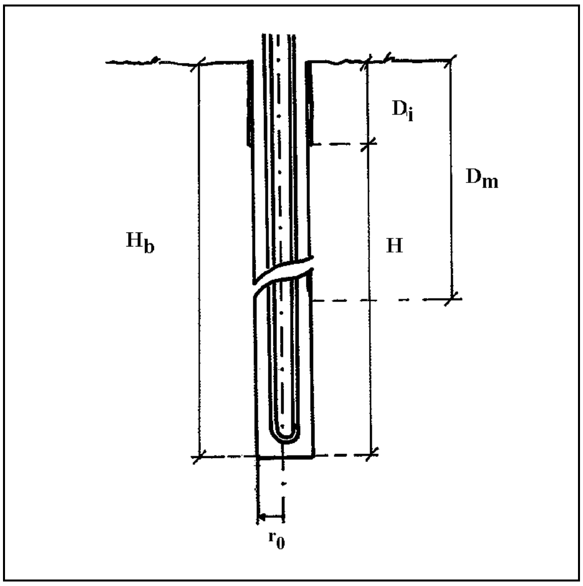


Figure 3.1

3.1 GEOMETRICAL PARAMETERS

D_i	[m]	Depth of insulated part of borehole
$D_m = D_i + H/2$	[m]	Mean depth of borehole
H	[m]	Efficient depth of borehole
$H_b = D_i + H$	[m]	Total depth of borehole
r	[m]	Radius
r_0	[m]	Borehole radius
r_w	[m]	Radius of groundwater well
L_p	[m]	Total lenght of pipe

3.2 PHYSICAL PARAMETERS

λ	[W/m, K]	Thermal conductivity of rock
λ^*	[W/m, K]	Assumed thermal conductivity of rock
c_r	[J/kg, K]	Heat capacity of rock
c_f	[J/kg, K]	Heat capacity of heat carrier fluid
C_r	[J/m^3,K]	Volumetric heat capacity of rock, $C_r = c_r \cdot \rho_r$
C_f	[J/m^3,K]	Volumetric heat capacity of heat carrier fluid, $C_f = c_f \cdot \rho_f$
$a = \lambda / C$	[m^2/s]	Diffusivity
q_{geo}	[W/m^2]	Geothermal heat flow
R_b	[K/(W/m)]	Thermal resistance between heat carrier fluid and borehole wall

3.3 THERMAL PARAMETERS

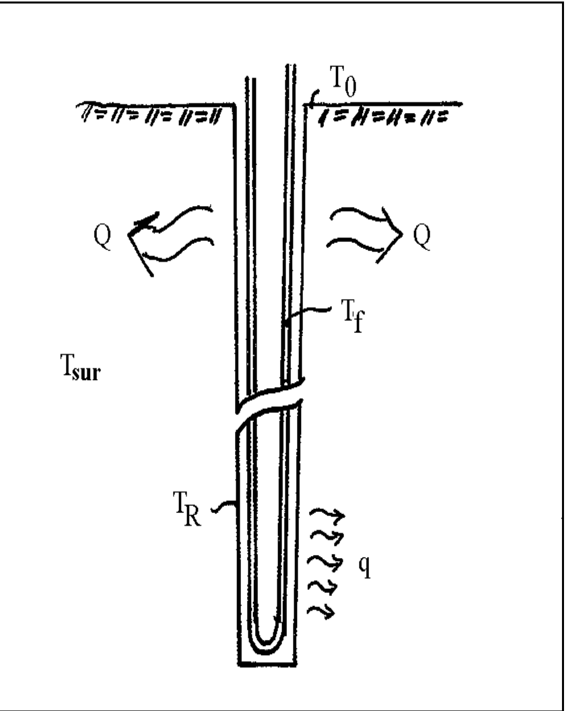


Figure 3.2

T_0	[°C]	Annual mean temperature of ground surface
T_{sur}	[°C]	Mean temperature of undisturbed rock
T_r	[°C]	Temperature of rock at borehole wall
T_f	[°C]	Mean temperature of heat carrier fluid
T_{in}	[°C]	Temperature of the heat carrier fluid going into the borehole
T_{out}	[°C]	Temperature of the heat carrier fluid going out of the borehole
Q	[W]	Heat injection /extraction rate
q = Q/H	[W/m]	Heat injection/extraction per meter

3.4 HYDRAULIC PARAMETERS

K	[m/s]	Hydraulic conductivity
s	[m]	Hydraulic drawdown in a groundwater well
B	[m]	Thickness of groundwater aquifer
T_{aq} = K*B	[m^2/s]	Hydraulic gradient
h	[m]	Hydrostatic pressure
h_w	[m]	Groundwater level in well

3.5 OTHER PARAMETERS

t	[s]	Time
t_s	[s]	Break time from transient to stationary conditions
t_b	[s]	Break time for time criteria

3.6 CONSTANTS

$\gamma = 0.5772$ Eulers constant

3.7 STATISTIC PARAMETERS

R^2 Standard deviation

4. THEORY

In this chapter we briefly the theory to understand the response test. If you are already accustomed to heat transmission, super positioning, transient and stationary conditions, and dimensioning of underground heat systems, you may well proceed to the next chapter.

4.1 HEAT TRANSFER

Transfer of heat can occur in three different ways, through conduction, convection and radiation.
If there is to be a transfer of heat there has to be a temperature difference *within* the medium (conduction) or *between* media (convection and radiation).

> A medium is **homogenous** when a certain property is equal in every point. Otherwise the medium is **heterogeneous**. If a certain property of a medium is independent of direction, the medium is **isotropic** in this point.

Conduction of heat

The diffusivity, a, depends entirely on material properties and shows whether a material is a good thermal conductor or not - the better heat conductor the higher the parameter a. The diffusivity is expressed: $a=\lambda/C$.

The fundamental equation of heat conduction shows how the temperature depends on a:

$$\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}+\frac{\delta^2 T}{\delta z^2}=\frac{1}{a}\frac{\delta T}{\delta t} \qquad (4.1)$$

The temperature, T, in a point with the coordinate (x,y,z) is determined by the time, t, and by the diffusivity, a.

Transient (time dependent) conditions occur , for example, when there is a sudden change of temperature in a body, a periodically altering temperature or a time dependent supply of heat. During *stationary* conditions the heat capacity looses importance and so does the time derivative. The equation of heat conduction can then be represented by the Laplace equation [10]:

$$\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}+\frac{\delta^2 T}{\delta z^2}=0 \qquad (4.2)$$

The two equations above are valid for a infinite, solid material in a Cartesian coordinate system. The material has to be homogenous and isotropic.

Convection of heat

Natural convection occurs when density differences cause circulation. Forced convection occurs when external forces affect the medium to such extent that the density differences can be neglected (in running water, for example).
To determine the transfer of heat by convection it is necessary to define a *heat transfer index*. The heat transfer index is not a material constant as the *diffusivity*, but an index that depends on the properties of the medium and on the state of flow. The heat transfer index is calculated with the aid of dimensionless numbers and can also be expressed as an equivalent λ-value.

Radiation of heat

Transfer of heat by radiation occurs when the energy is transported by electromagnetic waves.

4.1.1 HEAT TRANSFER IN BEDROCK

In a solid material the heat is transmitted solely by conduction. Therefore it is easy to understand that conduction is the main heat transfer in bedrock. A rock is usually heterogeneous and non-isotropic, however. In cracks and fissures filled with air and water heat is transmitted both by convection and conduction. The transfer depends on the size of the fissures and the properties of the medium that fills the fissures. It is usually assumed that transfer of heat between air/water and bedrock occurs between plane surfaces. Radiation between two surfaces in a crack is usually neglected [3].

4.1.2 CONDUCTION OF HEAT IN A DUCT ENERGY SYSTEM

A duct energy system is associated with complicated thermal processes. In the following chapters we will take a look at the fundamental processes that occur in a detached energy well. These fundamental thermal processes can then be super positioned to describe interaction between a number of wells.
Since the thermal response test is performed on a *detached* borehole with a *constant* heat injection rate we will not take into consideration nearby wells will affect each other and that the heat injection rate often varies.

The principle of super positioning:
If two different temperature fields each satisfies the equation then this is also true for the sum of the temperatures.

When applied on the equation of thermal conduction the **principle of super positioning** has some limits however:

1. It is not valid when freezing occurs and the phase change has to be taken into account.
2. It is not applicable to a temperature process with running water since this also gives transmission of heat by convection.

The ground temperature increases with increasing depth. This is called the geothermal gradient. The temperature field that under normal conditions exists beneath the ground surface is considered stationary. The geothermal gradient does not vary with time and the seasonal temperature changes of the ground surface do not affect the temperature > 10-15 meter. When heat is injected into a borehole, the temperature field begins to change, however.
The more heat that is injected into the borehole the warmer the ground will become undisturbed ground temperature will be found further away from the well. If the injected heat rate is constant, the temperature field will become stationary again, but it will take 20-25 years (see section 4.1.5).
The temperature in the ground satisfies the three-dimensional, non-stationary equation of thermal conduction, eq 4.1 The different forms of the equation is mainly linear, partial differential equations. This means that different solutions can be super positioned and complicated temperature processes can be made quite simple.

The thermal process that takes place in the ground when heat is injected can be divided into three different parts:

1. A **transient process** when the temperature of the ground increases. (Figure 4.2). The transient phase eventually turns into
2. A **stationary process** when the temperature of the ground no longer increases since heat leaves the ground surface at the same rate as injected into the well (Figure 4.1). When the heat

injection rate varies with time the stationary temperature field lies as an annual mean value.

3. A **pulse that is superimposed** on the stationary temperature when the heat injection varies with time.

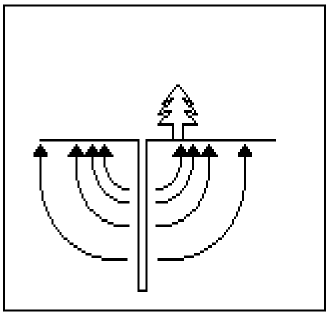


Figure 4.1During stationary conditions the injected heat is balanced by the atmosphere.

4.1.3 THE TRANSIENT PROCESS AND SUPERPOSED PULSE

There are two differences between the transient process and the superposed pulsation. Firstly the transient process eventually leads to stationary conditions while the superposed does not since it is limited in time. Secondly the transient process of the increase in temperature is superimposed to the undisturbed ground temperature, T_{sur}, while the pulsation is superimposed to the stationary mean temperature, T_r.

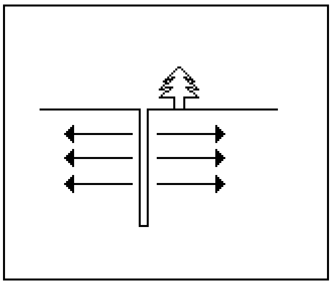


Figure 4.2 During the transient process the injected power is heating the ground.

The real temperature by the borehole wall will be

for the **transient process**:

$$T_r(t) = T_{sur} + T_{rq}(t) \qquad (4.3)$$

for the **superposed pulsation**:

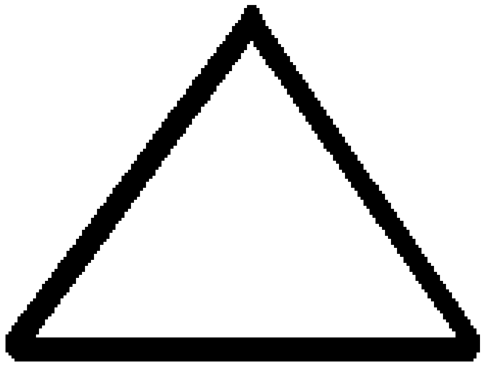
$$T_r(t) = T_r + T_{rq}(t) \qquad (4.4)$$

Where:

T_r (t) - the well temperature at time t
T_r - stationary well temperature due to injected fluid mean temperature (see section 4.1.4)
T_{sur} - the undisturbed ground temperature
T_{rq} (t) - change in well temperature due to deviation from mean fluid temperature

When injecting heat, an increase in temperature will occur. But how large will this increase be at different locations?

From now on we only look at the *transient process* since the superimposed pulse is not important to the thermal response test.



WARNING!

The following derivation is quite boring and should not be read by persons who already at this point have trouble keeping awake. Persons not interested in the details of heat conduction should proceed immediately to section 4.1.6 " Important equations - Summary" .

To find the answer to the question above we begin with the fundamental heat equation eq 4.1 and an instant point source. The following derivation is taken from [4 and 5]:

The fundamental equation of thermal conduction is satisfied by:

$$T = T_q(r,t) = \frac{q}{8(\pi\lambda t)^{3/2}} e^{-r^2/4at} \qquad (4.5)$$

where $a = \dfrac{\lambda}{c}$

and

$$r^2 = (x-x')^2 + (y-y')^2 + (z-z')^2$$

T(r,t) is the temperature in the point (*x,y,z*). The point source has the power q at the time t=0 and is located in the point (*x',y',z'*). The initial temperature of the material is 0°C.
A borehole made through bedrock can not be approximated with a point source however, but with a line source. By integrating the equation above eq 4.5, the equation for a line source is achieved:

$$T_q(r,t) = \frac{q}{8(\pi\lambda t)^{3/2}} \int_{-\infty}^{\infty} dz' e^{-r^2/4at} = \frac{q}{4\pi\lambda t} e^{-\left\{(x-x')^2+(y-y')^2\right\}/4at} \qquad (4.6)$$

The line source goes through the point (*x',y'*) and is parallel to the z-axis.

Now it is necessary to have the heat power *q* over a longer period of time, not only at t=0. From eq 4.6 we can derive an expression for a continuos line source. If the power *Φ(t')* is injected, starting when t=0 and the temperature of the rock is zero, then at time *t* the temperature will be:

$$T_q(r,t) = \frac{1}{4\pi\lambda} \int_0^t \Phi(t') e^{-r^2/4a(t-t')} \frac{dt'}{t-t'} \qquad (4.7)$$

Φ(t')=q and constant gives:

$$T_q(r,t) = \frac{q}{4\pi\lambda} \int_{r^2/4at}^{\infty} \frac{1}{s} e^{-s} ds = \frac{q}{4\pi\lambda} E_1\left(\frac{r^2}{4at}\right) \qquad (4.8)$$

where $E_1(r^2/4at) = \displaystyle\int_{r^2/4at}^{\infty} \frac{1}{s} e^{-s} ds$

This solution can be represented in two different ways depending on what one is looking for. In our case it is most interesting how the temperature changes with time at a certain radial distance from the line source. This gives:

$$T_q(r,t) = \frac{q}{4\pi\lambda} E_t\left(\frac{at}{r^2}\right) \qquad (4.9)$$

Where:

$$E_t(\tau) = E_1\left(\frac{1}{4\tau}\right) = \int_{1/4\tau}^{\infty} \frac{1}{s} e^{-s} ds$$

and $\tau = \frac{r^2}{at}$

The function $E_t(\tau)$ gives the temperature change with time at the radial distance r from the borehole.

For $\tau \geq 0.5$ the following equation is valid with a maximal error of 1 %:

$$E_t(\tau) \approx G_t(\tau) = \ln(4\tau) - \gamma - \frac{1}{4}\left(\frac{1}{\tau} - \frac{1}{16\tau^2}\right)$$

Where γ=0.5772 (Eulers Constant)

(4.10)

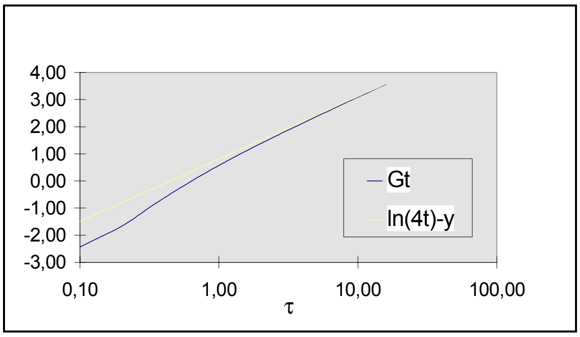


Figure 4.3 The functions $G_t(\tau)$ and $\ln(4\tau)-\gamma$ plotted against τ. This shows that for larger values of τ the function $G_t(\tau)$ can be approximated with $\ln(4\tau)-\gamma$.

For $\tau \geq 5$ there can be further simplifications:

$$E_t\left(\frac{at}{r^2}\right) \approx \ln\left(\frac{4at}{r^2}\right) - \gamma \qquad (4.11)$$

And since $\tau = \frac{r^2}{at}$ we will have:

$$E_t(\tau) \approx \ln(\tau) - \gamma \qquad (4.12)$$

With a maximum error of 2 percent we will have:

$$T_q(r,t) = \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4at}{r^2}\right) - \gamma\right)$$

$$= \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r^2}\right) - \gamma\right) \qquad (4.13)$$

When $\tau = \frac{at}{r^2} \geq 5 \Rightarrow t \geq \frac{5r^2}{a}$

For values not satisfying the time criteria in eq 4.13the heat capacity of the borehole filling will affect the result.

We are interested in the temperature at the borehole wall, i.e. $r=r_0$:

$$T_q(r,t) = T_{rq}(t) = \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right) \qquad (4.14)$$

For $t \geq \frac{5r_0^2}{a}$

Eq 4.14 is for heat **injection**. When heat is **extracted** the equation becomes:

$$T_{rq}(t) = -\frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right)$$

For $t \geq \frac{5r_0^2}{a}$

By inserting eq 4.14 into eq 4.2 the temperature at the borehole wall during the transient process is expressed:

$$T_r(t) = T_{sur} + \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right) \qquad (4.15)$$

For $\quad t \geq \dfrac{5r_0^2}{a}$

Eq 4.15 shows the connection between the undisturbed ground temperature, T_{sur}, and the temperature at the borehole wall, $T_r(t)$. A more interesting connection is the one between the T_{sur} and the temperature of the heat carrier fluid, T_f. In the heat exchanger there exists a *thermal resistance*, R_b [K/(W/m)], between the heat carrier fluid and the borehole wall. The thermal resistance is for heat injection defined as:

$$T_f - T_r(t) = R_b \cdot q \qquad (4.16)$$

Then eq 4.16 into eq 4.15 gives:

$$T_f + R_b q - T_{sur} = \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right) \qquad (4.17)$$

Which then can be written as:

$$T_f = \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right) + \frac{QR_b}{H} + T_{sur} \qquad (4.18)$$

4.1.4 THE STATIONARY PROCESS

The connection between the undisturbed ground temperature and the temperature by the borehole wall can be derived by approximating the well with a thin rotation ellipsoid and using mirroring to consider the conditions at the ground surface. The derivation also assumes that the borehole radius, r_0 and the insulated depth, D_i, are small compared to the depth of the borehole, H. The following derivation is taken from [4]:

$$Q = \frac{2\pi\lambda H(T_r - T_{sur})}{\ln\left(\dfrac{H}{r_0\sqrt{1.5}}\right) - \dfrac{1}{2(1 + 2D_i/H)}} \qquad (4.19)$$

Which can be simplified to:

$$Q = \frac{2\pi\lambda H(T_r - T_{sur})}{\ln\left(\dfrac{H}{2r_0}\right) - 0.01 + \dfrac{D_i}{H}} \qquad (4.20)$$

And then to:

$$Q = \frac{2\pi\lambda H(T_r - T_{sur})}{\ln\left(\dfrac{H}{2r_0}\right)} \qquad (4.21)$$

The error in these equations are a few percent maximum. They are fundamental since they give the amount of heat that can be injected annually when the temperature difference is T_r-T_{sur}.

The fluid temperature, T_f, will be given if eq 4.21 is inserted into eq 4.16:

$$T_r - T_{sur} = \frac{Q}{2\pi\lambda H}\ln\left(\frac{H}{2r_0}\right) =$$

$$T_f - T_{sur} = \frac{Q}{H}\left(\frac{1}{2\lambda\pi}\ln\left(\frac{H}{2r_0}\right) + R_b\right) \qquad (4.22)$$

4.1.5 BREAK TIME BETWEEN TRANSIENT AND STATIONARY CONDITIONS

The break time, t_s, between transient and stationary conditions is obtained by setting eq 4.18 equal to eq 4.22:

$$\underbrace{\frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^{\,2}}\right)-\gamma\right)-\frac{QR_b}{H}}_{Transient}=$$

$$\underbrace{\frac{Q}{H}\left(\frac{1}{2\lambda\pi}\ln\left(\frac{H}{2r_0}\right)-R_b\right)}_{Stationary}$$

This will give:

$$\frac{16at}{H^2}-\gamma=0 \quad \Rightarrow$$

$$t=t_s=\frac{H^2}{9a} \qquad (4.23)$$

EXAMPLE:

The break time, t_s, is calculated for a borehole with the following data:

Depth of borehole, H=100 m
Thermal conductivity, λ=3.5 W/m, K
Thermal capacity, C=2200 kJ/m^3, K

$$\mathrm{t_s}=\frac{\mathrm{H}^2}{9\mathrm{a}}=\frac{100^2}{9\cdot 3.5/2200000}=22\mathrm{years}$$

4.1.6 IMPORTANT EQUATIONS - SUMMARY

When heat first is injected into a borehole a transient process starts. The connection between the different parameters involved is described in eq 4.18:

$$\boxed{T_f=\frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^{\,2}}\right)-\gamma\right)+\frac{QR_b}{H}+T_{sur}}$$

For $\quad t\geq\frac{5r_0^{\,2}}{a}$

After a certain time, t_b, the transient process ends and the conditions become stationary eq 4.23:

$$\boxed{t_b=\frac{H^2}{9a}}$$

Eq 4.22 describes the connection between the parameters during stationary conditions:

$$\boxed{T_f-T_{sur}=\frac{Q}{H}\left(\frac{1}{2\lambda\pi}\ln\left(\frac{H}{2r_0}\right)+R_b\right)}$$

4.2 DIMENSIONING OF AN UNDERGROUND THERMAL ENERGY SYSTEM

When dimensioning an energy well one often starts with a given heat injection rate (or, as the case often is, a heat extraction rate) that varies over the year. There is also a limit for how high (or low) the temperature is allowed to become in the borehole. What one wishes to know is the temperature of the heat carrier fluid during different times of the year.

Several parameters decide how the bedrock temperature is affected by heat injection in a borehole. From the equations of heat conduction we realise that the following properties have to be known if we know the heat injection rate and want to know the temperature of the heat carrier fluid:

Ground properties:
λ - thermal conductivity[1] [W/m, K]
C - thermal capacity[1] [J/m^3,K]
T_{sur} - undisturbed ground mean temperature [^{o}C]

Borehole properties:
H - depth [m]
r_0 - radius [m]

Heat exchanger properties:
R_b - thermal resistance between heat carrier fluid and borehole wall [K/(W/m)]

[1] This parameter is only needed when calculating a superposed pulse or transient phase.

	ρ [kg/m^3]	λ [w/m,K]	c [J/kg,K]	C [kWh/m^3,K]
water	1000	0,6	4180	1,2
granite	2700	2,9-4,2	830	0,6
gabbro	3000	2,2-3,3	860	
gneiss	2700	2,5-4,7	830	0,6

Table 4.1 Density, thermal conductivity and thermal capacity for some materials. (After Ericsson, 1985).

There are, however, several parameters that affect the temperature of the heat carrier fluid that can not be seen in equations of heatl conduction. Some of the properties mentioned above are dependent of other parameters. The thermal resistance, for example, is a complex factor that considerably with the design of the heat exchanger. Some other properties are left out of account by the equations because they are assumed not to exist or to have a negligible influence. Some properties that are not seen in the equations of thermal conduction are:

Ground properties:
Conditions on the ground surface
Geothermal gradient [^{o}C/m]
Other physical properties, i.e. groundwater conditions and cracks

Borehole properties:
Thermal insulation of the upper part of the borehole

Heat exchanger properties:
Type of borehole filling[2]
Pipe properties:
- type[2] (coaxial, U-pipe etc)
- radius [m]
- wall thickness[2] [m]
- thermal conductivity[2] [W/m, K]

Heat carrier fluid properties:
- thermal conductivity [W/m, K]
- thermal capacity [J/m^3,K]
- density [kg/m^3]

[2] These parameters are only relevant in closed systems

viscosity [kg/m, s]
freezing point [°C]
flow rate [m^3/s]
state of flow (laminar/turbulent)

Miscellaneous:
Convection [W/m^2]

Below follows a perspicuous summary about how the parameters mentioned above affect the energy well. The description is not complete but is meant to give a picture of the problem.

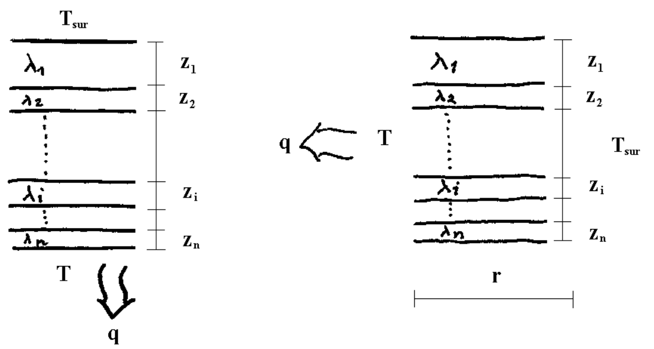
4.2.1 GROUND PROPERTIES

The different properties of the ground is of great importance to the energy well. They can, however, not be altered and are sometimes hard to determine. When designing a energy well it is important to chose a location with proper ground properties.

Thermal conductivity

The thermal conductivity of a rock mostly depends on the conductivity of the rock forming minerals. The thermal properties of the minerals depend on the size of the crystals and possible defects in the lattice [3]. The thermal conductivity is also affected by the occurrence of air and water in the ground.

The thermal conductivity of the bedrock is of great importance for the energy well. In the equations of heat conduction the temperature difference (T_f-T_{sur}) is inversely proportional to the thermal conductivity (λ). In the equation that describes the transient process this relationship is complicated by the fact that the coefficient of thermal conductivity (a) is a function of both λ and time - a changed λ corresponds to a change in the time scale. It is however the direct proportionality that is most important - the change in the time scale is of less importance [4].



Perpendicular heat flow:

$$q = \frac{T_{sur} - T}{\sum_i^n \frac{z_i}{\lambda_i}}$$

Parallel heat flow:

$$q = \frac{\sum_i^n \lambda_i z_i}{\sum_i z_i} \cdot \frac{T_{sur} - T}{r}$$

Figure 4.4 Left: When the heat flow is perpendicular to a number of homogenous layers the heat conduction is principally determined by the harmonic mean value of the thermal conductivity of the different layers. Right: When the heat flow is parallel to a number of homogenous layers the thermal conduction is determined by the weighted arithmetic mean value of the thermal conductivities of the different layers. (After Ericsson, 1985)

Often the ground is not homogenous but consists of layers with different thermal conductivity.
This affects the energy well, but it is safe to use a mean value of the thermal conductivity when dimensioning (see Figure 4.4).
In many cases the bedrock is covered with a layer of soil that has different thermal properties than the bedrock. This is usually disregarded. Even a 10 meter thick soil layer gives a small error when determining the temperature of the heat carrier fluid without taking into account the different thermal properties [4]. The error becomes bigger the thicker the soil layer and the shallower the borehole.

Heat capacity

The heat capacity depends, just like the thermal conductivity, on the mineral composition and on the air and water content of the bedrock.
The thermal capacity of the ground only affects the energy well during the transient process. The thermal capacity (C) is inversely proportional to the diffusivity (a). This means that a high thermal capacity gives a low coefficient of thermal conductivity and a larger difference between the ground temperature and heat carrier fluid temperature is needed for a given heat injection into the well.

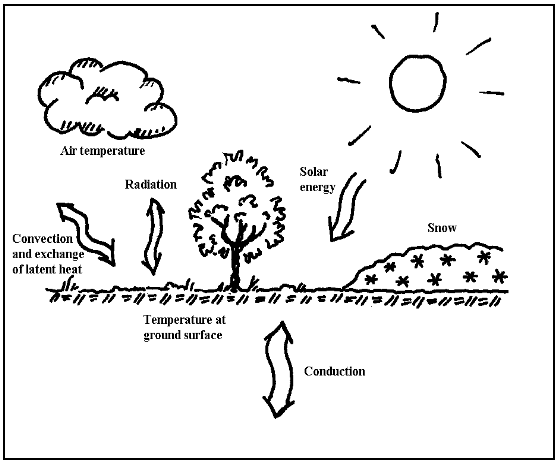


Figure 4.5 Conversion of heat on the ground surface (After Ericsson, 1985)

4.2.2 CONDITIONS AT GROUND SURFACE, GEOTHERMAL GRADIENT AND UNDISTURBED GROUND MEAN TEMPERATURE.

The undisturbed ground mean temperature (T_{sur}) is an important parameter when dimensioning an energy well. It is the temperature difference between the heat carrier fluid and the ground that creates a gradient for the heat flow from the fluid to the ground - a larger gradient gives a larger heat flow.

The ground temperature is dependent on the availability of solar energy and on the heat exchange process with the atmosphere. The heat exchange between ground and air is a rather complicated process that depends on several parameters such as air temperature, wind, snow and frozen soil.

The annual temperature changes of the ground surface only affect the ground temperature to a depth of about 10 to 15 meters. Deeper down it is mainly the geothermal gradient that determines the temperature. The temperature variations of the surface is negligible to an energy well with a depth of more than 100 meters [4].

As mentioned previously, the ground temperature increases with increasing depth. This geothermal gradient is a result of the thermal conductivity and radiogenic heat production of the bedrock.

The undisturbed ground temperature, T_{sur}, at a certain depth, z, is given by:

$$T_{sur} = T_0 + q_{geo} \cdot z/\lambda = T_0 + \Delta T_{geo} \cdot z$$

The geothermal gradient, ΔT_{geo}, varies between 10 and 40 °C/km in Sweden - the mean geothermal heat flow, q_{geo}, is 0,056 W/m^2 [3].

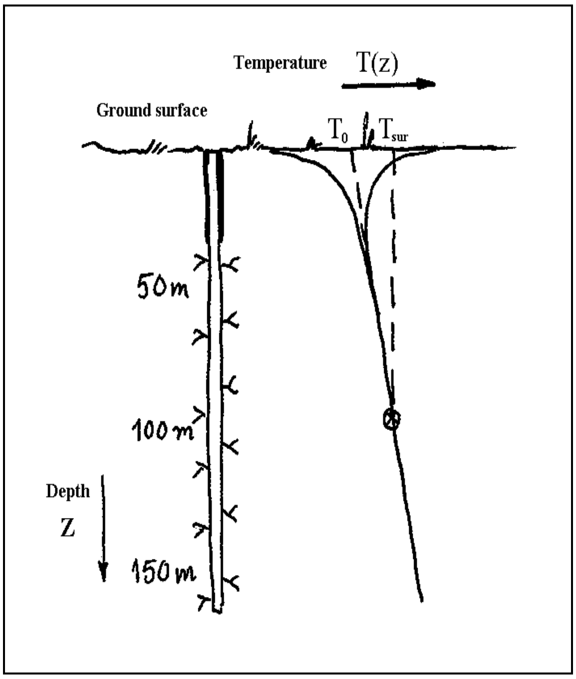


Figure 4.6 An illustration showing the undisturbed temperature conditions for a energy well.(After Ericsson, 1985)

The undisturbed ground mean temperature is quite difficult to measure and is therefore often approximated with the annual mean air temperature - a parameter that is more easily determined. In making this approximation the geothermal gradient is left out of account and the deeper the borehole, the less accurate the approximation becomes. According to some literature (e.g. [3]) it is not necessary to take the thermal gradient into account, while according to other literature (e.g. [4]) the thermal gradient affects deep energy wells and has to be regarded. In general, the thermal gradient has little influence on high temperature systems, but should be taken into account for low temperature systems.

In urban areas the ground temperature is influenced by heat leakage from buildings and district heating pipes. This influence is often much greater than the geothermal heat flow and can affect energy wells in urban areas. When this is the case, it is necessary to make a more accurate determination of the ground mean temperature than the estimation above.

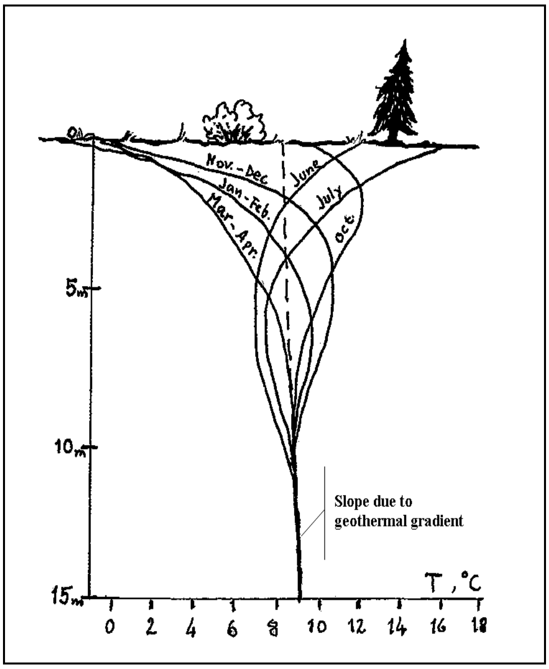


Figure 4.7 Schematic seasonal temperature variation in the ground. The oscillations are dampened by the depth and below 15-20 meters the temperature is mainly dependent on the geothermal gradient. (After Ericsson, 1985)

4.2.3 GROUND WATER FLOW

The different analyses of the equations in the foregoing chapters have presumed pure heat conduction in the rock surrounding the borehole. Disturbances because of groundwater movements have been neglected. It is usually presumed that the effect of natural groundwater movements, homogeneously spread through the bedrock, is negligible. The effect of other kinds of groundwater movement is more difficult to foresee. An inclined crack with a large water flow may, for example, cool the energy well. This is difficult to take into consideration when dimensioning the well but can be of great importance to its efficiency [4].

4.2.4 BOREHOLE PROPERTIES

The borehole properties are easily manipulated to bring out the best of the energy well.

Depth and radius
From the equation of heat conduction eq 4.22 it is easy to see the importance of the borehole depth. The depth, H, is inversely proportional to the temperature difference, T_f-T_{sur}, i.e. the deeper the borehole the smaller the temperature difference for a constant heat extraction.
The relation between the temperature difference and the borehole radius is more complicated. During transient conditions the temperature difference, T_f-T_{sur}, is proportional to the natural logarithm of the inverse radius raised to second power (ln $(1/r^2)$. This means that the radius has a greater influence during transient conditions than during stationary conditions, where the temperature difference is proportional to the natural logarithm of the inverse radius (ln(1/r)). In both cases a larger radius demands a smaller temperature difference between the heat carrier fluid and the bedrock with a given heat injection.

The thermal resistance is measured per meter well and is therefore not affected by the borehole depth. The radius, on the other hand, affects the thermal resistance in closed systems since the thermal resistance is dependent on the distance between the pipes and the borehole wall. The thermal resistance is also dependent of the borehole filling (air, water, soil etc.).

Thermal insulation of upper part of borehole

The upper part of the borehole is usually thermally insulated to protect the heat carrier fluid from chilling during wintertime. The insulation is applied from the ground surface and down to the depth, D_i - usually a few meters.

4.2.5 HEAT EXCHANGER PROPERTIES

Thermal resistance, borehole filling, pipe properties and heat carrier fluid

The heat transfer between the heat carrier fluid and the surrounding bedrock depends on the design of the heat exchanger, the properties of the heat carrier fluid and on the state of flow in the pipes [6]. Heat exchange occurs between the different flow pipes and between the flow pipes and the surrounding rock.

The heat flow between two surfaces depends on the temperature difference and the thermal resistance. The relation between the heat flow, q [W/m], and the temperature difference, ΔT [K], over the resistance R [K/(W/m)] is (see also eq 4.16):

$$\Delta T = q \cdot R$$

(Observe the similarity to an electrical circuit, $U = I \cdot R$).

The thermal resistance in a closed system consists of several components:
- thermal resistance between heat carrier fluid and flow pipe wall
- thermal resistance over flow pipe wall
- thermal resistance between outer pipe wall and surrounding rock

In a closed system there is also a thermal resistance between the pipes and in the boreholes.

In an open system the heat carrier fluid is in contact with the surrounding rock and the total thermal resistance mainly consists of one component.

The components mentioned above are used to determine the total thermal resistance between heat carrier fluid and surrounding rock - a thermal resistance defined as:
$R_b = (T_f - T_R)/q$
The heat carrier fluid temperature, T_f, varies in the well, but it has been shown that T_f, defined as the mean value between in- and outlet temperature, is a good approximation.

The borehole filling is only of interest in a closed system. Open systems are generally filled with water. To decrease the thermal resistance and the effect of groundwater movements, it is possible to fill the borehole of a closed system with, e.g. sand.

The thermal properties of the pipes are crucial to the thermal resistance. It is important that the heat is transported easily though the pipe walls and the walls should therefore not be too thick or have an insulating effect. As mentioned above different closed systems have different thermal resistance. In a closed system it is also important how the pipe is placed in the borehole. For the thermal resistance it is important that the pipes are centered in the borehole.

The properties of the heat carrier fluid also affect the thermal resistance - the thermal conductivity and the heat capacity of the fluid decides how good the fluid really is at ”carrying heat”. To get a low thermal resistance it is also important to have a turbulent state of flow in the pipe. The viscosity, geometry and flow rate of the fluid decide this (i.e. Reynold’s number, Re).

In an open system the only available heat carrier fluid is water. This means that the temperature in an open system always has to be above 0 ^{o}C. In a closed system, using a heat carrier fluid with freezing point below zero, it is possible to use the latent heat of freezing water.

In a closed system the thermal resistance between heat carrier fluid and borehole wall often varies between 0,10 and 0,20 K/(W/m). In an open system typical values are 0,01 to 0,1 K/(W/m). When considering the different parameters determining the thermal resistance for open and closed systems it is not difficult to understand why the resistance is lower in an open system than in a closed. The advantage of an open system is the low thermal resistance, while the advantage of closed system is the possibility of using temperatures below 0^{o}C. The closed system can alway be used.
As the thermal resistance between heat carrier fluid and borehole wall is a very complex parameter it is often experimentally determined rather than calculated.

4.2.6 MISCELLANEOUS

Convection
When using the equation of heat conduction it is assumed that the convective contribution to the heat transfer is negligible. The bedrock however contains fissures and fractures that are filled with air and water and convection occurs when a gas or fluid in movement is transporting heat. When using a UTES system the temperature and density differences in the fissures of the bedrock are quite small and natural convection hardly ever occurs. [3]. On the other hand, there are several forms of forced convection that could occur and affect the energy well. If the well is bored through a system of fissures with different hydrostatic pressure, a flow is created - a flow that depends on the pressure differences and the permeability properties of the bedrock. The temperature of the water that will enter the well will be about the temperature of the surrounding, undisturbed ground. This may either cool or heat the well. The same situation occurs if an open system is created in a well with good hydraulic capacity and groundwater is pumped from the well.

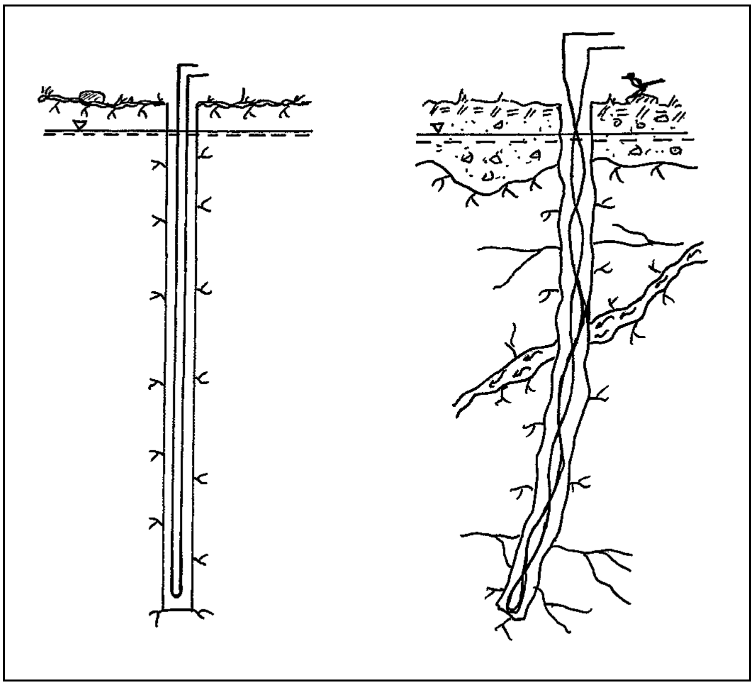


Figure 4.8 The ideal conditions of the theory (left) do not often correspond with the conditions in reality (right)

5. THE RESPONSE TEST

The idea of a thermal response test is to determine the thermal properties of a borehole in situ. Each type of borehole installation (see chapter 2) also gives a different thermal loss, and by testing various types of installations in the same borehole, one may compare the thermal resistance of the installation types.

5.1 RESPONSE TEST

There is a clear analogy between *hydrological* and *thermal* response tests. The flux that in hydraulic tests consists of groundwater extraction/injection (Q_w [m^3/s]) corresponds in the case of a thermal test with the heat extraction/injection (Q [W]). The temperature (T) in the ground corresponds to the hydrostatic pressure of the groundwater (h). There is a parallel between the thermal conductivity, λ [W/m, K], and the hydraulic conductivity, K [m/s], of the ground.

Note: $\frac{Q_w}{m \cdot h} \Leftrightarrow \frac{Q}{m \cdot T}$

and $$\begin{cases} K = \dfrac{Q_w}{m \cdot h} \Rightarrow \left[\dfrac{m^3/s}{m \cdot m}\right] \\ \lambda = \dfrac{Q}{m \cdot T} \Rightarrow \left[\dfrac{W}{m \cdot K}\right] \end{cases}$$

As it is often easier to visualise hydraulic than thermal conditions, we will here give an example of the hydraulic drawdown expression, from [7]:

In a groundwater aquifer, the groundwater conditions are described by geometry, geology and hydraulic parameters. A disturbance (e.g. pumping water from one or a number of wells) will affect the groundwater conditions. The influence in time and space depends on the magnitude of the disturbance and of the properties of the groundwater aquifer. A *controlled disturbance* means that the amount of water, being pumped out or injected per time unit will be held constant and that the change of groundwater level in the aquifer is being observed.

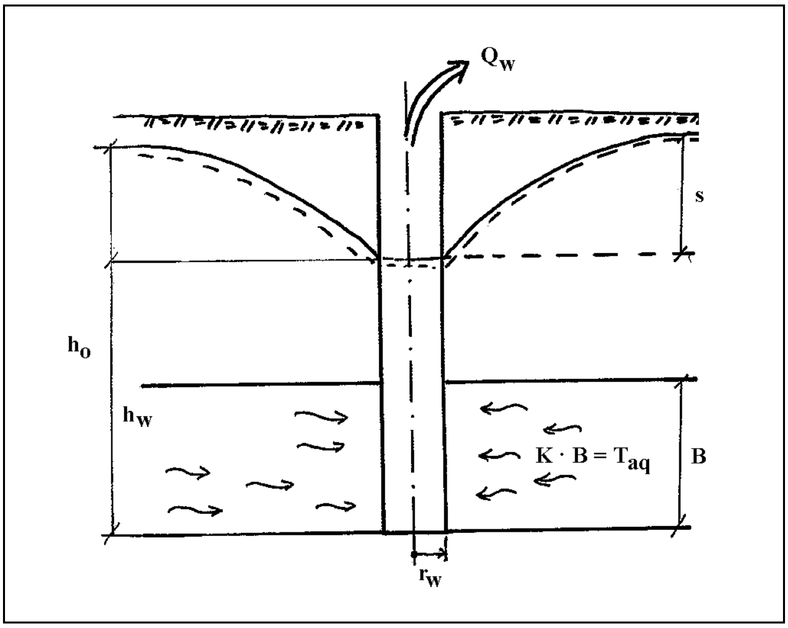


Figure 5.1 Hydraulic drawdown from extraction of groundwater in a single well.

When water is pumped out of the well, the groundwater level can be described as a cone with its point downwards in the well (Figure 5.1). During the early stage of the pumping, the water will mainly come from the aquifer close to the well, and the groundwater pressure will change quickly. As the drawdown cone expands to include larger areas, the speed of which the groundwater pressure changes decreases. After a long time the drawdown will not change any more. This type of hydraulic response test is mainly done in order to study and determine the hydraulic properties and limits of the aquifer.

The stationary condition of a hydraulic profile can be described with the following expression (see Figure 5.1):

$$s = \Delta h = h_0 - h_W = \frac{Q}{2\pi T} \ln \frac{R_0}{r} \qquad (5.1)$$

where $T = K \cdot B$
T = Transmissivity [m^2/s]
K = Hydraulic conductivity[m/s]
B = Thickness of aquifer [m]

The expression can be derived as follows:

Thiems equation for a closed homogenous two-dimensional groundwater aquifer says:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T} \cdot \frac{\partial h}{\partial t} \qquad (5.2)$$

For stationary conditions the right side of the equation is zero, as no changes is to be seen in the well. As we are studying the radial flux around the well, it is wise to rewrite the equation with polar co-ordinates, where upon the equation obtains the following form:

$$\frac{d^2\phi}{dr^2} + \frac{1}{r} \cdot \frac{d\phi}{dr} = 0 \qquad (5.3)$$

where $\phi = h \cdot T = h \cdot K \cdot B$

Derivation of ϕ gives that $\phi' = \frac{d\phi}{dr}$

By inserting ϕ into eq 5.3 we obtain

$$\frac{d\phi'}{dr} + \frac{\phi'}{r} = 0 \qquad (5.4)$$

Integration gives that

$$r \cdot \phi' = C_1 = const.$$

Going back to ϕ and anew integrating eq 5.4 gives:

$$\begin{cases} \phi = h \cdot K \cdot B \\ r\phi' = C_1 \Rightarrow \phi = C_1 \ln r + C_2 \end{cases} \Rightarrow h \cdot K \cdot B = C_1 \ln r + C_2 \qquad (5.5)$$

Now we are ready to take a look at the geometrical conditions of the well. The flux from a cylindrical body can be expressed as:

$$Q = 2\pi r \cdot B \cdot K \cdot \frac{dh}{dr} = 2\pi \cdot r \cdot \frac{d\phi}{dr} \qquad (5.6)$$

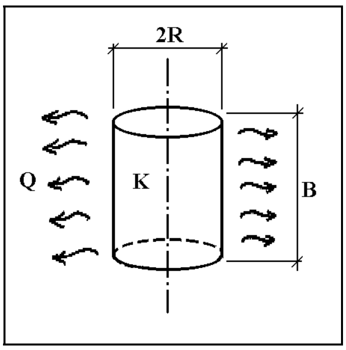


Figure 5.2 The mantel area of a cylindrical body is determined from the radius and the height, which in this case is the thickness (B) of the aquifer.

As $C_1 = r\phi' = r \cdot \frac{d\phi}{dr} = \frac{Q}{2\pi}$ (Eq 5.5)

the following relation is seen:

$$\begin{cases} C_1 = \frac{Q}{2\pi} \\ C_1 = \frac{hKB - C_2}{\ln r} \end{cases} \Rightarrow h = \frac{1}{K \cdot B}\left(\frac{Q}{2\pi}\ln r + C_2\right) = \frac{Q}{2\pi T}\ln r + Const. \quad (5.7)$$

If the undisturbed groundwater level in the well is known, h_W, the integration constant is determined:

$$h = \frac{Q}{2\pi T}\ln\frac{r}{r_w} + h_w \quad (5.8)$$

The equation predicts that the groundwater level will grow to infinity when r increases, which of course is not possible for physical reasons. The equation is only valid for stationary flux in a cylindrical aquifer with the radius R_0 and a groundwater level h_0 by the cylinder wall. With these parameters inserted, we obtain:

$$h_0 - h = s = \frac{Q}{2\pi T}\ln\frac{R_0}{r} \quad (5.9)$$

This expression has a very good analogy with the expression for the temperature around a homogenous two-dimensional thermal borehole when heat is injected:

$$T_{om} - T_r(t) = \frac{Q}{2\pi\lambda H}\ln\frac{H}{2R_0} \quad (5.10)$$

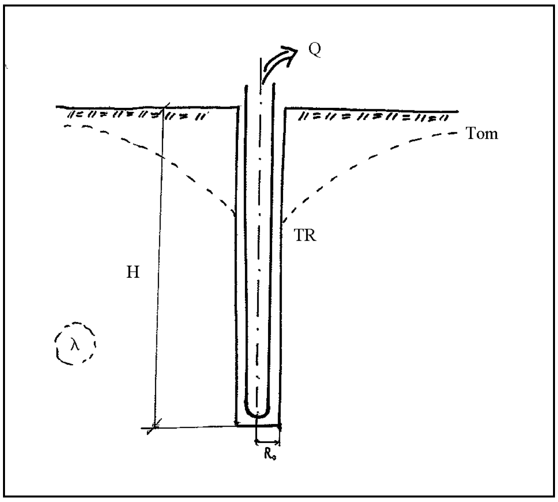


Figure 5.3 Thermal drawdown at heat extraction from a single borehole. The low temperature heat carrier fluid in the pipes is heated by the warmer surrounding rock, and the temperature in the rock decreases with decreasing distance from the borehole wall.

5.2 THE IDEA BEHIND THE THERMAL RESPONSE TEST

In section 4.2 we discussed how different parameters affect a heat injection well. The idea behind the thermal response test is to inject a constant heat power into a borehole with known depth and known radius. By measuring the in- and outlet temperatures of the heat carrier fluid during a period of time, the mean temperature T_f is determined for different values of *t*. The heat injection starts a transient process and eq 4.18 shows that the parameters λ, R_b, a and T_{sur} are unknown The parameters T_{sur} , λ and R_b are determined by the thermal response test. diffusivity, *a*, has to be determined in some other way for the bedrock in question.

As we have mentioned previously it is necessary that the injected power rate is *constant*. It is possible however to use a *stepwise constant* heat power, which is useful if for example a shut down occurs.
In the following chapters we will take a look at how the undisturbed ground temperature, the thermal conductivity and

the thermal resistance for a certain borehole installation are determined with a thermal response test, using constant and stepwise constant heat power.

5.2.1 UNDISTURBED GROUND TEMPERATURE

The undisturbed ground temperature must be determined before the well is taken into service. The temperature is determined by measuring at several different depths in the well and then calculating a mean value. Another way is to measure the temperature of the heat carrier fluid while circulating it without any heat power supply. This gives a good approximation of the undisturbed ground mean temperature if the pump is not heating the fluid too much [4].

5.2.2 THERMAL CONDUCTIVITY AND THERMAL RESISTANCE

5.2.2.1 CONSTANT HEAT POWER

In section 4.1.3 we derived the following relation between the temperature of the heat carrier fluid, T_f, and the temperature of the undisturbed ground, T_{sur}:

$$T_f = \frac{Q}{4\pi\lambda H}\left(\ln\left(\frac{4at}{r_0^2}\right) - \gamma\right) + \frac{QR_b}{H} + T_{sur}$$

(4.18)

Where $a = \frac{\lambda}{c_r}$, γ=0.5772 and $t \geq \frac{5r_0^2}{a}$

There is a linear relation between T_f and *ln(t)* and we can rewrite eq 4.18 on the form [4 and 8]:

$$T_f = k\ln(t) + m \qquad (5.11)$$

Which becomes:

$$T_f = \frac{Q}{4\pi\lambda H}\ln(t) + \left[\frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(\ln\left(\frac{4a}{r_0^2}\right) - \gamma\right) - R_b\right) + T_{sur}\right]$$

For $t \geq \frac{5r_0^2}{a}$ (With a maximum error of 2%)

(5.12)

Now it should be easy to determine the thermal conductivity and the thermal resistance:

1. Determine the time when eq 5.12 is valid, i.e. when $t \geq 5R_0^{\,2}/a$ is satisfied. To determine the parameters *a,* λ and c_r have to be approximated (e.g. taken from a table) for the bedrock in question.
2. Plot T_f against *ln(t)* for all values satisfying the time criteria
3. Determine the inclination of the line achieved in step 2. Since eq 5.11 and eq 5.12 give that the inclination k equals Q/4πλH and the injected heat power and the depth of the borehole hopefully are known, the thermal conductivity is easily determined.
4. For every pair of T_f and t, a value for the thermal resistance is determined by using the λ determined in step 3. This is done by using eq 5.13. Suitably a mean value is then calculated.

$$R_b = \frac{H}{Q}\left(T_f - T_{sur}\right) - \frac{1}{4\pi\lambda}\cdot\left(\ln(t) + \ln\left(\frac{4a}{r_0^2}\right) - \gamma\right) \qquad (5.13)$$

For further information about calculations of R_b and λ see chapter 7 ”Measurements and Results”.

5.2.2.2 STEPWISE CONSTANT HEAT POWER

Sometimes it is impossible to keep the power constant during the whole test period, maybe because of a power failure. If the heat power is stepwisely constant the following method is used [8]:

$$q(t) = \begin{cases} q_1 \rightarrow t_1 < t < t_2 \rightarrow (t_1 = 0) \\ q_2 \rightarrow t_2 < t < t_3 \\ . \\ . \\ . \\ q_N \rightarrow t_N < t < t_{N+1} \end{cases} \qquad (5.14)$$

The principle of super positioning gives that the temperature in the bedrock increases as a sum of the contribution of each power step.

The following equation is used:

$$T_f = \sum_{n=1}^{N} \frac{q_n - q_{n-1}}{4\pi\lambda} \ln(t - t_n) + \left[q_N \left(\frac{1}{4\pi\lambda} \left(\ln\left(\frac{4a}{r_0^2}\right) - \gamma \right) + R_b \right) + T_{sur} \right] \qquad (5.15)$$

Which also can be expressed as:

$$T_f = \frac{q_{ref}}{4\pi\lambda} \tau_N(t) + \left[q_N \left(\frac{1}{4\pi\lambda} \left(\ln\left(\frac{4a}{r_0^2}\right) - \gamma \right) + R_b \right) + T_{sur} \right]$$

When $t_N + r_0^2/5a < t < t_{N+1}$ and q_0=0

(5.16)

The dimensionless parameter τ_N is defined as

$$\tau_N(t) = \sum_{n=1}^{N} \frac{q_n - q_{n-1}}{q_{ref}} \ln(t - t_n) \qquad (5.17)$$

When $t_N + r_0^2/5a < t < t_{N+1}$

This expression for τ_N will change value for every stepwise change in heat power. The temperature is a linear function of τ_N in each time interval $t_N + r_0^2/5a < t < t_{N+1}$. The inclination, k, of the line will give the thermal conductivity according to:

$$\lambda = \frac{q_{ref}}{4\pi k} \qquad (5.18)$$

Since the parameter q_{ref} is only used to get the dimension less parameter τ_N, q_{ref} can be given any value except 0. The parameter q_{ref} is eliminated when eq 5.17 is inserted into eq 5.16.

5.3 HOW DIFFERENT PARAMETERS AFFECT THE THERMAL RESPONSE TEST

In section 4.2 "Dimensioning of an underground thermal energy system" we looked at how different properties affect the energy well. This chapter will show how the results from the thermal response test are affected by different parameters.

5.3.1 GROUND PROPERTIES

Thermal conductivity

When performing a thermal response test, one of the goals is to determine the thermal conductivity. The value of the thermal conductivity given by the test will be a mean value for the bedrock around the borehole, and represents the *effective* thermal conductivity that includes the influence of fractures, groundwater flow, bedrock etc.

Heat capacity

When evaluating a thermal response test it is necessary to *assume* a heat capacity, to be able to calculate the thermal conductivity and the thermal resistance. Some values for different different types of bedrock are given in Table 4.1.

Conditions on the ground surface, geothermal gradient and undisturbed ground mean temperature.

As we have seen in section 5.2.1 the thermal response test makes it possible to determine a value for T_{sur}. This value will show the actual mean temperature in the borehole when the test is made and will include the effect of the geothermal gradient and the current conditions on the ground surface. The question is whether the obtained value for T_{sur} will be the annual mean value needed for dimensioning or not. For a deep well it will not make a difference whether the measurement is made during winter or summer. In more shallow wells the season might make a difference in regions with big annual differences in the air temperature. It is necessary to further investigate this matter.

Ground water flow

The effect of ground water flow on the thermal response test is difficult to predict. If flowing groundwater cools the well, the thermal response test will give a higher value for the thermal conductivity than what is actually true for that certain bedrock. It may also give a lower thermal resistance than would be expected. This is not a problem. If the well is going to be used as a heat injection well, the thermal conductivity and the thermal resistance given by the response test reflect the real conditions in the borehole . If the well is to be used as a heat extraction well or as a part of heat storage, the given values will make it seem like the well is more efficient than it really is. It is also possible that the groundwater has a higher temperature then the surrounding rock and therefore, in the end, will give a heat contribution to the heat extraction well.
The existence of groundwater movement in the energy well is a very complicated issue both when it comes to dimensioning and to the thermal response test.

5.3.2 BOREHOLE PROPERTIES

Depth and radius

The depth and radius of the borehole should not affect the outcome of the thermal response test if the parameters were correctly determined and correctly used when evaluating the test. However, if the purpose of the response test is to evaluate the thermal resistance of a certain borehole installation it is important to remember that the thermal resistance is dependent on the borehole radius.

Thermal insulation of upper part of borehole

The thermal insulation should not affect the results of the thermal response test When performing a thermal response test on a well with the upper part insulated it is important to take this into account when using the obtained values.

5.3.3 HEAT EXCHANGER PROPERTIES

Thermal resistance, borehole filling, pipe properties and heat carrier fluid properties

The value of the thermal resistance given by the thermal response test only applies to that certain borehole installation, heat carrier fluid, state of flow and borehole filling.

However, by using the response test it is easy to change the different parameters and determine how each property affects the thermal resistance. Some of the properties are of less importance than others and can be neglected.

As mentioned previously the thermal resistance is affected by the way that the pipes are placed in the borehole. This property is quite difficult to determine and difficult to recreate in another borehole. It is important to further investigate the effect that the placing of the pipe in the borehole has on the thermal resistance. Maybe the placing is of no significance at all, maybe it is of great importance.

6. EQUIPMENT FOR THERMAL RESPONSE TEST

6.1 THE MOBILE EQUIPMENT FOR THERMAL RESPONSE TESTS

The basic equipment required for this type of measurement is very simple; a thermal response test requires only a normal water pump, a water heater, a tank, some temperature sensors for measuring inlet and outlet temperatures and a data logger to collect the data. To make the equipment mobile it should all be set up on a common car trailer of moderate size. The only claim that must be made upon the test site is that electricity supply is available.

The plastic pipes from the borehole are connected to the quick couplings of the pipe ends on the trailer. The pipes are filled with heat carrier fluid from the tanks and the fluid in pumped through the system via the pump. On its way, the fluid passes through the water heater which heats the fluid at constant power. As the fluid in the pipes passes the temperature sensors at the inlet and outlet pipes, the temperatures are recorded by the logger. Date, time and the two temperatures are logged at the selected time interval.,
The expansion tank allows the fluid in the pipes to expand as the temperature increases due to the heating. The pressure watch switches off the pump after a certain set time if the pressure has not yet reached a certain minimum level, and opens the pressure relief valve if the pressure reaches a maximum level.
The whole equipment is powered by the socket attached to the electrical unit.

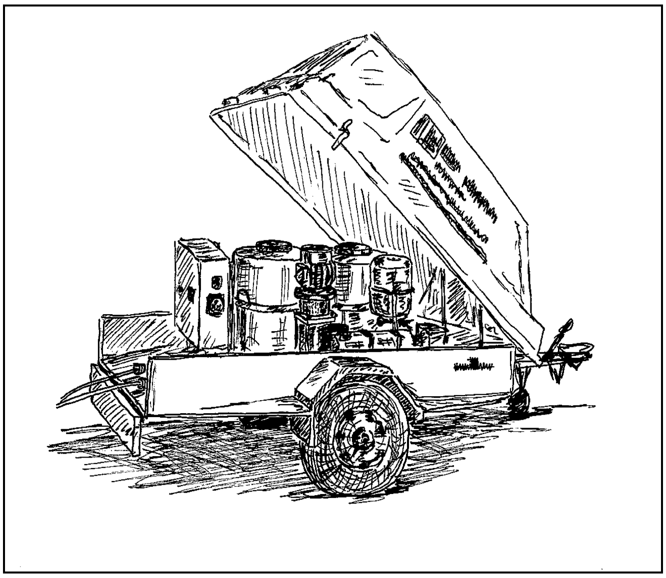


Figure 6.1 TED. The entire response test equipment is set up on a small trailer.

6.2 TED - A FIRST CONSTRUCTION

In order to make the mobile equipment for thermal response test easier to refer to, and also to give it a more personal touch, the whole construction was named TED, which does not refer to anything in particular. We will throughout this paper refer to the equipment as TED.

The equipment was designed as a project in a course in Solar Energy and Heat Storage, given by the division of Water Resources Engineering, LuTH [1]. Based on this design, the equipment was constructed by IdéArktica in Övertorneå, Sweden. In January 1996 the construction was delivered along with some insulated extension pipes of 30 meters length, in case of test boreholes being situated far from a suitable parking place for the trailer.

The covered trailer was delivered in a very delightful design. The pumping device was installed on a board on the trailer. The electrical unit was bolted to the trailer's floor. This first construction is shown in Figure 6.2 and it contained:

1. **An electrical unit**
containing timer for the heater and the pressure watch, a data logger for collecting the temperature data and a socket for 16 Ampere electricity supply.
2. **Two plastic tanks**
à 140 litres, coupled in series and used for the heat carrier fluid
3. **A pump**
(Movichrom 6 3/12 PN25 62, code 48533049, 1,5 kW, 220V/5,7A)
4. **A pressure watch**
5. **An expansion tank**
(ZILMET IPX, Type 000206, 25 litres, Maximum pressure 3.5 bar)
6. **A water heater**
of 9 kW power (VB 9003 F, 9 kW, 400V/13A)
7. **A switch for the heater power**
8. **Two temperature sensors**
9. **Two quick couplings**
for connection to the borehole pipes (LUDECKE SKG 25 and KAG 10)

6.3 Experience and Further Development of TED

Already when TED first arrived to us, one of the tank valves was leaking due to freezing during the transport. This gave us a hint of TED being quite sensitive to cold climate when not in operation, and a good action would be to fill the pipe system with glycol to prevent freezing.

When operating the device, we soon made some useful notations. The valve to the *upper* tank (Tank 2B) must be closed under operation as the fluid is otherwise pumped directly back to the tank which causes an immediate pressure drop. When having finished a test, the heat carrier fluid in the system is regained by opening the valve to the tank and allow the fluid to return to the tanks. (This is also a way to lower the pressure in the system before releasing the quick couplings…).

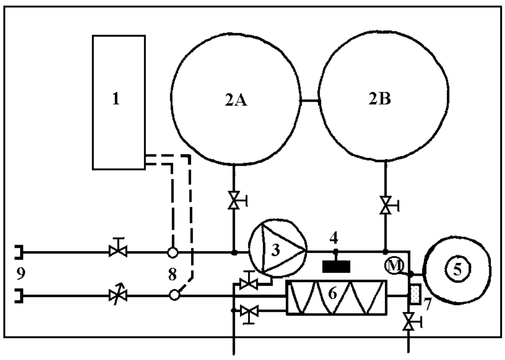


Figure 6.2 A schematic picture of TED. The measures of the trailer are 2,7 x 1,5 meters.

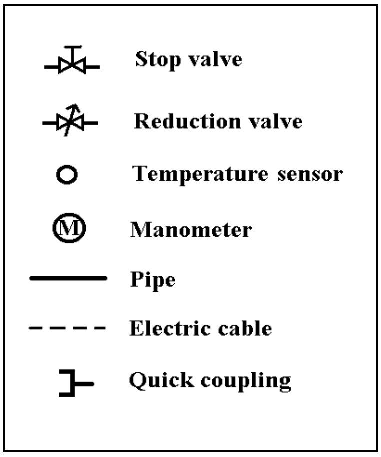


Figure 6.3 An explanation to the symbols used in Figure 6.2 and Figure 6.5.

The valve to the *lower* tank (Tank 2A) is used to regulate the pressure in the closed loop, as the fluid from the tank is being sucked into the system when the valve is open when operating the equipment.

The electrical system had to be altered so that the logger could run even when the pump was switched off. A red was installed to indicate when the logger was in running mode.
A power control was installed so the heater could be run with only half power, 4.5 kW, if necessary.

After a disastrous field test at a borehole in Lillpite, when the climate suddenly changed from moderately mild spring weather to arctic conditions with temperature below -20°C, TED got terribly frost-bitten. The equipment froze and broke down completely as the glycol mixture was not strong enough to protect it. We also discovered that the temperature sensors were out of function and had been so ever since the device was delivered. Being repaired, the pump was now running better than ever, and TED delivered our first meaningful data.

6.4 RUNNING THE MACHINE

As the groundwater level in northern Sweden the winter 1995-96 was very low, most of the boreholes drilled were groundwater wells. During our study we have therefore only had the opportunity make successful measurements with TED at three different sites. One situated outside the F-building at the University of Luleå and the two remaining at two telephone stations in Stockholm.
The technical observations described below are based on these thermal response tests. Descriptions of the boreholes and results from the measurements are given in chapter 7 ”Measurements and Results”.

The pump
We ran some tests with no heat power injection into the borehole. From the slight incline of the temperature over time, it was obvious that the pump itself contributes with a power of approximately 1 kW. These tests also indicated that the air temperature changes affect the measurements and must be taken into account in some cases (see further section 7.1.2).

Some problem occurred when filling the pipe system if the extension pipes to the borehole connection were not entirely kept in a lower level than TED. It would simplify the measurements if the pump would be of a type that could be used for suction as well as for pressure. This would also help to empty the pipes when necessary.

The logger
It is necessary to install a direct display of the current measurements to see that the logger and the sensors actually work. If e.g. over-heating etc. occurs, the test can then be cancelled. This would also be useful to supervise the operation.
A suitable measurement frequency for the logger appeared to be 15-60 minutes.

Air in the system
Considerable problems with air in the system occurred when the equipment was run with a loop that was not vertical like a borehole. Such a situation occurred for example when the borehole pipes were connected to insulated extension pipes on the ground. The bubbles could easily be observed when we started to use transparent extension pipes. The air was not easily removed from the system, and could not, as we had thought, be de-aerated from the pump. We therefore concluded that some kind of de-aeration unit must be added to the construction to make it work properly.

Pipes

The transparent extension pipes also helped to discover the suction/pressure conditions in the pipes on both sides of the pump. It appeared to be such a high friction in the total system of the 150 meters boreholes, that the mechanical resistance in the pipes caused a serious flattening of the soft extension pipe on the suction side and a bulking situation on the pressure side of the pump. This effect could be mastered by reducing the power of the pump, but as no power control was available, we had to reduce the flow by partly choking the valve on the suction side. We also tried to reduce the power of the pump by running it backwards, which reduced its capacity to 60 %.

On regard of the suction/pressure problem, this worked out very well, but unfortunately running the pump backwards causes the protective motor switch to release.

The pressure relief

During our initial test-runs at the university, we used water as a heat carrier fluid as a safety detail in case of leakage or splashing, an action which we often came to feel grateful for.

In the Stockholm measurements, the heat carrier fluid was glycol and ”brineol. Then we first observed that the outlet from the pressure relief was not ideally placed- on the side of the trailer - letting the brine out in the surroundings. We first considered it mainly a pollution problem, but when TED was placed right beside a rather busy foot-path, we suddenly got these frightening visions of the pressure relief releasing and spitting out warm brine over the unfortunate pedestrians. As an action against this, the outlet from the pressure relief should be led back to the tank, where any excess brine belongs.

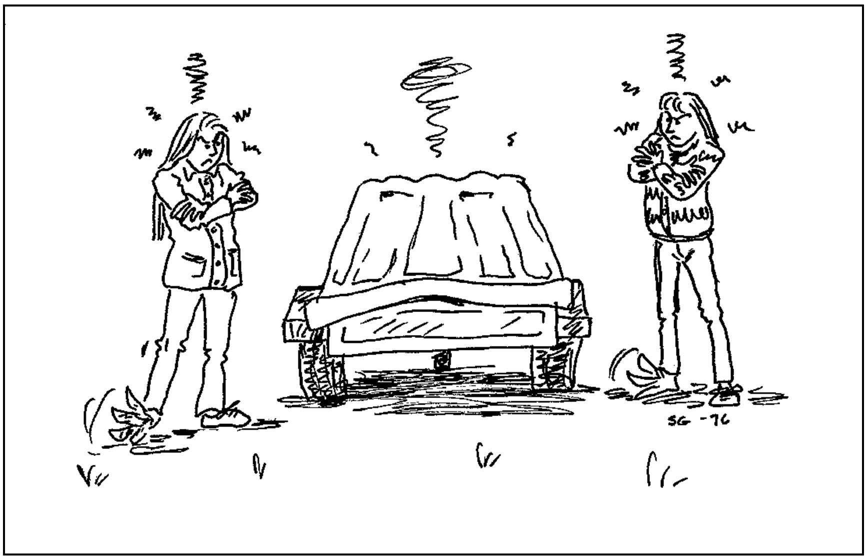


Figure 6.4 Teenager TED and his two mothers did not always agree on things….

6.5 MATURED TED

TED has proved to be a machine worth developing. For the future we therefore suggest a couple of improvements. This new design will not only simplify the measurements and evaluations, but will also help to track and remedy possible faults and problems during the measurements.

The developed design is shown in Figure 6.5 and is suggested to contain:

1. **An electrical unit**
containing:
    - timer for the heater and the pressure watch
    - logger for collecting the temperature data, air temperature, hydraulic pressure, flow in pipes
    - socket for 16 Ampere electricity supply.
2. **Display showing the current data**
3. **Plastic tank for the heat carrier fluid** with pressure valve on lid
4. **A pump**
with power control and which can be used both as a suction pump and as a pressure pump
5. **A pressure watch**
6. **An expansion tank**
7. **A water heater**
of about 9 kW maximum power
8. **A switch for the heater power**
so the heater can be run on full or half power
9. **Two temperature sensors**
10. **Two manometers**
transferring pressure data to logger
11. **Two quick couplings**
for connection to the borehole pipes with a chute for excess fluid when pipes are disconnected
12. **De-aeration pipe**
13. **Pipe and valve for draining the tank**

Note also that we suggest a stop valve as well as reduction valve for *both* inlet and outlet pipes, and that the outlet from the pressure relief is connected to the tank for reasons of minimising the emission of the fluid.

Of course the placement of the units may be rearranged.

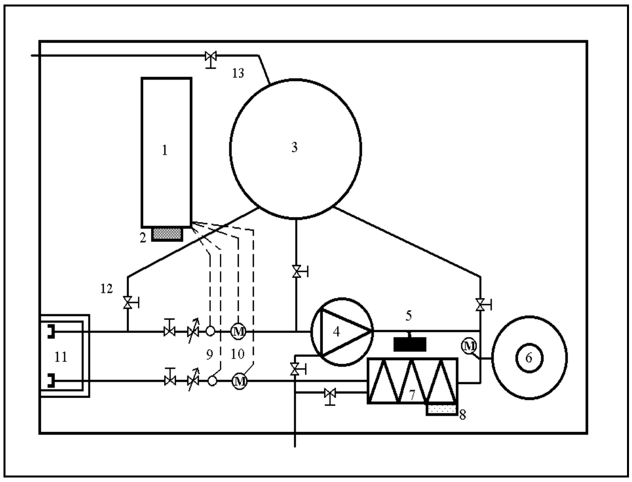


Figure 6.5 A schematic view of a suggested second generation TED.(c.f. Figure 6.2).

6.6 QUALITIES OF SECOND GENERATION TED

The function of the second generation TED would be:

Pipes
As before the plastic pipes from the borehole are connected to the quick couplings of the pipe ends on the trailer.

A plastic chute under the couplings collects any excess fluid from disconnected pipes, so it can be drained off to a bucket or similar. Stop valves are also available for both pipes when direct closing of the pipes are needed e.g. for disconnecting the quick couplings. The reduction valves on each pipe is used to change the pressure in the system.

The Tank
The system is filled with heat carrier fluid from the only tank and the fluid is pumped through the system via the pump which can work both as a suction pump and a pressure pump.
Only one tank is required, because the borehole system in general is already filled with fluid when the measurements will be made. This gives also more space for extension pipes and electric cable which must be transported along with the trailer.
In case of TED being used for geothermal survey or at boreholes that are not yet filled with heat carrier fluid, it might still be useful with a larger tank volume, preferably by two tanks connected in series as on the original TED. In that case a stop valve should be installed between the two tanks so that only one tank could be used if required, as in most cases.
The tank is drained from a valve *under* the tank so that the it can be entirely emptied.
A grading on the tank indicates the contained volume so that the right volume of brine can be added directly in the tank.
The tank lid has the same diameter as the tank itself in order to simplify the cleaning of the tank after a test. The lid has a valve to control the pressure inside the tank when the fluid volume in the tank changes.

The Heater
The fluid passes through the water heater and is heated with a constant power of either 4.5 kW or 9 kW. The power is regulated by two power switches that each give half power.

De-aeration
Before the test has started and the power has been switched on it is possible to get rid of air bubbles in the system by pumping the fluid through the tank via the de-aeration pipe (No12 in Figure 6.5).

Figure 6.6 When releasing the quick couplings, make sure they are held downwards….

Inspection holes
Transparent inspection holes are installed on the inlet and outlet pipes so that occurring gas bubbles can be observed.

Measurements
The temperature sensors at the inlet and outlet pipes, collect temperature data for the logger. The logger records date, time and the two temperatures at an interval of 1-120 minutes. A manometer on each pipe collects pressure data to determine the pressure drop in the borehole.
The atmosphere temperature is also recorded so that any effect from daily temperature changes can be seen and taken into account. A flow meter is connected to one or both reduction valves and data is sent to the logger.

A display on the electrical unit shows the current data, indicating that the logger and sensors work properly. Any malfunction can also be noticed in that way.
Inside the electrical unit the logger is held by a snap latch so that it could easily be removed or replaced. The connection between the logger and the computer is easily accessible.

The Pump

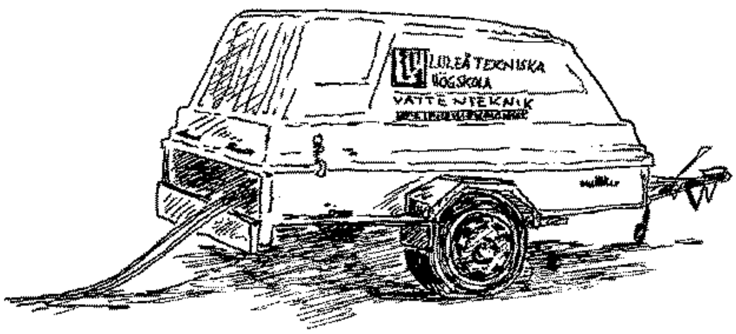
The pump has now a power control for pressure adjustment. This adjustment can also be done by the reduction valves on each pipe.

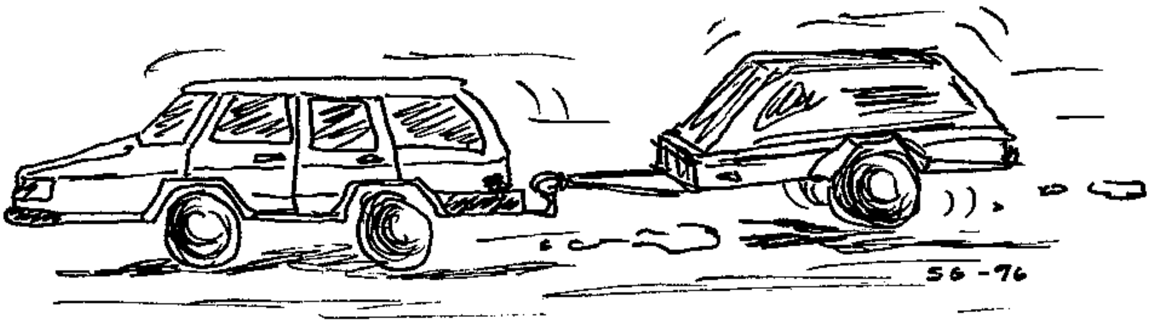
Pressure Relief

The expansion tank allows the fluid in the pipes to expand as the temperature increases due to the heating. The pressure watch switches off the pump after a certain set time if the pressure has not yet reached a certain minimum level, and opens the pressure relief valve if the pressure reaches maximum level. The fluid from the pressure relief is led back to the tank in order to minimise pollution.

Maintenance

To make maintenance of the equipment easier, a possibility would be to set the equipment up on a board on a roller rail. In that way, the equipment could be rolled backwards and forwards and so make hidden points available.




SG-76

TED


LULEÅ TEKNISKA
HÖGSKOLA
VATTENTEKNIK
TERMISK RESPONSTEST


EUROPETRA
ADF 301


EUROBATEX

7. MEASUREMENTS AND RESULTS

The groundwater situation in northern Sweden was very bad during 1995-96. Many groundwater wells dried up, leaving households without water. Under these circumstances, the drilling companies were caused to give priority to groundwater wells instead of thermal wells. Thus the supply of test holes for TED was scarce. The measurements done for this thesis work are therefore based on three different test holes. The first borehole was located within the University area, and the two others in Stockholm at two borehole systems used for cooling of telephone stations.

The time criteria

When making our calculations we used the equations and methods shown in chapter 4 and 5. In these an approximation is made and a time criteria is introduced. It was told that eq 4.18 is used with an error of maximum 2% if $t>5r_0^2/a$.

It is not difficult to understand that eq 4.18 becomes more accurate the larger *t* is (see Figure 4.3). When making a thermal response test, however, time is money and it is impossible to wait too long for the test. The question is how much money it is worth to get a more accurate result.

We decided to use to different time criterias when making our calculations. The one mentioned in the theory chapter, $t>5r_0^2/a$, was reached pretty fast and we were interested in how the results would look if we ran the test longer before using the achieved data in our calculations.

F-building, Luleå Univ. of Technology
U-pipe, PEM
$L_p = 35$ m
$H = 31$ m
$r_0 = 0.038$ m
$r_w = 2.2$ m
$T_{sur} = 13^oC$

Table 7.1 Parameters of borehole at F-building

In the following chapters the time criterias will be called t_{b1} and t_{b2} and they are defined as:

$$t_{b1} = \frac{5r_0^{\ 2}}{a}$$

$$t_{b2} = \frac{50r_0^{\ 2}}{a}$$

The maximum error should be about 2% for t_{b1} and considerably smaller for t_{b2}.

7.1 THE F-BUILDING

Our very first measurements were performed at the borehole outside the F-building at Luleå University of Technology. The borehole was drilled 20 years ago as a test for a new bore for some research project. Its properties have not been documented. Several measurements were done at the borehole, but only the most interesting tests are presented here.

Since the borehole is located close to the university building (Entrance F10) it is therefore most likely affected by heat leakage and water drainage etc. from the building. The radius and depths were measured and we had a suitable plastic loop constructed for it. The data of the borehole at the F-building are shown in Table 7.1.

7.1.1 DETERMINING THE THERMAL CONDUCTIVITY

A response test for determining the thermal conductivity and thermal resistance of the installation was performed on April 25th, 1996. Water was used as heat carrier fluid and as the borehole depth is only 31 m, ”half” heat power (4.5 kW) was used during the test. The temperature limit for PEM pipes is about 50°C, and therefore the test had to be ended already after 23 hours. This short test time proved to be sufficient for such a short borehole.

Figure 7.1 shows the inlet and outlet temperatures of the borehole. During the first part of the measurement (to the left of t_o), no power was injected into the borehole. This was done in order to determine the temperature of the undisturbed ground surrounding the borehole. T_{sur} was estimated to 13 °C.

At the time t_o, 4.5 kW power is switched on and the temperature of the fluid increases rapidly. The two break times are calculated, t_{b1}=1 h 15 min and t_{b2} = 12 h 30 min. The linearized function of T_f (Figure 7.2) also shows the two different break times.

As shown in chapter 5, the linearized function of T_f is used as an approximation of eq 4.18, or $T_f = k\ln(t)+m$

where $k = \frac{Q}{4\pi\lambda H} \cdot \ln(t)$

Thus λ is given by $\frac{Q}{4\pi H k}$. The inclination of the function for t_{b1} is shown in Figure 7.3 and for t_{b2} in Figure 7.4. Using the parameters given in Table 7.1, the λ for t_{b1} is determined as 3.9 W/m,K and for t_{b2} as 3.7 W/m,K. The values of the thermal conductivity are relatively high for a granite (standard value for this type of granite is 3.4-3.6 W/m,K). Since the value of the thermal conductivity determined by a response test is regarded as the *effective* thermal conductivity, it is likely that the high values indicate the occurrence of groundwater flow affecting the borehole (see section 5.3.1).

7.1.2 DETERMINING THE THERMAL RESISTANCE

Now let us take a look at the thermal resistance of the borehole, that the response test will give us. eq 4.18 is now used for determining R_b. Using the values from Table 7.1 and inserting the thermal conductivity from above, the thermal resistance will show as a function of time as seen in Figure 7.5 and Figure 7.6. For t_{b1} the thermal resistance of the borehole is determined as 0.06 K/(W/m) and for t_{b2} as 0.08 K/(W/m). As shown in the figures, the resistance appears to be kept rather constant over time. The values of R_b are fairly good, as a standard value for the thermal resistance in a borehole system is normally set to 0.1 K/(W/m). This may also indicate the presence of groundwater flow.

	k	λ [W/m,K]	R_b [K/(W/m)]
t_{b1} 1 h 15 min	3,62	3,9	0,06
t_{b2} 12 h 30 min	3,85	3,7	0,08

Table 7.2 Summary of results from F-building

The Effect of Air Temperature

In another test at the F-building borehole, TED was run without power injection, just circulating the water in the borehole. The idea was originally to determine the power contribution from the pump itself (approximately 1 kW), but when drawing the graph we could also see a clear periodic variation of the temperatures over the days. (Figure 7.7 and Figure 7.8). By the time of the measurements, the difference between day and night temperature in the atmosphere was about 10-15 centigrade, and the pipes from the borehole were connected to TED by un-insulated pipes of about 4 m length in free air. That is about 15% of the total pipe length, as the depth of the borehole was 31 m.

The inlet and outlet temperatures are following each other with a temperature difference of about 0.7°C, but do also show a recurrent dip at 2 AM and a peak at 3 PM. These correspond very well with known facts about meteorological variations over the day [9]. Thus we conclude that if the variation of the atmosphere temperature is great, or if the temperature difference between atmosphere and fluid is great, the measurements may be affected. In winter time this may be a problem.

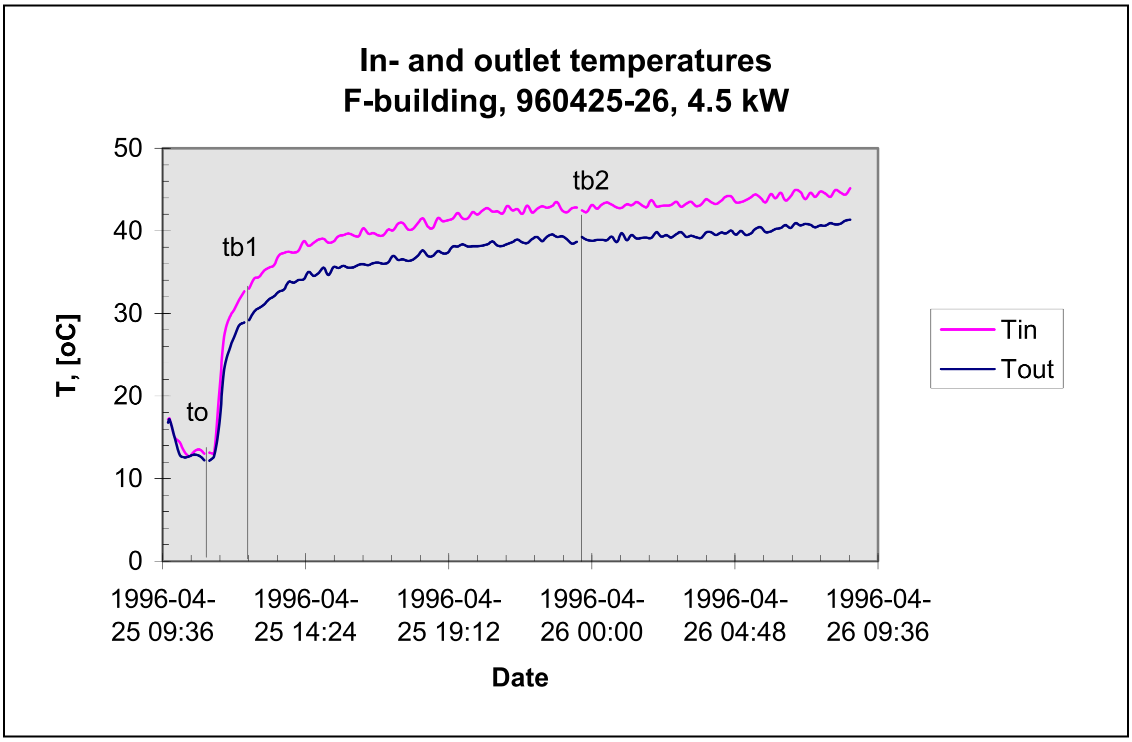


Figure 7.1 Inlet and outlet temperatures. The power (9 kW) is switched on at 't_o'. During the initial stage, the temperatures increase drastically, but already after a few hours, the increase of temperature is more moderate.

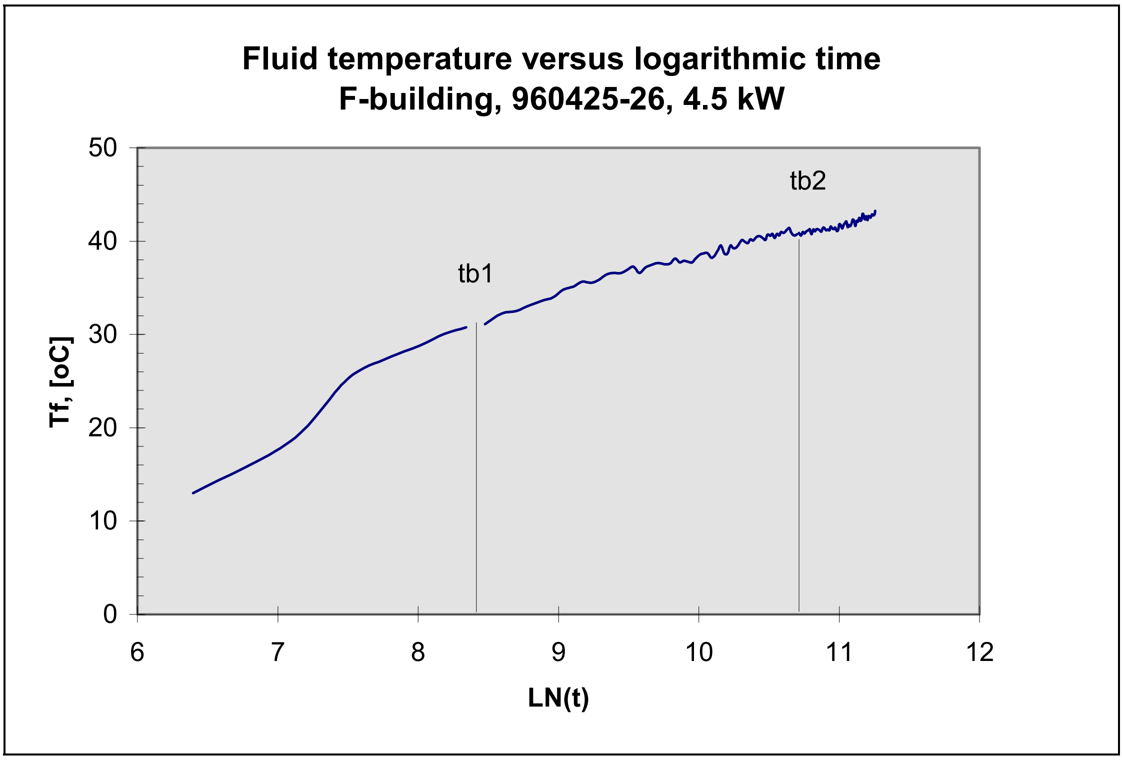


Figure 7.2 The linearized function of the mean fluid temperature (T_f) with the two break times, t_{b1} and t_{b2}, marked out. The function is a good approximation of a straight line, but the incline of the line depends on the break time chosen.

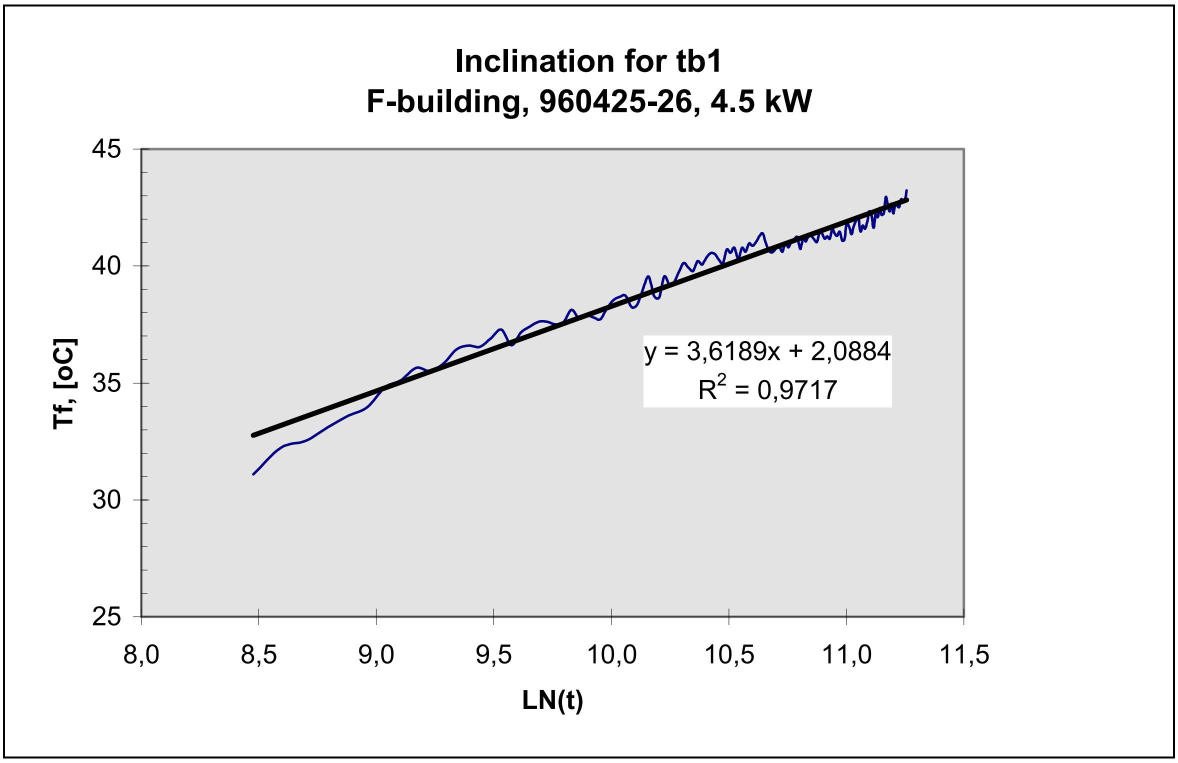


Figure 7.3 The inclination for the linearized function of T_f after t_{b1} (1 h 15 min) is determined to k = 3.62. Using the parameters from Table 7.1, the thermal conductivity is calculated to λ = 3.9 W/m,K.

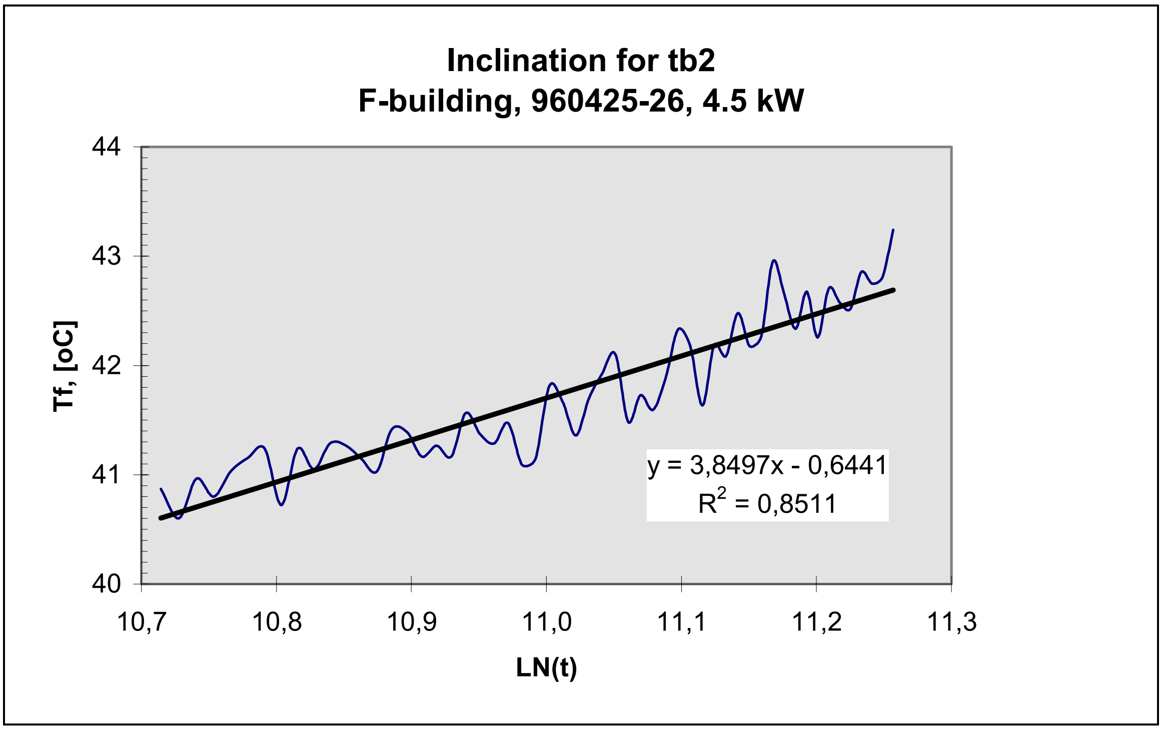


Figure 7.4 The inclination for the linearized function of T_f after t_{b1}(12 h 30 min) is determined to k = 3.85. Using the parameters from Table 7.1, the thermal conductivity is calculated to λ = 3.7 W/m,K.

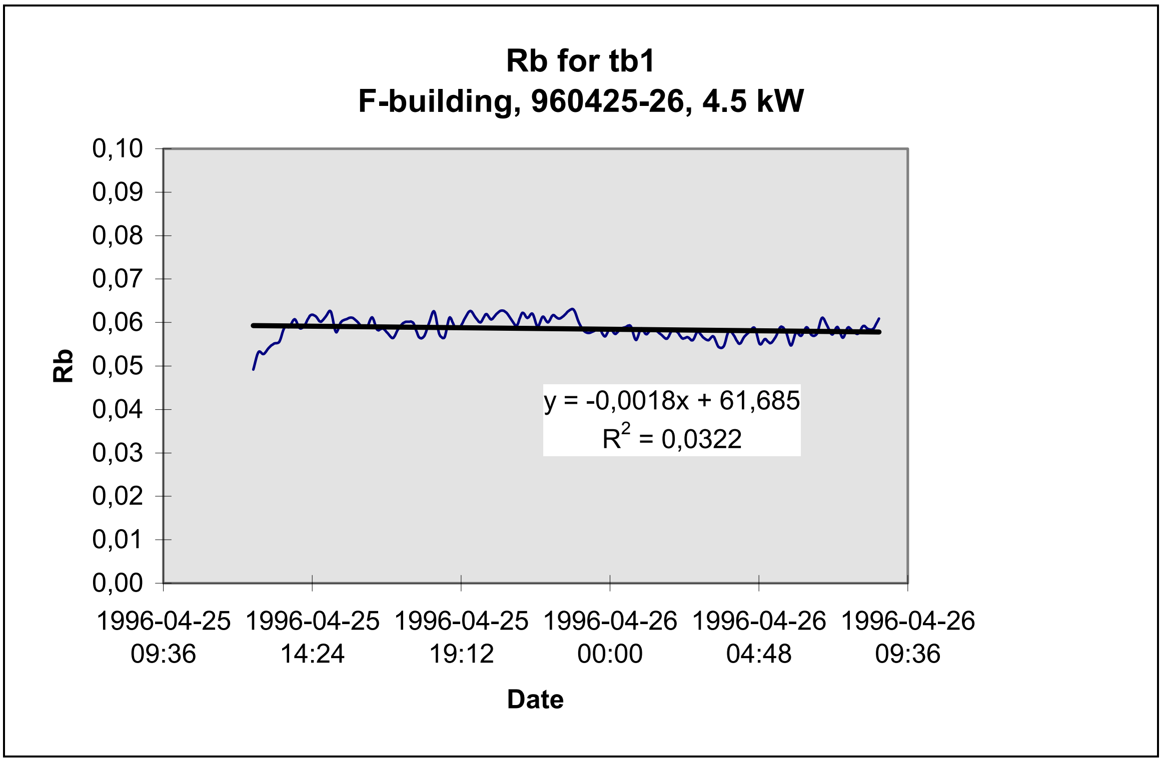


Figure 7.5 The thermal resistance, R_b, is rather constant over time as can be seen in this figure. The value determined from the thermal conductivity for t_{b1} is R_b = 0.06 K/(W/m).

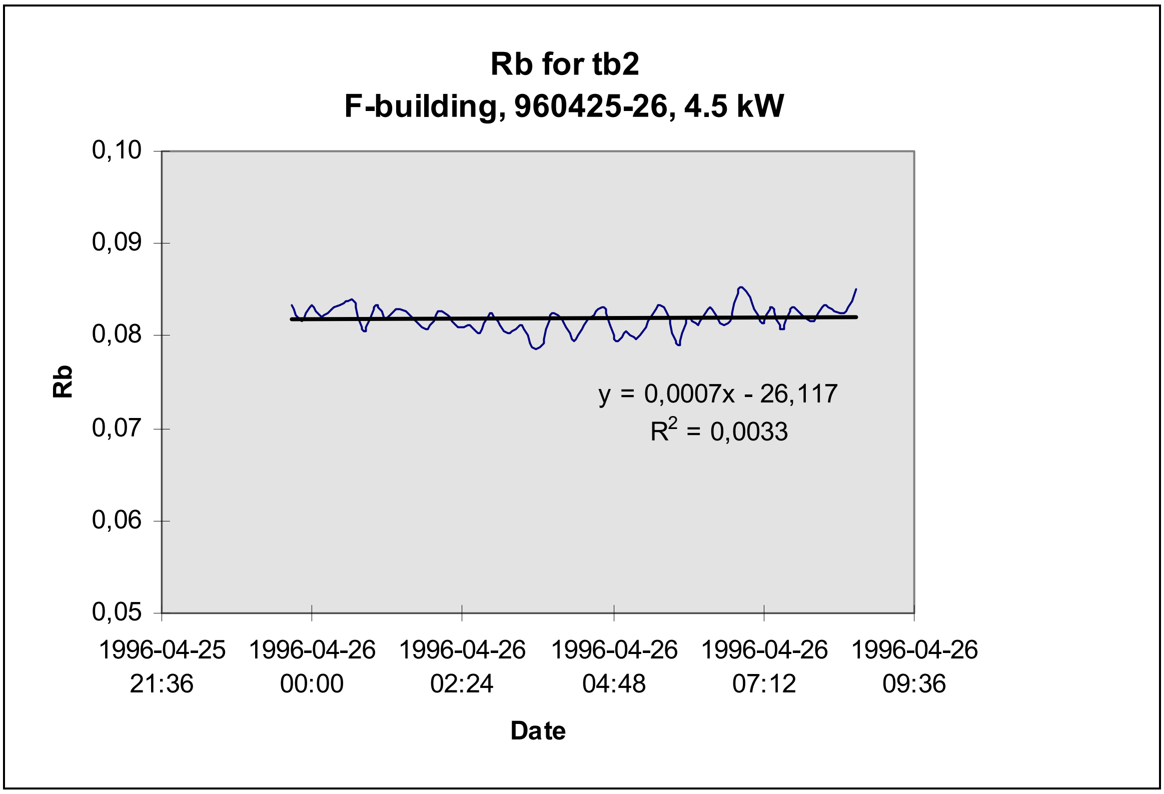


Figure 7.6 The thermal resistance, R_b, is rather constant over time as can be seen in this figure. The value determined from the thermal conductivity for t_{b2} is R_b = 0.08 K/(W/m).

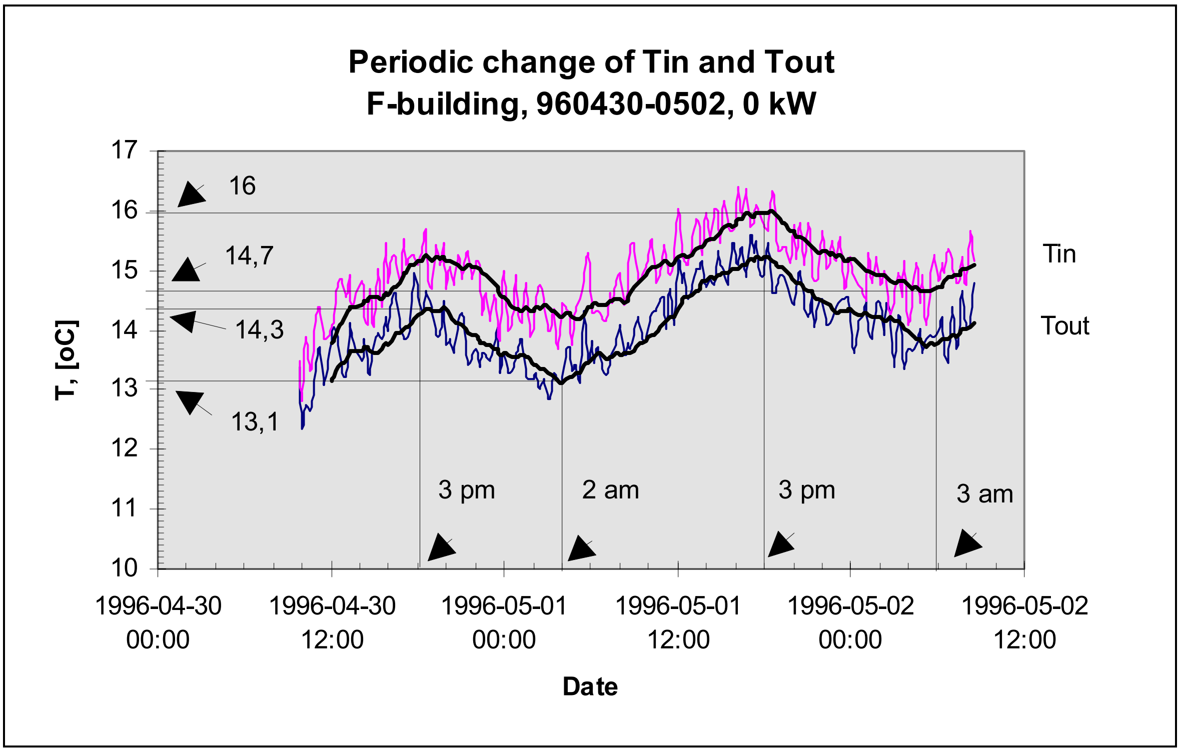


Figure 7.7 The temperature difference between the inlet and outlet is rather constant over time (about 0.8 ^{o}C). The difference is proportional to the power contribution from the pump itself, as no power from the heater is added in the test.

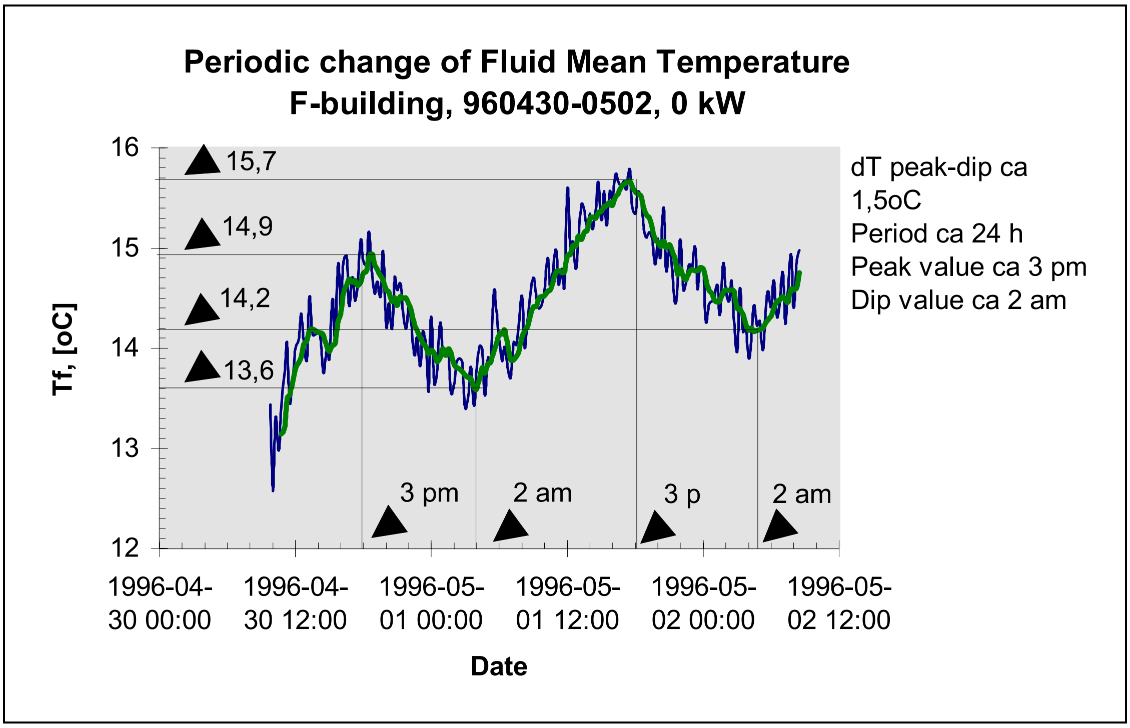


Figure 7.8 The mean temperature shows a periodic change over time. The period is very even with dips at 2 am and peak values at 3 pm, and is similar to well known periodic changes of the atmosphere temperature. This indicates that the air temperature affects the measurements.

7.2 A REQUEST FROM TELIA

In May we got a request from TELIA, the Swedish telephone company, if we could perform response tests at two locations in Stockholm. TELIA have recently built two borehole systems for cooling telephone stations at Drevikstrand and Ängby, Stockholm. The systems have been in operation since February 1995, and have been working very well. In fact better than the computer presimulations predicted. Now TELIA asked us to make a response test with TED at the two locations, to get an explanation to the deviation.

The response tests at Drevikstrand and Ängby would give us a perfect opportunity to control the accuracy of TED's results. The mission was to determine the capacity of the cooling systems with a response test and then compare the results with the actual operating capacity and the results from the computer simulations.

The two boreholes that we used in our tests had both been used for cooling, but at the time of the measurements they had been out of operation for quite a long time. This made it possible for us to consider the bedrock surrounding the borehole as thermally undisturbed.

7.2.1 DREVIKSTRAND

The telephone station Drevikstrand is located in Skogås, Stockholm. Four boreholes of about 160 m depth and 5 m spacing are placed in a line and connected to the machine room by horizontal pipes in the ground at about 0.5 m depth (Figure 7.9). The heat carrier fluid used is 38% glycol and the system is operated to cool the heat carrier fluid from 22°C (inlet) to 16°C (outlet). The data of the test hole (borehole 1) are shown in Table 7.3.

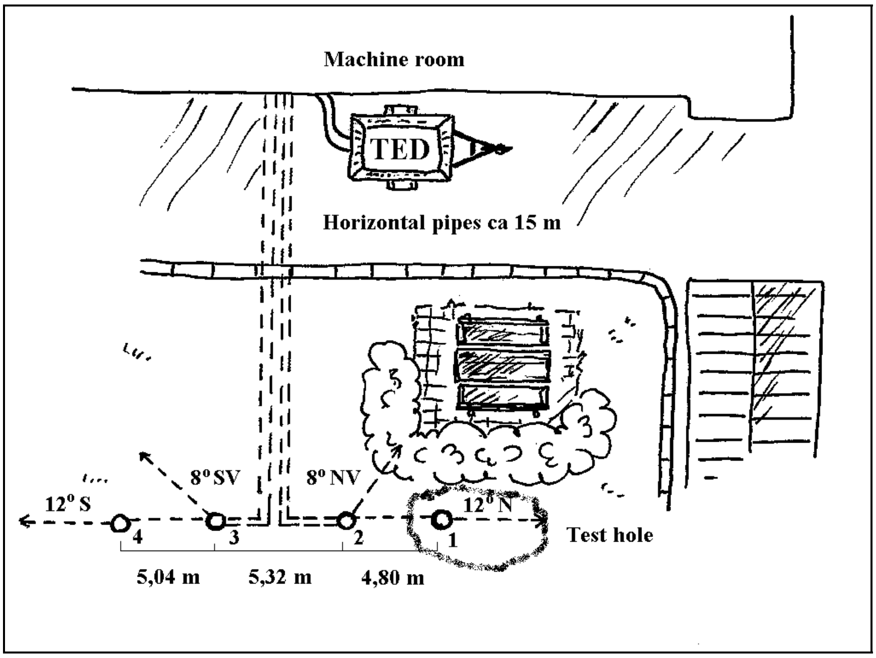


Figure 7.9 The boreholes in Drevikstrand, Stockholm. The 4 boreholes are placed in a line with about 5 m spacing in average. The test hole is borehole 1. Dotted lines show the horizontal connection pipes from the boreholes to the machine room.

Drevikstrand
U-pipe, PEM
H = 163 m
R_b = 0.0653 m
$C_r = 0.194*10^7$ J/m^3,K
λ^* = 3.4 W/m,K
$T_{sur} = 9.2^oC$

Table 7.3 Parameters for test hole at Drevikstrand.

7.2.1.1 DETERMINING THE THERMAL CONDUCTIVITY

The Drevikstrand measurements were performed during one week. After four days the power injection of 9 kW was decreased to 4.5 kW. The idea was to investigate the effect of natural convection, due to the temperature gradient between fluid and borehole wall. If 9 kW gives a lower R_b than 4.5 kW, the improved heat transfer is caused by a density dependent convective heat transfer in the borehole. This part of the test has not yet been evaluated and will not be discussed further in this paper. The effect of such a decrease of power during the measurements is seen in Figure 7.12. The last three days of the measurements at Drevikstrand (after the heat power decrease) has been removed in the rest of the figures shown in this paper.

Figure 7.13 shows the linearized function of T_f with the two break times t_{b1} for $t>5r^2/a$ (3 h 20 min) and t_{b2} for $t>50r^2/a$ (33 h 45 min) marked out. Unfortunately an adjustment of the temperature sensors had to be done during the test period, as the temperature sensors used for the test were not our original sensors, and did not fit perfectly at the measuring point. The time for the adjustment is in Figure 7.13 seen as a discontinuity of the

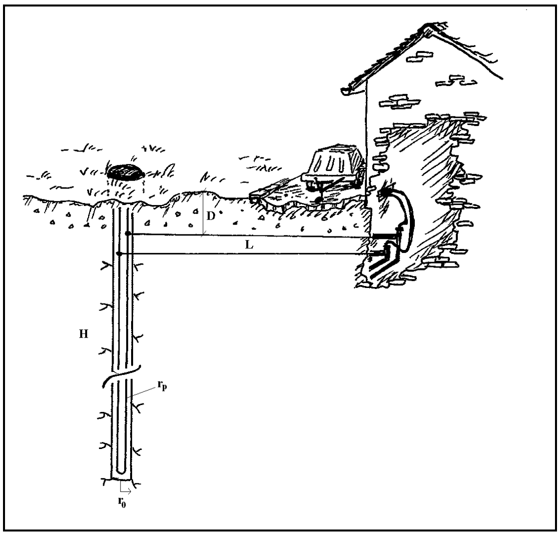


Figure 7.10 TED was connected to the borehole via the machine room. Extension pipes were led to the machine room through a ventilator grill in the wall of the telephone station.

curve. Figure 7.11 shows the inclination of the linearization, based on the two break times, respectively. For t_{b1} the inclination was determined to 1.35 which gives the thermal conductivity λ = 3.61 W/m,K, and for t_{b2} the inclination is 1.09, giving λ = 4.48 W/m,K. The difference between the two values is partly explained by the unfortunate adjustment of the temperature sensors. Also the last value is high for a granitic rock, which may indicate a rather large contribution from groundwater flow (see section 5.3.1). The assumption of a large groundwater flow is supported by the fact that the telephone station is located at the foot of a hill with crackled rock which is likely to transport groundwater.

7.2.1.2 DETERMINING THE THERMAL RESISTANCE

The thermal resistance determined from the estimated values of the thermal conductivity is shown in Figure 7.14. Using the values from Table 7.3, the thermal resistance of the borehole was found to be for t_{b1}, R_b = 0.07 K/(W/m), and R_b = 0.09 K/(W/m) for t_{b2}.

7.2.1.3 COOLING CAPACITY OF DREVIKSTRAND

Using these values of R_b and λ, it is possible to estimate the maximum mean capacity that is obtained during continuous operation of the system. Given that the mean value of the heat carrier fluid must not exceed T_f = (22+16)/2 = 19°C, the capacity for stationary conditions of the measured borehole is 4.3 kW (27 W/m) for the values of t_{b1} and 4.9 kW (30 W/m) for the values of t_{b2}. Stationary conditions will for this type of system be reached in about 30 years. The values from TED show that the mean capacity of the system after one year of continual operation will be 30 W/m. In April -96 the cooling system had been in operation periodically for about one year. The mean capacity obtained from the system was 40 W/m, and the simulations predicted about 25 W/m.

	k	λ [W/m,K]	R_b [K/(W/m)]
t_{b1} 3 h 20 min	1,35	3,61	0,07
t_{b2} 33 h 45 min	1,09	4,48	0,09

Table 7.4 Summary of results from Drevikstrand

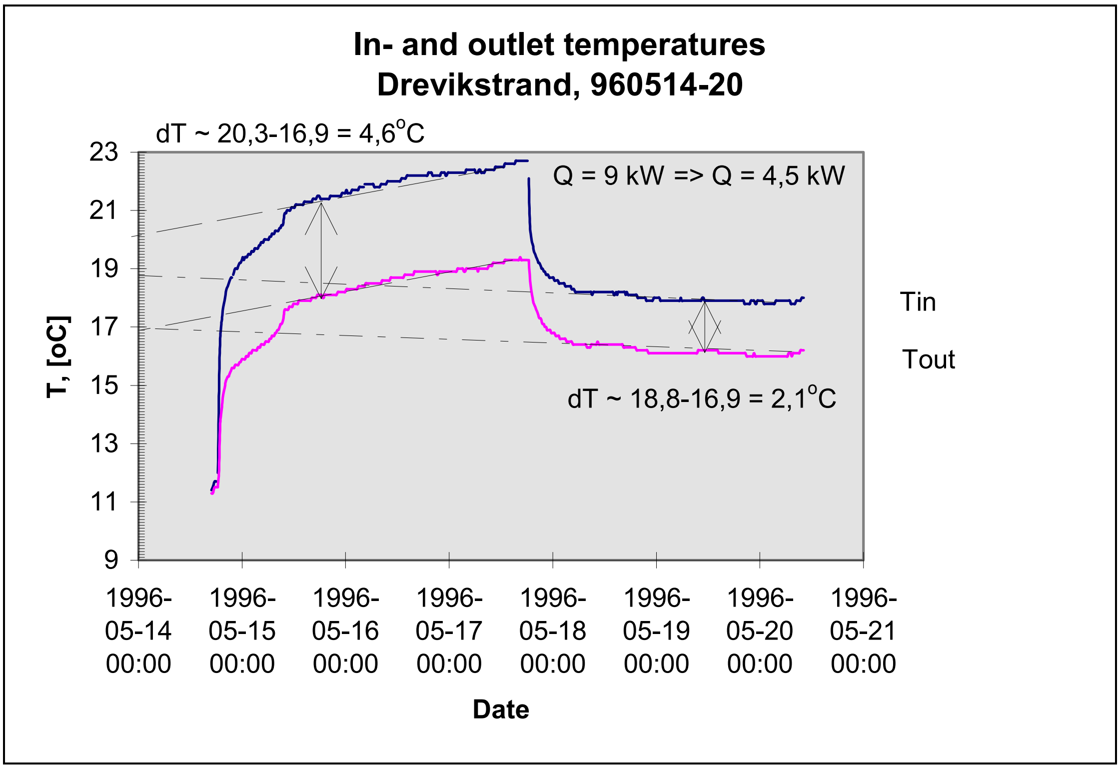


Figure 7.12 Inlet and outlet temperatures. The power (9 kW) is switched on at 't_o'. In the initial stage, the temperatures increase drastically, but already after a few hours, the increase of temperature is more moderate. After four days the power injection is decreased to 4.5 kW in order to control the effect of natural convection. This part of the test is not further discussed here.

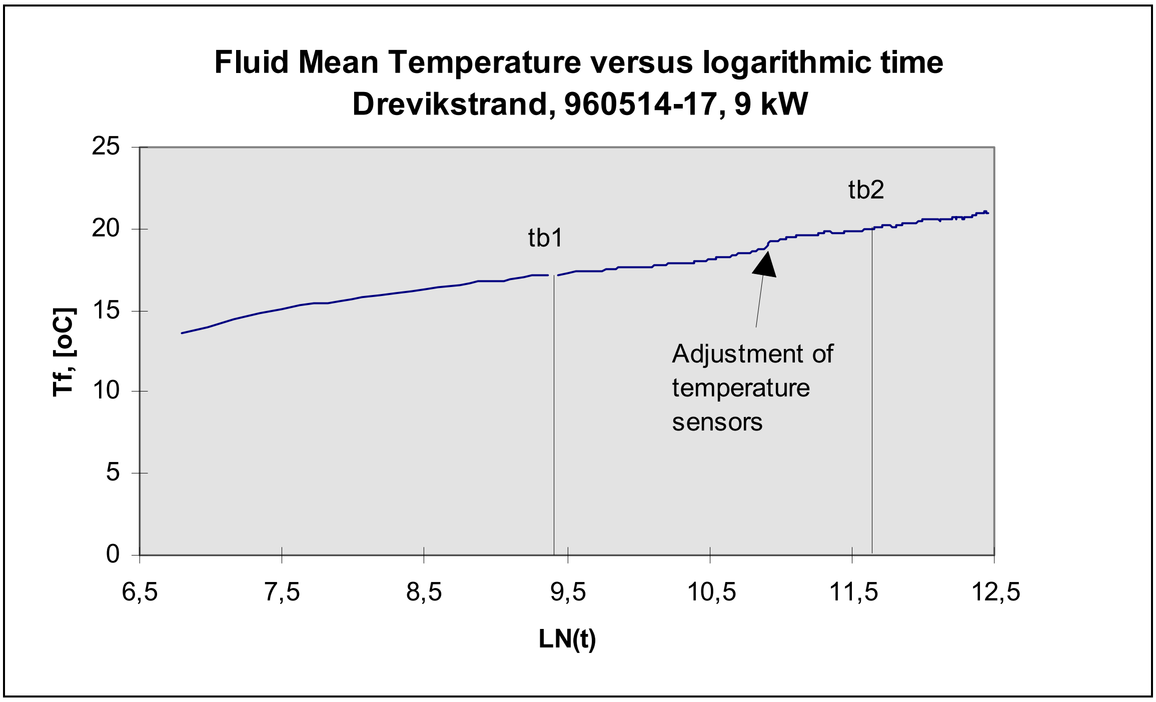


Figure 7.11 The linearized function of the mean fluid temperature (T_f) with the two break times, t_{b1} and t_{b2}, marked out. The function is a good approximation of a straight line, but the incline of the line depends on the break time chosen. An adjustment of the temperature sensors is seen in the figure as a discontinuity of the function.

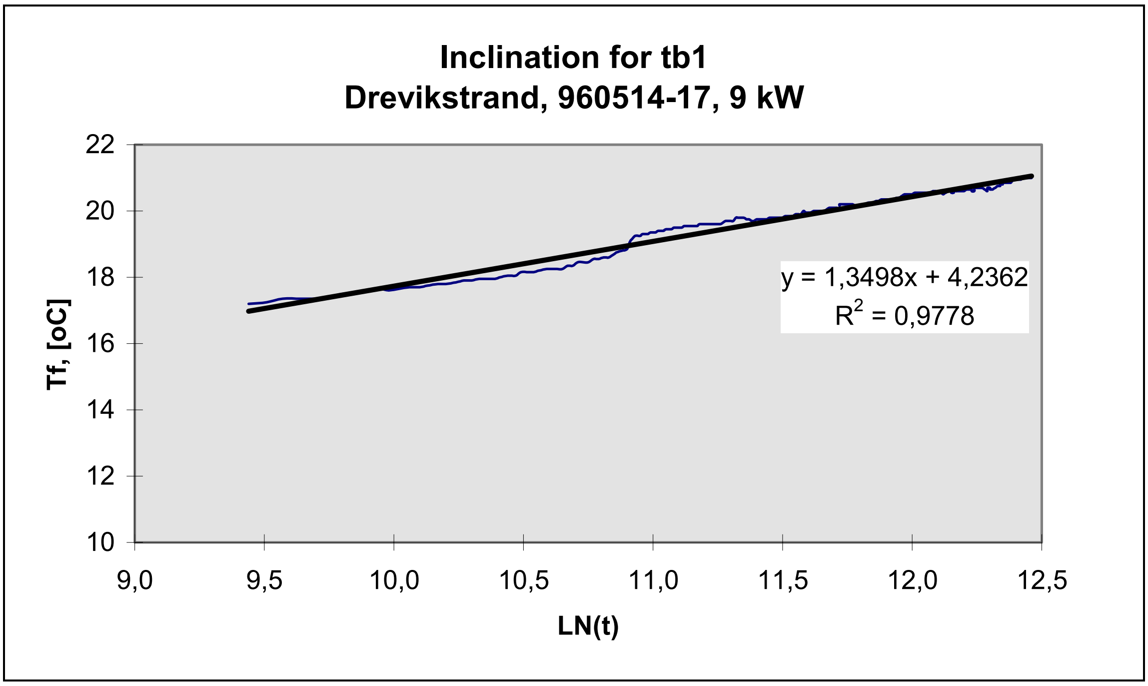


Figure 7.13 The inclination for the linearized function of T_f after t_{b1}(3 h 20 min) is determined to k = 1.35. Using the parameters from Table 7.3, the thermal conductivity is calculated to λ = 3.61 W/m,K.

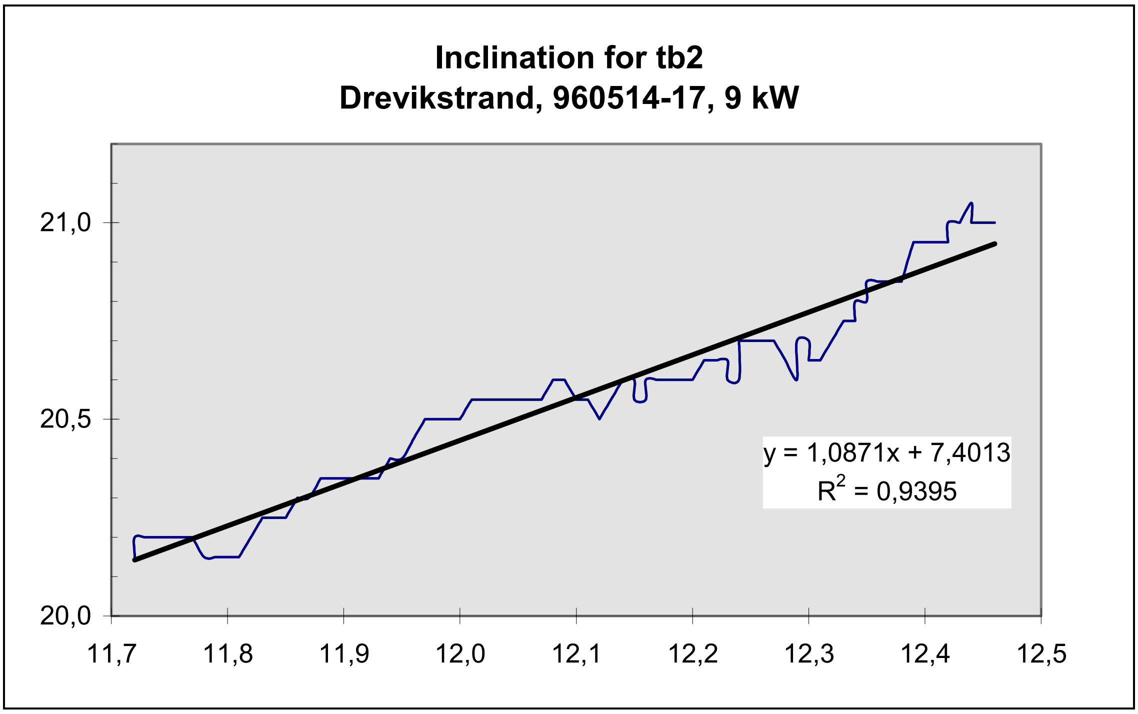


Figure 7.14 The inclination for the linearized function of T_f after t_{b2} (33 h 45 min) is determined to k = 1.09. Using the parameters from Table 7.3, the thermal conductivity is calculated to λ = 4.48 W/m,K.

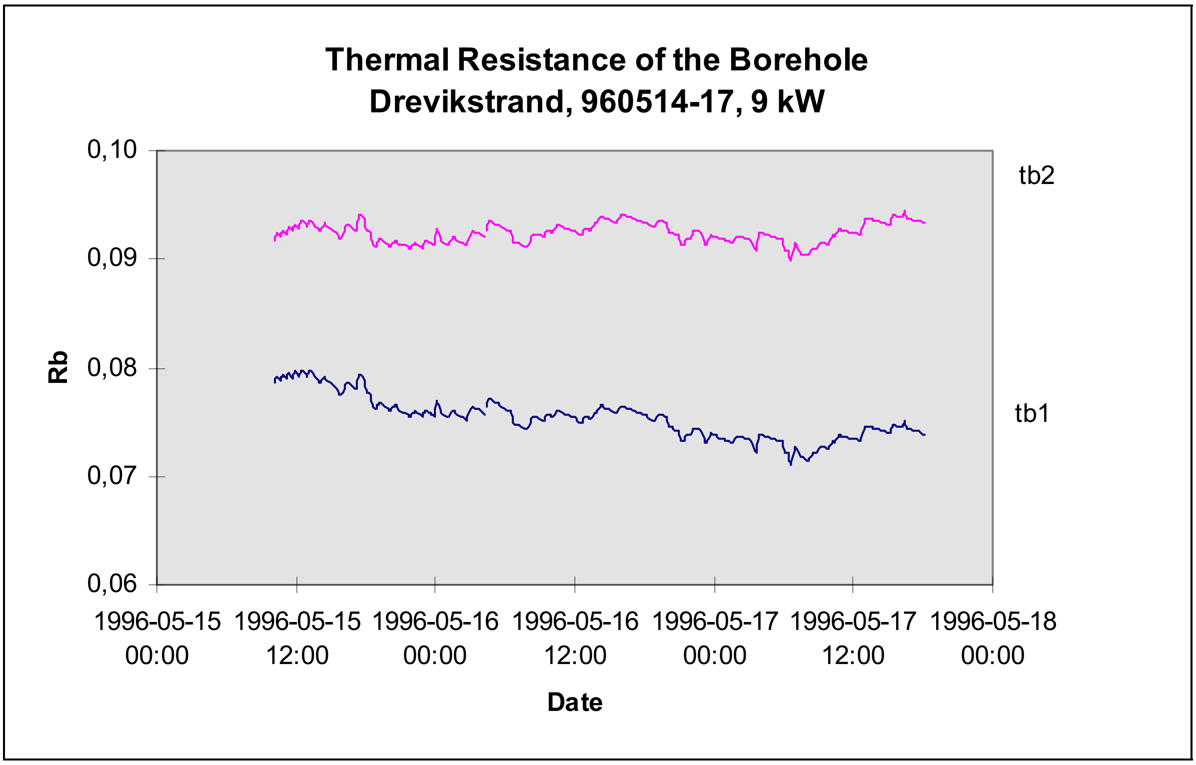


Figure 7.15 The thermal resistance, R_b, is rather constant over time as is seen in this figure. The value determined from the thermal conductivity for t_{b1} is R_b = 0.07 K/(W/m) and t_{b2} gives R_b = 0.09 K/(W/m .

7.2.2 ÄNGBY

The telephone station Ängby is located in Bromma, Stockholm. Thirteen boreholes of about 130-160 m depth, placed in an irregular pattern are connected to the machine room by horizontal pipes in the ground at 0.6-0.8 m depth (Figure 7.16) Today only 6 boreholes are in use, as the capacity of the total system of 13 boreholes proved to exceed the needs. The heat carrier fluid used is 38% brineol and the system is operated to keep a T_f of maximum 17°C. The data of the testhole (borehole 3) are shown in Table 7.5.

7.2.2.1 DETERMINING THE THERMAL CONDUCTIVITY

Measurements were done at Ängby during 4 days with 9 kW power injected. Figure 7.20 shows the linearized function of T_f with the two break times t_{b1} for $t>5r^2/a$ (2 h 25 min) and t_{b2} for $t>50r^2/a$ (24 h 15 min) marked out. Unfortunately an adjustment of the temperature sensors had to be done at this test as well.

The time for the adjustment is in Figure 7.19 seen as a discontinuity of the function.

In Figure 7.21 and Figure 7.22 the inclination of the linearization, based on the respective break times, is seen. For t_{b1} the inclination is determined to 1.52 which gives the thermal conductivity λ = 3.77 W/m,K, and for t_{b2} the inclination is 1.23, giving λ = 4.65 W/m,K. The difference between the two values is partly explained by the unfortunate adjustment of the temp sensors. The values are probably too high, as the effect of the horizontal pipes connecting the borehole with the machine room has not been taken into account, and would decrease the conductivity.

Ängby
U-pipe, PEM
H = 139 m
R_b = 0.05525 m
C_r = 0.194*10^7 J/m^3,K
λ^* = 3.4 W/m,K
T_{sur} = 12°C

Table 7.5 Parameters for testhole at Ängby.

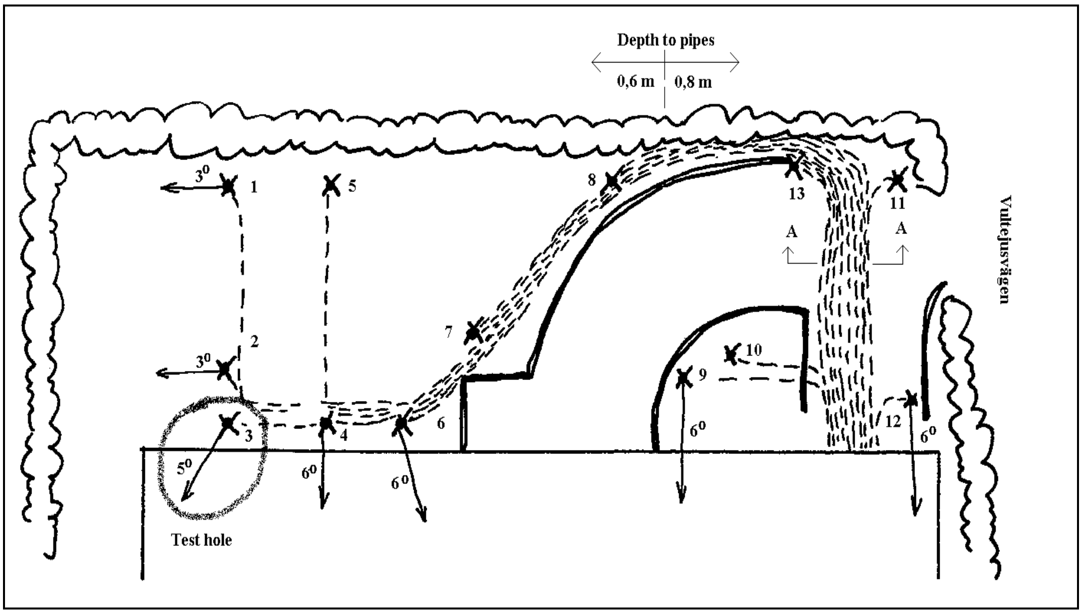


Figure 7.16 The borehole site at the telephone station at Ängby, Stockholm. The 13 boreholes are spread over the area outside the building in an irregular pattern. Only 6 of the boreholes (borehole 1, 4, 8, 9, 11 and 12) are in use. The test hole is borehole 3. Dotted lines show the horizontal connection pipes to the machine room in the lower right

7.2.2.2 DETERMINING THE THERMAL RESISTANCE

The thermal resistance determined from the estimated values of the thermal conductivity is shown in Figure 7.23. Using the values from Table 7.5, the thermal resistance of the was found to be for t_{b1}, R_b = 0.04 K/(W/m), and R_b = 0.05 K/(W/m) for t_{b2}.

	k	λ [W/m,K]	R_b [K/(W/m)]
t_{b1} 2 h 25 min	1,52	3,77	0,04
t_{b2} 24 h 15 min	1,23	4,65	0,05

Table 7.6 Summary of results from Ängby

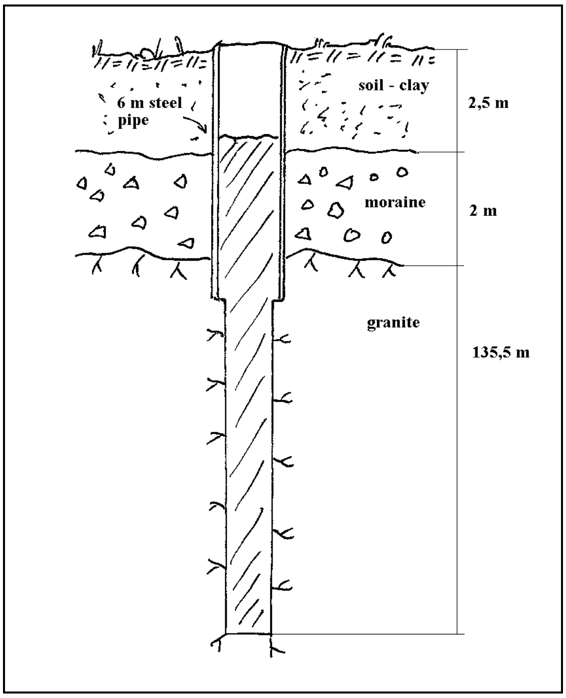


Figure 7.17 The test hole at Ängby (borehole 3) is filled with groundwater. The upper 4,5 meters of the borehole is surrounded by a soil/clay layer and a moraine layer. The rest of the borehole is drilled through granite rock to a total depth of 139 m. A steel pipe protects the uppermost 6 m of the borehole from any damage due to frost, settling or violence.

7.2.2.3 COOLING CAPACITY OF ÄNGBY

Using the values of R_b and λ obtained in section 7.2.2.2, the maximum mean capacity is obtained for continual operation of the system. Given that the mean value of the heat carrier fluid must not exceed $T_f = (20+14)/2 = 17^oC$, the capacity for stationary conditions of the measured borehole is 2.0 kW (15 W/m) for the values of t_{b1} and 2.4 kW (17 W/m) for the values of t_{b2}. Stationary conditions will for this type of system be reached in about 30 years. In April -96 the cooling system had been in operation periodically for about one year. The mean capacity obtained from the system was 27 W/m (6 boreholes). The presimulations predicted about 13 W/m.

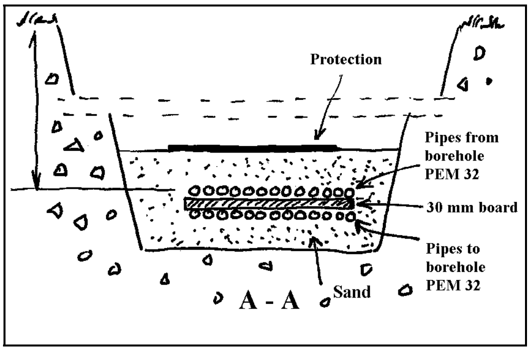


Figure 7.18 The trench through which the horizontal connection pipes are led from the boreholes to the machine room has a depth of 0,6-0,8 m. The pipes are placed side by side with a 30 mm thick board to separate the inlet pipes from the outlet pipes. The surrounding material is sand.

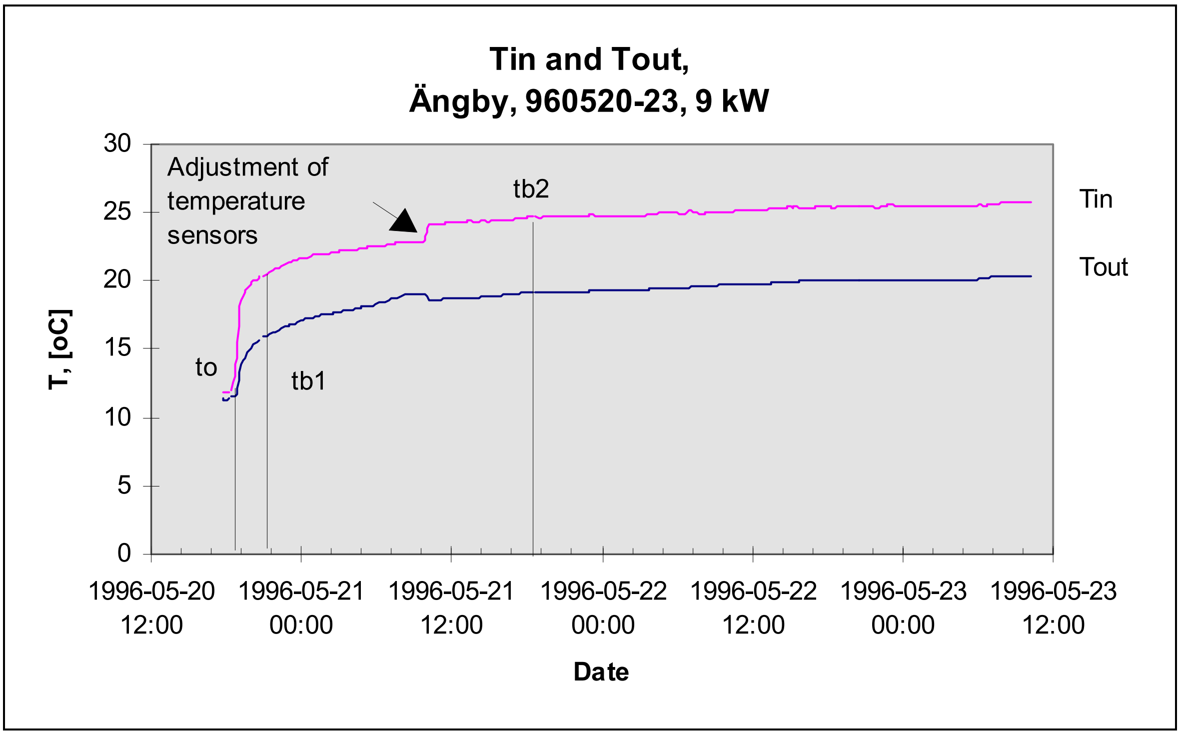


Figure 7.19 Inlet and outlet temperatures. The power (9 kW) is switched on at 't_o'. In the initial stage, the temperatures increase drastically, but already after a few hours, the increase of temperature is more moderate. An adjustment of the temperature sensors is seen in the figure as a discontinuity of the function.

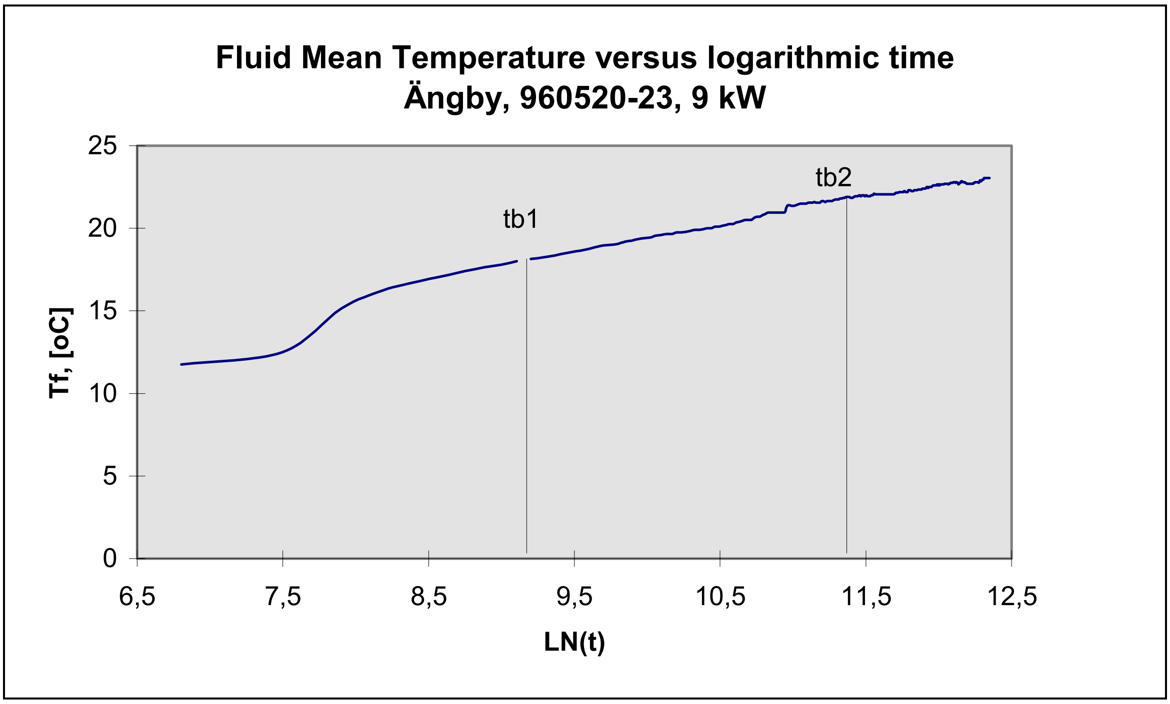


Figure 7.20 The linearized function of the mean fluid temperature (T_f) with the two break times, t_{b1} and t_{b2}, marked out. The function is a good approximation of a straight line, but the incline of the line depends on the break time chosen.

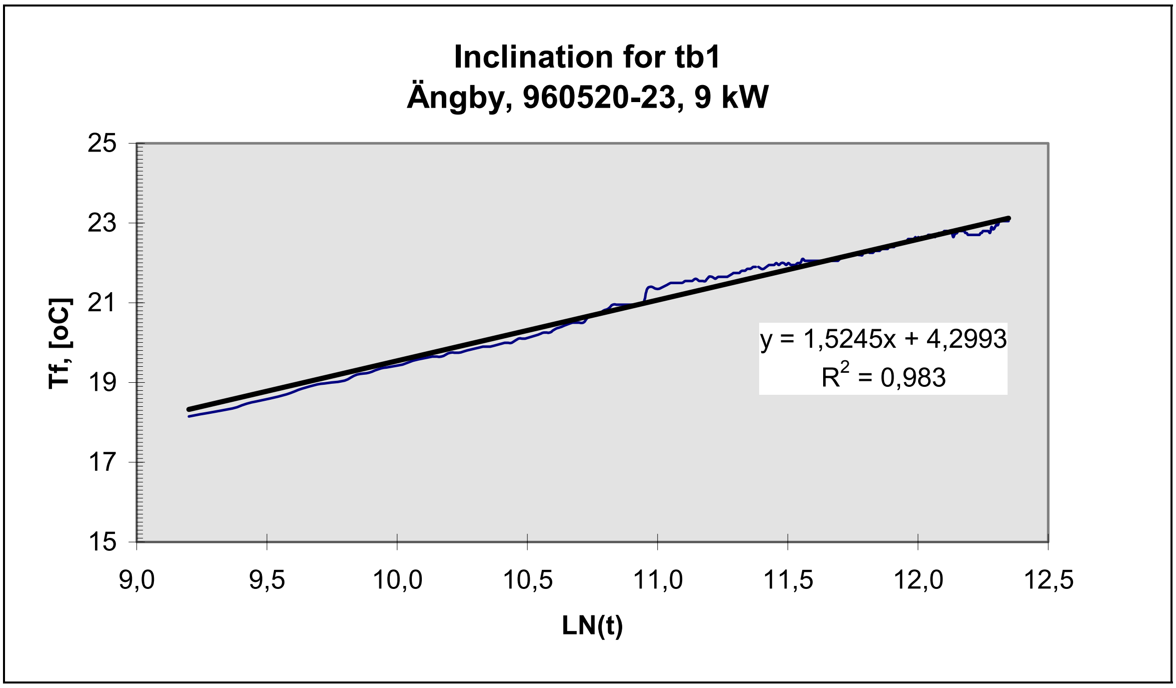


Figure 7.21 The inclination for the linearized function of T_f after t_{b1}(2 h 25 min) is determined to k = 1.52. Using the parameters from Table 7.5, the thermal conductivity is calculated to λ = 3.77 W/m,K.

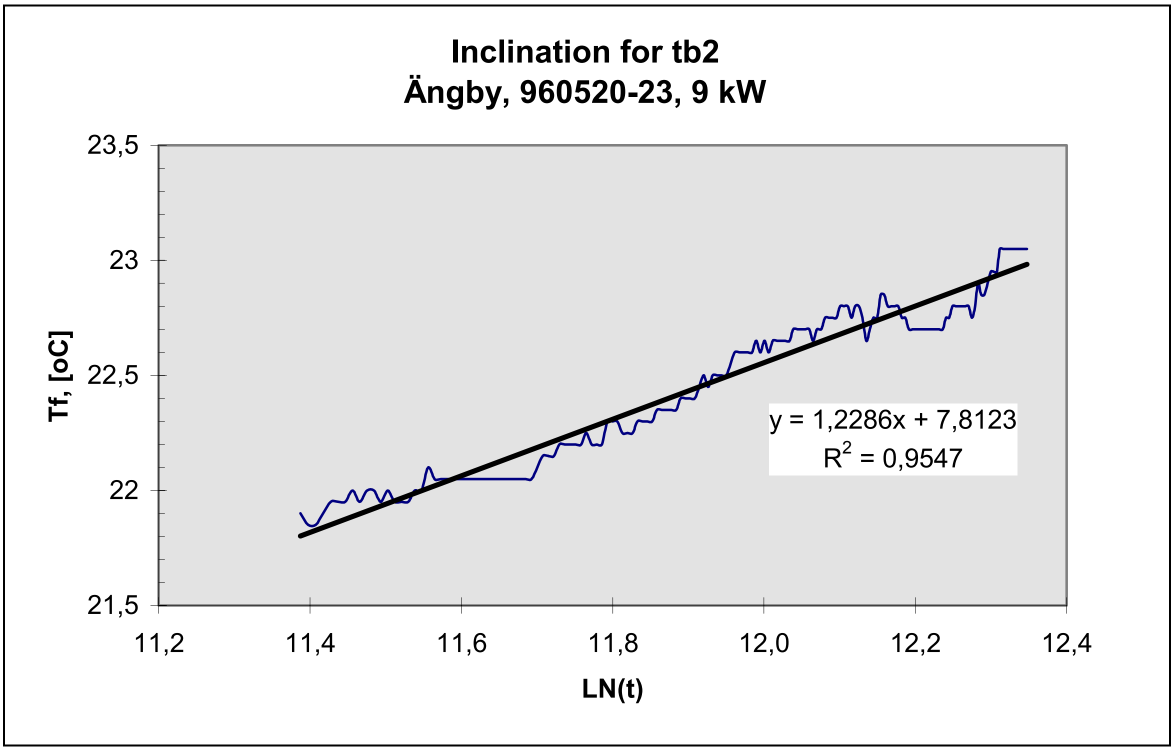


Figure 7.22 The inclination for the linearized function of T_f after t_{b2} (24 h 15 min) is determined to k = 1.23. Using the parameters from Table 7.5, the thermal conductivity is calculated to λ = 4.65 W/m,K.

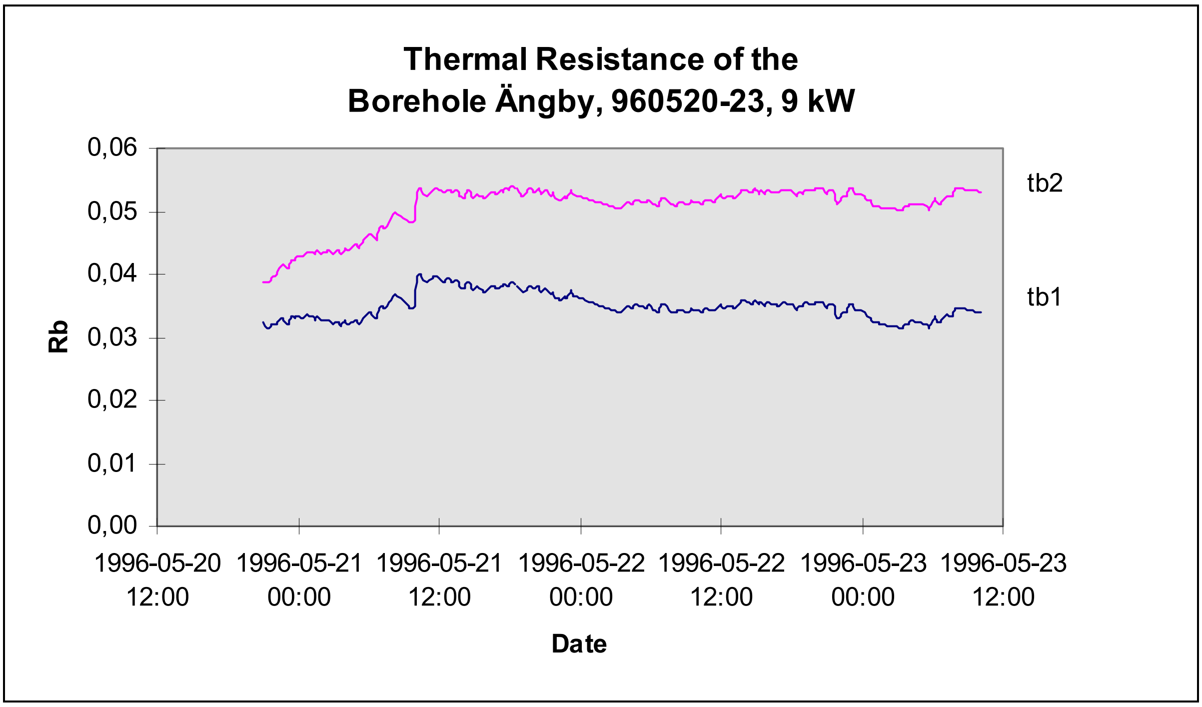


Figure 7.23 The thermal resistance, R_b, is rather constant over time as is seen in this figure. The value determined from the thermal conductivity for t_{b1} is R_b = 0.04 K/(W/m) and t_{b2} gives R_b = 0.05 K/(W/m).

7.3 CONCLUSIONS

The cooling power capacity of the systems at Drevikstrand and Ängby estimated by the measurements from TED are shown in Figure 7.24.The values from TED are mean values of the results from the two break times, and are calculated for the cooling capacity after 30 years when stationary conditions are reached. The values are compared with the precalculated computer simulations and the obtained power capacity from the systems by the end of 1995.

The cooling capacity of the systems decrease with time until stationary conditions occur. This is due to the fact that the distance to the undisturbed ground temperature increases until a balance with the atmosphere is obtained (see section 4.1.2). Therefore it reasonable to assume that the obtained cooling capacity today is higher than the stationary cooling capacity. The cooling systems have only been run for a couple of years, yet.

For Drevikstrand, the precalculations suggested a mean capacity of about 25 W/m, while the obtained cooling capacity of the system is estimated to 40 W/m after operation from February to September 1995. TEDs measurements suggest that the cooling capacity at stationary conditions is 30 W/m.

The precalculations for Ängby suggested 13 W/m, but after one year of operation, the obtained cooling capacity is 27 W/m. TEDs measurements suggests 16 W/m at stationary conditions.

The capacities for stationary conditions are about 20 % better than the precalculations predicted. That means that for Ängby, the number of boreholes may have been reduced from 13 to 11 boreholes.
For the Drevikstrand case, the system was not dimensioned to cover the whole cooling demand, but to be supported by conventional cooling as well. Today additional cooling is not needed, because the underground cooling system exceeds the expectations.

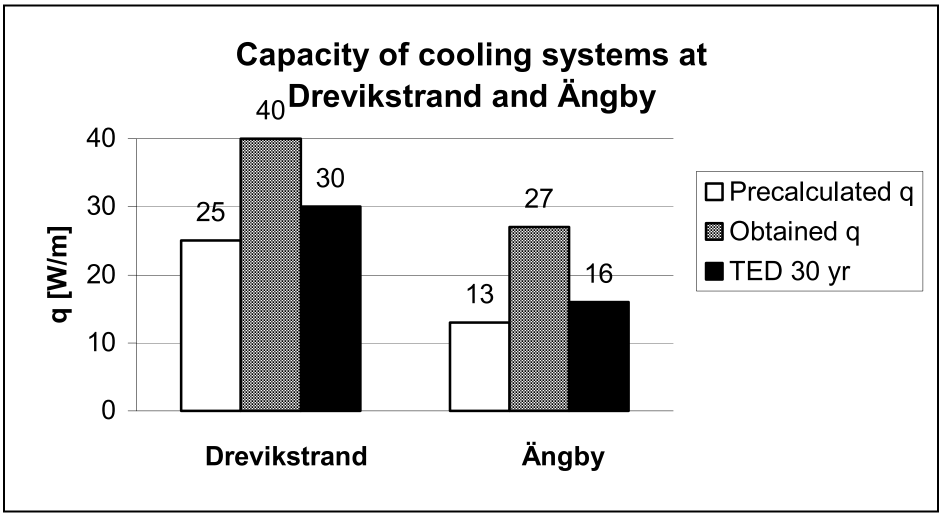


Figure 7.24 The diagram shows the expected cooling capacity (W/m) from the precalculations, with the obtained cooling capacity and the expected capacity at stationary conditions, based on the thermal response test.

For Drevikstrand, simulations have also been done for the outlet and inlet temperatures from the boreholes. Comparison has been done between the expected temperatures from the precalculated computer simulations, the simulated temperatures from the response test, and the measured temperatures of the system in operation. The simulations have been done by Dr. G. Hellström, LTH, and are here presented as comparisons between the mean fluid temperatures, T_f (figure 7.25).

The comparison shows that the measured temperature is in average 4°C lower than the expected temperature from the precalculations. The simulations based on the results from the response test correspond very well with the measured temperature from the system, and thus we conclude that thermal response test is a suitable tool for dimensioning UTES systems.

The improvements of the thermal capacities of the boreholes can probably be explained by the occurrence of groundwater flow in the rock and natural convection in the borehole systems.

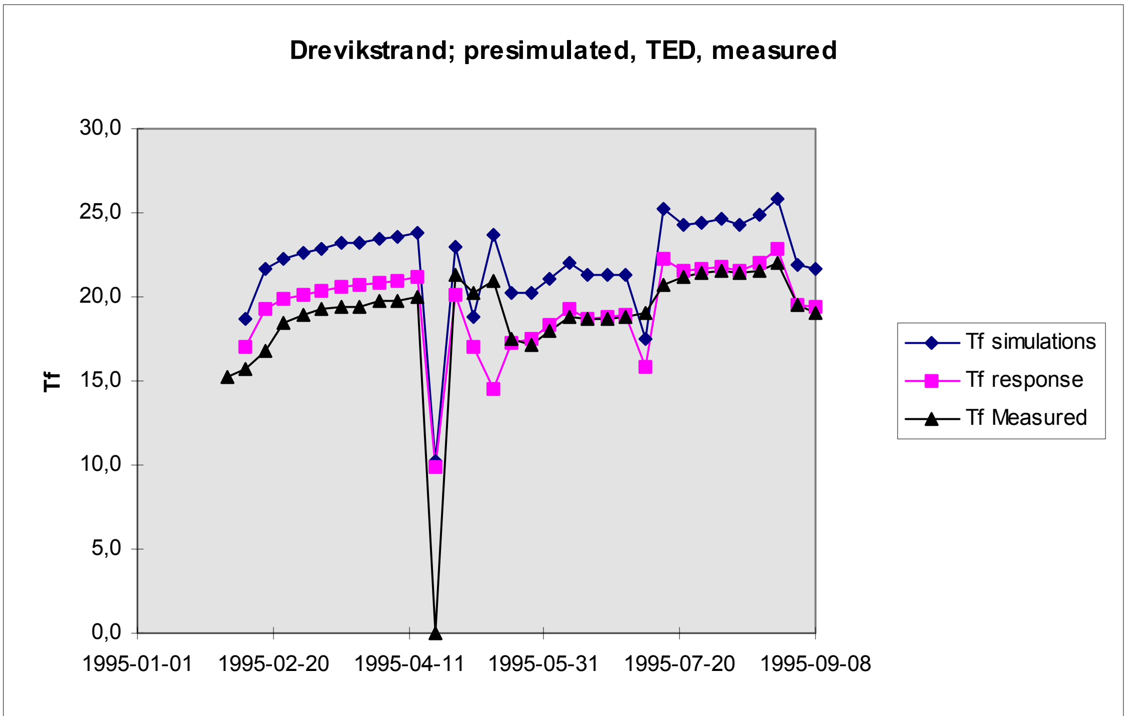


Figure 7.25 Measured mean temperatures at Drevikstrand, compared to simulations using R_b and λ from the presimulations and the response test.

8. GENERAL CONCLUSIONS

As a technical tool for marketing UTES systems, TED has proved to be worth further developing. There are still a few technical details to work on, and a general observation is that it is better with too many parameters measured than too few, at least at the research stage.

TED has a technically very simple construction, and is therefore easy to use and maintain. The results from the measurements are simple to evaluate and understand, which makes TED a useful tool with many possible applications.

TED makes it possible to determine the effective thermal conductivity and the total thermal resistance of a borehole installation. The reliability of the measurements done with TED seem to be good.

From the measurements at the telephone stations in Stockholm, one can conclude that if a response test had been done at one borehole before the rest of the system had been constructed, money had been saved by reducing the number of boreholes. For the Drevikstrand case, the system is now covering the total needs for the cooling capacity, which was not originally planned. It was originally meant as a complement to the ordinary freon heat exchanger.

Our conclusion is thus that thermal response test with mobile equipment should become a standard tool for dimensioning and evaluation of underground thermal energy systems.

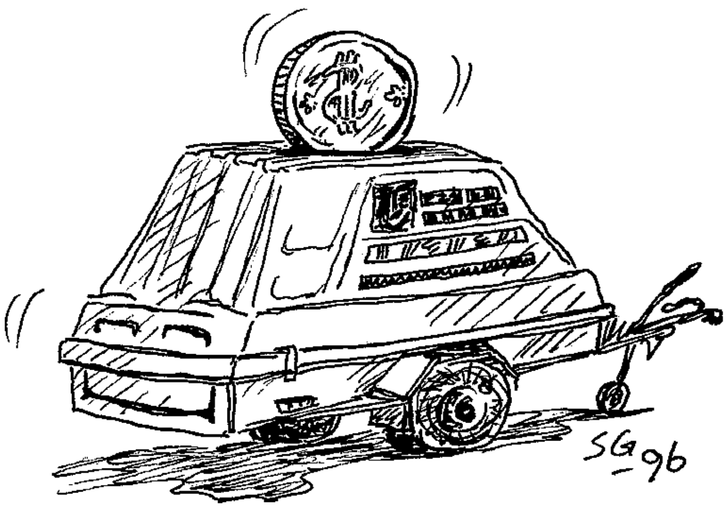
Soaked but proud. TED could sometimes show his special kind of humour.

The development of TED will now continue as a four years research project by S.Gehlin at the division of Water Resources Engineering, Luleå University of Technology, Sweden. There are now 120 well documented boreholes from a previous research project in Luleå available for further research with TED. They will be used for studying different types of borehole installations, materials of the pipes and fillings, installation techniques, heat carrier fluids, natural convection, forced convection, effects of cracks, groundwater flow, soil layers etc. The method can also be used for studying parameters in soil, clay and complex rock species.

TELIA is planning to expand the application of borehole cooling of telephone stations and have shown a great interest for the mobile response test equipment. With their help, a rough geothermal survey may also be done for Sweden, i.e. a map over the efficient thermal properties of the Swedish bedrock.

The Swedish Heat Pump Consortium, SVEP, is supporting the research, based on their interest of using thermal response test for solving juridical controversies with heat extraction boreholes that do not keep the promised capacity etc. and to avoid future controversies.

Already has the work with a mobile equipment for thermal response test been shown interest from several countries, among them Germany and Canada.



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