Characterization and Temperature Measurement Techniques of Energy Wells for Heat Pumps

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Abstract
Ground source heat pumps are a widely used approach to efficiently heat single family houses. In addition to using the ground as a heat source during the winter, it can be used as heat sink and as a free cooling source during the summer. The most common way to carry out the heat exchange with the ground is with the help of energy collectors (borehole heat exchangers) in vertical wells. The quality of the heat exchange depends on the type of collector and on the flow conditions of the circulating fluid. For a complete understanding of the heat transfer performance, it is necessary to carry out careful temperature measurements at research installations and to do a preliminary characterization of the boreholes. These activities might represent a significant cost saving since the system can be optimized based on their outcome. The characterization consists of determining the type of rock and its thermal properties, the groundwater flow at different depths, and the borehole deviation according to the expected position. A comprehensive study about these characterization actions as well as temperature measurement techniques in boreholes using thermocouples and fiber optic technology are described in this report. Study cases from real installations are also presented to exemplify the characterization and measurement methods.
Acknowledgements

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I want to thank the Swedish Energy Agency and all project sponsors who have materialized this idea of pointing out recommendations for design and installation of collectors in energy wells for heat pumps.

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Thank you!!

José Acuña
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Objectives

The project aims to describe in detail the borehole characterization procedures that need to be done prior to a vertical ground source heat pump installation. Additionally, it explains different temperature measurement techniques that can be used in boreholes to monitor their thermal performance.

The specific objectives are the following:

- Identify and understand existing methods for determining the thermal properties of the borehole surrounding rock
- Describe the response test method used for determining the thermal properties of the borehole surrounding rock
- Describe methods for measuring the ground water flow in boreholes
- Describe methods for measuring the borehole deviation with respect to the expected direction
- Determine possible methods to measure temperature in the secondary fluid side using thermocouples
- Explain advantages and disadvantages of different temperature measurement techniques in energy wells for heat pumps
- Exemplify borehole characterization methods with study cases
Methodology

The development of the project consists of the following parallel activities:

**Literature survey:**
- A theoretical research using bibliography and papers as well as information from the industry related to the project field. The most relevant information is filtered from all the sources and used as a foundation for the development of the thesis chapters.
- Description of the different characterization methods carried out during the project period

**Experimental work:**
- Investigate, apply, and develop a measurement technique for monitoring the secondary working fluid as well as the borehole temperature at different depths at a borehole installation by using thermocouples and fiber optic cables.

These activities are carried out during the period July 2007 to January 2008 at different ground source heat pump installations as well as in the Laboratory of Thermodynamics and Refrigeration at the *The Royal Institute of Technology KTH.*
1 Introduction

1.1 Characterization of energy wells for heat pumps

When referring to energy wells, it is meant vertical holes drilled into the ground in order to exchange energy in form of heat. Another common name for energy wells is boreholes.

The ground is mostly used as a heat source during the winter, but yet, at larger installations, it is also feasible for using it as a heat sink and as a free cooling source during the summer. This is feasible thanks to the fact that the bedrock is a stable heat source with near constant temperature along the year, as shown in Figure 1-1.

The most common method to exchange heat with the ground is by means of a borehole heat exchanger BHE installed into the ground and connected to ground source heat pump.

Figure 1-1. Rock Temperature profile (VVS audio-visual material)

The heat pump basically consists of an evaporator, condenser, expansion valve, and a compressor. These equipments are connected in a closed system with a circulating fluid (refrigerant) that alternates between a gaseous and a liquid state. They can therefore transfer heat from natural or man-made source such as air, ground, water and waste heat, to a destination of interest.

A Borehole Heat Exchanger conventional type consists of a U shape pipe (one tube going downwards and another going upwards, known as U-pipe). It is commonly made of Polyethylene (PE) and the pipes have an outer diameter of 40 mm with wall thickness of 2.4 mm. This pipe encloses a circulating heat carrier fluid that exchanges heat with the surrounding rock. Other BHE configurations also exist in the market to a minor extent although there is a significant approach to research and development. Figure 1-2 illustrates a typical U-pipe BHE with its respective specifications stamped on the tube surfaces.

Figure 1-2. Typical specifications of a BHE pipe

A general name used when all the system components are working together is Ground Source Heat Pump (GSHP) system. Figure 1-3 illustrates a typical system with all its elements. The process starts when a circulating fluid travels down into an energy wells and comes back relatively warmer through the BHE (illustrated with the red colour in the pipe). When this type of system is used for heating purposes, the heated fluid that comes back from the borehole gives part of the energy taken from the ground to the heat pump, which then forces the heat to travel towards a higher temperature environment, i.e. tap hot water and comfort heating.
The energy wells are very often, by nature, filled with ground water. There are also cases when the space between the BHE and the borehole wall is packed with a filling material. The systems where the circulating fluid is independent from the filling material are known as closed systems (Claesson 1985).

It is also possible to have an open system where the ground water is pumped up from the lower part of the borehole and, after giving the heat to the heat pump, sent back to the borehole upper part or casted away to another use.

Figure 1-3 illustrates a closed system. When dealing with closed systems, it is possible to work with temperatures lower than 0°C in the fluid that is circulating through the BHE. This is possible by means of using an antifreeze solution of water with an additive percentage of an alcohol which decreases the freezing point of the fluid. This avoids fluid freezing during cold seasons due to high heat extraction from the ground. It is important that the secondary fluid also has good pumping properties and that it is not hazardous to the environment. It should of course have appropriate thermal properties for the application. After this fluid passes through the ground loop, it is pumped up to the heat pumps which convert the low quality heat into high quality heat, finally transferred to the comfort and tap water circulation system of a building.

This technology has become more popular during the last two decades and its research is being encouraged on enhancing the heat exchange conditions with the ground. GSHPs in Sweden are normally designed to deliver up to 90% of the required heating to a building with an operation time that oscillates around 4000 hours per year (this can vary from country to country). Besides this, GSHPs represent a more environmentally friendly use of energy.

Another reason why this technology is very promising is that the rock temperature after the first 15 meters under the ground surface is relatively stable and constant along the year. This is observed from Figure 1-1. In other words, the bedrock temperature is not vulnerable to ambient temperature changes and this favours an optimal performance of the heat pump since it can work under constant conditions at the evaporator side. As an example, Figure 1-4 shows the average ground temperatures in Sweden.

Residential houses and office buildings are especially interested for this technology due to the fact that the total electricity consumption in buildings can be significantly reduced when installing a ground coupled heat pump system. The investment costs for bedrock couple heat pumps are rela-
tively high especially due to the drilling of boreholes. However, they provide with a long lasting heating alternative which not only provides comfort heating but also hot water.

With this general knowledge about the energy wells for heat pumps, it is possible to understand that the performance of the heat exchange with the ground depends on factors as

1. The thermal properties of the ground.
2. The ground water conditions around the BHE
3. The borehole characteristics
4. The borehole heat exchanger material, dimensions and geometry.
5. Flow conditions and temperature profile in the BHE

Each of these factors represents a thermal resistance for the heat exchange between the secondary working fluid and the bedrock. Chapter 2 “Determination of Rock thermal properties”, chapter 3 “Determination of ground water flow in boreholes”, and chapter 4 “Determination of borehole geometrical characteristics”, deal with studying these three factors so that the heat transfer performance with the ground can be improved by understanding them. This is what we called as “Characterization of energy wells for heat pumps”.

1.2 Temperature measurements in energy wells for heat pumps

Characterizing boreholes gives good information and descriptions about the ground as energy source and about what happens in the surroundings of the borehole heat exchanger. Nevertheless, a complete performance study needs to include a detailed investigation of the temperature profile of the secondary fluid along its trajectory through the BHE. Moreover, the geometry and BHE material could have many configurations which also might affect the heat transfer performance.

In order to carry out a complete study it is then necessary to determine appropriate measurement techniques so that reliable temperature values can be obtained. However, it is complicated to monitor a system located under the ground and therefore, many ground source heat pump experiments have been done by only analyzing the fluid inlet and outlet temperatures to and from the borehole. The ideal experiment would be to have as many temperature values as possible along the borehole depth both in the ground water (or filling material) side and in the circulating fluid side. Chapter 5 is dedicated to a comprehensive description of two different temperature measurement techniques that can be applied for this purpose.

1.3 Heat transfer generalities in energy wells

This subsection is a brief heat transfer introduction which might be of help for understanding some parts of this report.

At normal depth for vertical boreholes for heat pump source usage (150 m – 250 m), heat transfer within the earth occurs by conduction and convection. However, at normal bedrock conditions and low temperature gradients, the dominating heat transfer mode is conduction. Convection could be significant under the effect of ground water movement due to the presence of rock fissures and/or due to a marked temperature gradient which causes vertical movements of the water thanks to density differences.

The governing conduction heat transfer equation between the rock and the secondary fluid can be generally written as expressed in Equation 1-1. It represents the energy conservation and allows to obtain the temperature distribution in the different directions $T(x,y,z)$ as function of the time. The first three terms relate the heat flux in a control volume for each of the three Cartesian directions.
\[
\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + \dot{q} = \rho C_p \frac{\partial T}{\partial t}
\]  
Equation 1-1

With Equation 1-1, the temperature at any point of coordinate \((x,y,z)\) is determined by the time, the thermal conductivity \(k\) and the volumetric heat capacity \(\rho C_p\). From (Incropera 1996), it is known that these three variables are related by Equation 1-2. The resulting relation is well known as thermal diffusivity \(a\), an indicator of the material’s capacity to conduct heat with respect to its capacity to store it.

\[
a = \frac{k}{\rho C_p}
\]  
Equation 1-2

The thermal conductivity \(k\), indicates the ability of a material to conduct heat and the heat capacity \(\rho C_p\), is the capacity of a material to store thermal energy.

Considering a borehole as an infinite cylinder, assuming stationary conditions and that the temperature gradient only exists in the radial direction, the heat transfer could be seen as one-dimensional. Equation 1-1 can be simplified to Equation 1-3 where \(r\) denotes the radial direction. Steady state conditions are not always the case in borehole applications during normal heat pump operation. However, this simplification is done for better illustration purposes.

\[
\frac{1}{r} \frac{d}{dr} (kr \frac{dT}{dr}) = 0
\]  
Equation 1-3

Solving this equation for the conduction through a cylindrical tube (a typical borehole geometry), assuming that the conductivity value is constant, and applying the appropriate temperature boundary conditions (in this case, \(T_1\) and \(T_2\) are the temperatures at radius \(r_1\) and \(r_2\) respectively), it is possible to obtain the temperature \(T(r)\) associated with radial conduction. This is expressed in Equation 1-4.

\[
T(r) = \frac{T_1 - T_2}{\ln(r_1 / r_2)} \ln(r / r_2) + T_2
\]  
Equation 1-4

Equation 1-4 illustrates the fact that the temperature distribution through a cylindrical wall associated with radial conduction is logarithmic. The boundary conditions given above can be inserted in the Fourier’s law applied to a cylinder in order to obtain the following:

\[
q = -kA \frac{dT}{dr} = -k(2\pi L) \frac{dT}{dr} = q_r = \frac{2\pi L k (T_1 - T_2)}{\ln(r_2 / r_1)}
\]  
Equation 1-5

Where:

\(A\)… The area, perpendicular to the heat transfer direction

\(L\)… the cylinder length

\(q_r\)… The energy flow

\(r_1\) and \(r_2\) … The internal and external radius of the cylindrical wall, respectively

\(T_1\) and \(T_2\)… The corresponding temperature at \(r_1\) and \(r_2\) respectively.

Equation 1-5 is the generic heat transfer conduction equation for a cylinder and it applies to many of the cases dealing with borehole heat exchangers.
Knowing that there must exist a driving force (represented by a temperature difference) in order for heat transfer to occur, it is often convenient to use the concept of the thermal resistance $R_b$, which can be defined as the relation between this driving force and its consequent energy flow, as follows in Equation 1-6.

$$\Delta T = R_b \cdot q$$  \hspace{1cm} \text{Equation 1-6}

By making an analogy of Equation 1-6 with Equation 1-5, it is understood that the thermal resistance can be written as a function of the geometry in radial direction and the thermal conductivity for one-dimensional conduction.

As mentioned before, heat transfer in energy wells occurs mainly by conduction but under certain circumstances, convection can also be of relevance. The three homogeneous regions through which the heat would need to travel are: the filling material, the pipe wall, and the circulating fluid. Therefore, it might necessary to understand how the possible thermal resistance expressions that could have effect look like. These are shown in Table 1-1 for conduction and convection (Equation 1-7 and Equation 1-8, respectively). The variable “h” stands for the convection heat transfer coefficient in Equation 1-8.

Table 1-1. Conduction and convection thermal resistance equations

<table>
<thead>
<tr>
<th>Thermal resistance expression (applied to cylinders)</th>
<th>Conduction</th>
<th>Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{conduction}}$</td>
<td>$\frac{\ln(r_2 / r_1)}{2\pi Lk}$</td>
<td>$\frac{1}{2\pi Lh}$</td>
</tr>
</tbody>
</table>

Equation 1-7  \hspace{1cm}  Equation 1-8

This simple approach has been presented in order to illustrate some basic heat transfer concepts. Later, in chapter 2, a more real mathematical model governing the energy wells application will be presented as a tool to understand the thermal response test method for determining the rock thermal properties.
2 Determination of Rock thermal properties

One of the most important points when deciding how long energy wells for heat pumps should be is to evaluate the rock thermal properties of the location where the installation is to be made.

Bedrock thermal property judgement can be classified within theoretical, laboratory or field measurements (in situ); and generally, this is carried out by:

- Looking at geological tables and charts for the place of interest.
- Making laboratory and field measurements of rock samples.
- Making a thermal response test in situ by using the installed BHE.
- Making a thermal response test while drilling a borehole.
- Calculating the properties based on the rock composition.

(Sundberg 1991) states in the report “Termiska egenskaper i jord och berg” that measuring the rock thermal properties in the laboratory as well as in the field could sometimes not be 100% objective since the bedrock thermal conductivity is sensitive to possible natural changes in the borehole surroundings, such as ground water movements at local borehole sections or along its length. However, if this time dependent variables can be evaluated in a relevant way, the laboratory and practical measurements should be prioritized before calculation measurements. Moreover, according to (Gehlin 1998), in situ measurements of borehole thermal properties are a better approximation to the reality in view of the fact that many ideal assumptions are made when making mathematical models.

2.1 Rock thermal properties

The knowledge about the rock thermal properties is very important within the rock coupled heat pumps context. Since there is a remarkable difference among several soil and rock types such as sand, mud, limestone, granite, clay, among others.

The first indicator for determining these properties is the type of rock since this determines its thermal properties. Common types of rock are granite, gneiss, gabbro, limestone (kalksten), schist (skiffer), and sandstone, respectively. Figure 2-1 exemplifies the thermal conductivity values for these rocks.

![Conductivity of different rock types (Hellstrom 2007)]
It was explained in chapter 1 that conduction is the predominant heat transfer type in boreholes, and that three properties are normally of interest when analyzing the heat transfer in the rock: Thermal conductivity $\kappa$, the volumetric heat capacity $\rho C_p$, and heat diffusivity $\alpha$. Table 2-1 presents the values of these properties for two of the most common rock types is Sweden, granite and gneiss.

### Table 2-1. Thermal properties of common rock types (Eriksson 1985)

<table>
<thead>
<tr>
<th></th>
<th>Density [Kg/m$^3$]</th>
<th>Thermal conductivity [W/mK]</th>
<th>Specific Heat [J/Kg K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>2700</td>
<td>2.9 – 4.2</td>
<td>830</td>
</tr>
<tr>
<td>Gneiss</td>
<td>2700</td>
<td>2.5 – 4.7</td>
<td>830</td>
</tr>
</tbody>
</table>

Regarding these thermal properties, more specific aspects could have a significant effect over their values (especially over the conductivity) and therefore over the heat transfer within the rock. These have to do with rock water concentration, porosity, mineral content, temperature and degree of anisotropy. A very low thermal conductivity can represent a high thermal insulation for the heat transfer between the borehole wall and the bedrock, i.e. the heat transfer performance might not be as expected. Table 2-2 categorizes them according to their degree of influence on the conductivity values of the rock.

### Table 2-2. Factors influencing the conductivity of the rock (Sundberg 1991)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water concentration</td>
<td>Low</td>
</tr>
<tr>
<td>Porosity</td>
<td>Low</td>
</tr>
<tr>
<td>Mineral content</td>
<td>Very High</td>
</tr>
<tr>
<td>Temperature</td>
<td>High</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>Medium</td>
</tr>
</tbody>
</table>

The water concentration has a low influence in solid rock thermal conductivity (at least for Granite and Gneiss). However, it could play an important role when dealing with soils. Water ($k_w = 0.6$ W/m$^\circ$C) is a better conductor than the air ($k_{air} = 0.024$ W/m$^\circ$C). Therefore, high water concentration signifies that there is better contact between the soil grains which improves the conductivity value. Figure 2-2 illustrates three images with different degree of water saturation.

![Figure 2-2. Different water saturation states (Bear 1979)](image)

It can be observed in Figure 2-2 that the image closest to the right side presents a much higher amount of water between the rock grains.
The porosity and the mineral content of the bedrock have a protagonist role: a low porosity situation would mean that rock grains, through which the heat is transmitted, would be closer to each other and as a consequence, the heat transfer would be improved. Furthermore, the quartz concentration of a crystalline rock, as an example of mineral concentration, is directly proportional to the rock thermal conductivity, as shown in Figure 2-3.

![Figure 2-3. Relation between thermal conductivity and quartz concentration in crystalline rocks (Sundberg 1991)](image)

Figure 2-3 shows that the rock thermal conductivity (vertical axis) is proportional to its quartz concentration.

The rock temperature is also of relevance. The conductivity values in bedrock can decrease from 0 to 15% between a temperature change from 0 to 100 °C.

Particularly of interest is also to compare the difference between liquid and ice water since the conductivity value changes from 0.6 W/m°C to 2.1 W/m°C, respectively. This is relevant in water filled boreholes where the groundwater around the BHE could freeze due to the low working temperature levels stimulated by the heat extraction, causing a decrease in the temperature difference between the secondary fluid and the BHE surroundings.

In Sweden, the most common rock type is granite which has a conductivity value within the interval 3 – 4 W/m°C and geological maps are available at the Geological survey of Sweden SGU homepage where one can observe current rock types on different country locations. However, since the conductivity values for different rock types could vary within the shown ranges in Figure 2-1, it is very important to identify the exact value for a specific place in order to be able to design the system as efficiently as possible.

**2.2 Theoretical and Laboratory tests**

The simplest method to estimate the ground thermal properties is by the use of average values from geological maps. In Sweden, these are available from the Swedish Geological Research SGU. Nevertheless, there might be variations of up to 20% from the average value depending on the type of rock, e.g. the conductivity value for granite in Sweden is within the range 3.55 ± 0.65 W/mK (Gehlin 1998).

Calculating the thermal properties is also a simple and reliable method. This is done based on the mineral grain properties. According to (Sundberg 1991), for soil evaluations, the calculation methods have many advantages over practical measurements since the former allows to consider the material’s thermal dependence on the temperature and water concentration changes. For bedrock evaluations, calculations can be based on the mineral composition of a bedrock sample which are normally taken during routine geotechnical investigations of water concentration, pore volume and density (Rosén 2006).

For some small applications as BHE installed at family houses, it is normally sufficient to judge the thermal properties by qualitative evaluation of samples at the field.
Regarding the laboratory methods, (Sundberg 1991) states that mineral composition analysis can be done by putting a rock sample in contact with a heat generating probe and analysing its transient response.

The conductivity is determined by controlling the sample temperature profile versus time. This is called the probe method. (Rosén 2006) states in his report that in the laboratory, it is very important that the sample is representative and that the degree of anisotropy (distribution of the properties along the directions in the sample) must be taken into account. Figure 2-4 shows the used probe used in this method.

Rosén also mentions other names for laboratory alternatives that could be used. These are: the laser method, thermal hot strip, the thermal plane source technique (also called hot disk) and lastly, measuring with a calorimeter.

The hot disk uses a device based on Transient Plane Source (TPS) technique that can be used both in laboratory and in-situ measurements and it can measure thermal conductivities between 0.01 and 500 W/mK. The TPS method involves the use of a very thin (0,007 mm thickness) double metal (Nickel) spiral, located between two layers of Kapton (0,025 mm thickness) in close contact with the material to be investigated. The double metal spiral serves both as the heat source and as a resistance thermometer (Hot Disk AB, 2008).

When carrying out measurements in solid bodies, the spiral is located between two surfaces of the same material, as shown in Figure 2-5 and Figure 2-6. When the measurement is running, a current passes through the Nickel spiral and creates an increase in temperature. The heat generated dissipates through the sample at a rate that depends on the thermal properties of the material. Then, by recording the temperature versus time response in the sensor, these characteristics can accurately be calculated. The radius of the TPS sensor can vary between 2 mm and 30 mm thus, the sample size can vary between 8 mm and 120 mm or larger.

Although a TPS test can be carried out in situ, for big scale borehole heat exchange applications such as borehole thermal energy storage where thermal energy is stored in the bedrock through heat exchange from several boreholes, there is a motivation for carrying out in situ measurements instead of laboratory measurements. The most popular in situ method is called Thermal Response Test and it is developed in the following section.
2.3 The Thermal Response Test

During a thermal response test (TRT), a fluid is circulated through the borehole heat exchanger and a constant heat power is supplied or extracted so that the fluid is heated/cooled in a controlled way. The heat transport to/from the ground takes place by conduction through the borehole heat exchanger walls, the ground water and the bedrock. The duration of the test depends on the temperature field profile of the bedrock in comparison with temperature field profile around the borehole, but it generally is approximately of 72 hours. Figure 2-7 shows a scheme of a typical thermal response test equipment.

The measured variables during a TRT are the supplied heat, the outdoor temperature, the secondary fluid flow, and the borehole incoming and outgoing temperatures. The values of the variables are registered and recorded to finally determine the thermal conductivity of the ground and the borehole thermal resistance by using a line source model. These two parameters give useful information that can be used to optimize the borehole system since the surrounding hydrological and geological conditions of the site are taken into consideration. Carrying out the Thermal Response Test is very interesting when dealing with Borehole Thermal Energy Storage (BTES) systems, where energy is stored into the rock by exchanging heat between a warmer secondary fluid and a colder rock storage volume (Gehlin 1998). In this case, it is important to know how the bedrock reacts when intending to store heat into it.

(Gehlin 1998) states that in situ measurements of borehole thermal properties are a better approximation to the reality in view of the fact that many ideal assumptions are made when making mathematical models. There are factors such as; presence of rock fissures around the borehole which alter the heat transfer conditions, natural convection on the ground water side, borehole deviation from the planned position, BHE pipes might cross each other or not be centered in borehole; These issues indicate that it is difficult to trust laboratory measurements and mathematical models to the highest extent since the exact underground conditions are commonly unknown. Therefore, the thermal response test TRT represents a standard tool for dimensioning and optimizing borehole systems.

TRT dates from June 1983, when Palne Mogensen, together with two students from The Royal Institute of Technology KTH, Sweden, suggested and built the first rock thermal response tester arrangement. It consists of a chiller system (shown in Figure 2-9) with a regulator for constant cooling effect that works with Refrigerant R22 and has a power rate of 2,7 KW. The system can be connected to a one phase electricity plug for 220 Volts. The condenser side is cooled with water, and the evaporator side (included in the Aluminum cylinder) has connections for incoming and outgoing secondary fluid lines so the borehole can be cooled down. Moreover, a separate unit contained the circulation pump and PT100 temperature meters for continuous logging of the inlet and outlet temperatures of the circulating fluid.

The method by (Mogensen 1983) is able to calculate thermal resistance between the secondary working fluid and the borehole wall which in many cases was only decided through practical measurements and not in laboratory. The thermal conductivity is of course also determined.
Since then, TRT has been used on several sites for thermal response tests, and today, the most used equipment consists of a small trailer which contains an electric heater and a pump which uses a constant heat injection principle. The first trailers were developed at Luleå University of Technology (Figure 2-8), Sweden and at Oklahoma State University, USA (Figure 2-11). Figure 2-10 shows also a model from Germany.

As it was previously mentioned, the thermal response test also allows determining the borehole installation thermal resistance. This concept is of great significance today since it permits evaluating the performance of different borehole heat exchanger types. The most basic expression for understanding the thermal resistance concept was presented in section Equation 1-6.

The TRT equipment size is relatively big, which sometimes makes it difficult to be transported and to be installed in borehole installation with hard access. A solution for this is to build compact versions of TRT as the picture shown in Figure 2-12.

The thermal response test considers the interrelations existing among the bedrock, borehole filling, the collector pipes, and the secondary working fluid. Figure 2-13 illustrates the two general thermal resistances that exist between the heat source line (represented by the secondary working fluid at a mean temperature \( T_f \)) and an arbitrary point located in the surrounding rock which has a tempera-
ture $T_{\text{ground}}$. In this case, the borehole resistance $R_{\text{borehole}}$ between the secondary working fluid and the borehole wall includes three thermal resistances:

- The secondary working fluid
- The collector wall
- The ground water or borehole filling material

**2.3.1 The mathematics of the Thermal Response Test**

The mathematics of the TRT is based on the line source theory. In borehole applications, it is described in (Mogensen 1983) that this considers the temperature field around the borehole as a function of the time and the radius around the heat supply line (the borehole heat exchanger). Equation 2-1 expresses this assuming a constant heat flux from a line along the vertical axis of the borehole.

\[
\Delta T(r, t) = \frac{q}{4\pi L k} \cdot Ei \left( \frac{r_b^2}{4\alpha t} \right) 
\]

Equation 2-1

Where,

- $\Delta T(r, t)$ ... the temperature difference between the source line and the undisturbed ground temperature
- $q$ ... the heat injection rate
- $k$ ... the thermal conductivity
- $t$ ... the time after application of heat injection
- $\alpha$ ... the thermal diffusivity
- $r_b$ ... radius around borehole measured from the heat source line (BHE)
- $L$ ... the borehole active length
- $Ei$ ... is the exponential integral

In the paper “Fluid to duct wall heat transfer in duct system heat storages” from P. Mogensen, it is referred to a work done in 1948 by Ingersoll and Plass, where it is shown that, from Equation 2-1, the solution of the exponential integral can be approximated to the temperature of the borehole.
wall with an error less than 2% if \( t > \frac{(20 R^2)}{a} \), where \( R \) is the borehole radius, as follows in Equation 2-2. The radius of action of the heat injection will increase with increasing time.

\[
Ei \left[ \frac{r_b^2}{4 \alpha t} \right] \approx \ln \frac{4 \alpha t}{R^2} - \gamma \tag{Equation 2-2}
\]

Where \( \gamma \) is the Euler's constant = 0.5772…

The result of the approximation is shown in Equation 2-3, provided that \( t > 4R^2/\alpha \).

\[
T_w - T_{ground} = \frac{q}{4\pi Lk} \left[ \ln \frac{4 \alpha t}{R^2} - \gamma \right] \tag{Equation 2-3}
\]

A thermal resistance \( R_b \) is then added in order to account for the temperature difference between the secondary fluid and the borehole wall. This incorporates one more term into Equation 2-3. With the addition of \( R_b \), the left side of the equation is thus expressed as the one between the secondary fluid \( T_f \) and the undisturbed ground \( T_{ground} \), as follows in Equation 2-4.

\[
T_f - T_{ground} = q \left[ R_b + \frac{1}{4\pi Lk} \left( \ln \frac{4 \alpha t}{R^2} - \gamma \right) \right] \tag{Equation 2-4}
\]

For the effects of the thermal response test, it is of convenience to re-write Equation 2-4 as follows:

\[
T_f = \frac{q}{4\pi Lk} \ln(t) + q \left[ R_b + \frac{1}{4\pi Lk} \left( \ln \frac{4 \alpha t}{R^2} - \gamma \right) \right] + T_{ground} \tag{Equation 2-5}
\]

2.3.2 The results and analysis from a TRT
Equation 2-5 is a linear equation of the type \( T_f = m \cdot \ln(t) + b \), where the slope of the curve “\( m \)” is presented in Equation 2-6 and “\( b \)” is a constant as shown in Equation 2-7

\[
m = \frac{q}{4\pi Lk} \tag{Equation 2-6}
\]

\[
b = q \left[ R_b + \frac{1}{4\pi Lk} \left( \ln \frac{4 \alpha t}{R^2} - \gamma \right) \right] + T_{ground} \tag{Equation 2-7}
\]

Plotting the inlet and outlet temperature measured during the response test, two curves as the ones shown in Figure 2-14 are obtained. The mean fluid temperature \( T_f \) is obtained from these two values and then plotted against the logarithm of time as shown in Figure 2-15. It is known that, by doing this plot, the measured points fall on a straight line which slope is then used to determine the thermal conductivity of the rock (Equation 2-6). Furthermore, the thermal resistance of the borehole can also be calculated.

It is important to mention that Equation 2-3 assumes an infinite length of the borehole and also constant temperature along its axis. The
latter is not the case in practice. However, due to that the temperature change in the axial direction is small when compared with the temperature change in the radial direction the validity of the equation is not compromised.

![Figure 2-15 Mean fluid temperature vs. logarithmic time (Gehlin 1997)](image)

Aware of this and in addition to logical assumptions of the rock volumetric heat capacity, a calculated value for the borehole wall temperature can be drawn in the same diagram for the same time lapse, resulting in a straight line with the same slope as the observed temperatures. The temperature difference between both lines corresponds to the temperature drop that occurred between the circulating fluid and the borehole wall which, together with the measured heat addition or extraction, finally guides to a simple calculation of the rock thermal resistance.

A good estimation of the borehole active depth and the undisturbed ground temperature is very important when analyzing the response test results. The former is estimated by circulating the secondary fluid for a period of approximately one day without adding or extracting any heat. This permits that the fluid temperature is balanced with the ground temperature. Figure 2-16 shows the measured values of inlet and outlet fluid temperature as well as ambient temperature vs. time from the beginning of a response test carried out at Vigo, Spain (Hellström 2007).

![Figure 2-16 Measured values of inlet and outlet fluid temperature as well as ambient temperature vs. time from the beginning of the test](image)

It can be seen in Figure 2-16 that the inlet and outlet fluid temperatures during the first 25 hours of the test were almost a constant equal to approximately 16 °C which corresponds to the undisturbed ground temperature $T_{\text{ground}}$ that would later be used for the calculations and results interpretation.

Regarding the active borehole depth, it is important to have the borehole protocol from the borehole driller and, if possible, to carefully measure the ground water level before the test.

### 2.3.3 Thermal Response Test while drilling

To finalize this chapter, it is worth to mention that there is a method presented by (Tuomas 2004) for carrying out the thermal response while drilling the borehole. It consists of analyzing the heat transferred in the rock during the drilling activities.

The working principle of this test is basically the same as the one previously presented for the TRT. Nevertheless, the heating is in this case caused by heat dissipation from the drilling activities. This heat is transferred to the drilling fluid and then to the rock formations. This transfer will depend on the rock thermal properties.
The heat during drilling is supplied through the drill string by pressurizing the drilling fluid which dissipates into in the hammer tool. The water temperature at the drill will depend on different factors such as the heat transferred to the bedrock, the inlet water temperature, the heat released in the hammer, among others. The conductivity is then measured by monitoring and analyzing the values of the inlet and outlet drilling water as well as the power injection into it.

This method allows obtaining the conductivity along the borehole depth instead of an average value for the whole well. However, it does not give a value for borehole thermal resistance and therefore it is not possible to analyze the thermal performance of different borehole heat exchangers.
3 Determination of ground water flow in boreholes

The heat transfer between the bedrock and the borehole heat exchanger is also influenced by the ground water flow around the borehole. There exists an endless water circulation between the atmosphere, land and oceans known as the hydrologic system. Groundwater is a natural resource which originally comes from rain water as well as melted snow which reaches the ground level. A percentage of this water is evaporated and another part reaches the pores and fractures of the ground which are filled with water and then infiltrated into the ground surface. From the water volume that finds its way into the ground, a part is absorbed in organic activities such as root and animal water intakes while the rest travels into the soil and reaches what is called the water table. Not until this moment, it is called groundwater. Its location is illustrated in Figure 3-1. It can be observed that it is located at what is called zone of saturation where the rock pores are filled with water (TREMBLAY 1996).

Lack or excess of rain and snow make an influence on the amount of ground water that might be at a certain location. Then, there might be water movements in different directions under the ground due to the presence of cracks around the borehole or natural convection occurring due to ground water density differences. These are governed by the climatic conditions and topography at a certain location.

3.1 The effect of ground water in energy wells

It is common in Sweden to find that the energy wells are filled with ground water. The presence of the ground water greatly influences the thermal resistance between the rock and the circulating fluid since it determines the section of the borehole heat exchanger that will be exposed to effective heat transfer. This is due to the fact that water has a better conductivity value than air.

The heat transfer from the rock to the secondary fluid becomes better as the ground water level is higher. The borehole portion which is under the ground water level is known as “active borehole length”. This concept is illustrated in Figure 3-2. The thermal transport between the bedrock and the borehole heat exchanger BHE is proportional to the ground water level in the borehole.
A higher mass flow of the ground water around the BHE improves the heat transfer to the secondary fluid. The water flow transfers sensible heat since it comes from where the ground temperature is undisturbed and it is cooled down as it comes into the area of the borehole. The local convection heat transfer coefficient might also increase due to the local higher water velocity around the BHE. Therefore, the heat transferred to the secondary working fluid increases and it is of importance to know to the highest extent how the ground water behaves. This might be influenced by different factors such as the presence of cracks around the borehole and natural convection occurring due to ground water density differences along the borehole length. It is known from (Claesson 1985) that the significance of natural ground water movement effect over the heat extraction from the ground can vary depending on how homogeneous it is along the borehole or due to punctual ground water flow at some place in the borehole.

Regarding the effect of ground water density differences, sometimes called thermosyphon effect, there is a natural ground water movement due to temperature differences at different depths. This phenomenon is of higher relevance when using borehole energy storage systems since the ground water temperature is altered significantly when sending heat to the ground.

When dealing with heat extraction problems in energy wells, we usually do not know about the ground water flow around the BHE. Thus, no convection considerations are often taken into consideration and, unless we measure a relevant flow, we have to assume that it is zero, i.e. the heat transfer is considered to happen purely by conduction.

### 3.2 A simple estimation method

A method to have a rough estimation of how porous the rock is consists of injecting water into the borehole and registering how long it takes for it to disappear. This gives an idea of how much volume per unit time runs through the borehole.

This estimation can be carried out with an instrument that consists of a packer with open ends surrounded by an expandable volume that can be filled with gas. Figure 3-3 shows an instrument of this type called Petrometalic 102 from the Swedish company Geosigma AB.

For carrying out the measurement, the packer is inserted under the ground water level into the borehole. Subsequently, the pressure of the expandable volume (black section in Figure 3-3) is increased causing an inflation which permits the packer to be tight against the borehole walls and hence divides the borehole in two parts.

The upper open end of the packer is tightly screwed with subsequent tubes (with known dimensions) until the desired height at the ground level. At this point, it is possible to pour water at steady state through the upper end of the pipe so that it flows down into the borehole. The injection water pressure represented by the water column between the ground water level and the injection point makes the water enter the borehole with a certain flow rate. This flow value represents a rough estimation of how much water runs
through the well.

Figure 3-4 shows a curve which relates the packer diameter with the gas pressure that is used when inflating. This is a very useful tool since it permits finding the appropriate gas pressure of a given borehole diameter.

Figure 3-5 is a picture while injecting the water into the borehole during a field measurement. It is also seen the gas tank used to inflate the packer expandable section.

3.2.1 Study case of simple ground water flow measurements
An estimation of ground water flow in a borehole was recently made using the equipment previously presented. The borehole is 220 meters deep and has a diameter of 140 mm. The experimental procedure was the following:

- Measure ground water level
- Insert the Petrometalic 102 carefully into the borehole and screw it (tightly) together with water pipes as it goes down until it is submerged under the ground water level
- Make sure that the Petrometalic 102 hangs safely into the borehole
- Inflate the Petrometalic 102 slowly with gas until it reaches a pressure of 6 bar which corresponds to a diameter of 180 mm. This ensures that the instrument is tight into the borehole and that there will be no flow coming upwards when injecting the water.
- Identify the height of the point from which the water will be injected with respect to the ground water level.
- Measure the initial volume of the water in the tank or weight the tank before starting the water injection.
- Select a visible height reference point to set the start and stop point of the time measurement. This is done by selecting a point where the water level is constant while pouring it through the pipes into the borehole under stationary conditions.
- Pour water into the pipes until the tube is filled up to the reference level.
- Start injecting water constantly and measuring the time.
- After the water has been poured, measure the final volume of water in the tank or weight the water tank into the system (the important volume is the one added during the measured time).
- Calculate water flow with the injected volume and the measured time.

The results of the tests are shown in Table 3-1.
Table 3-1. Results from simple ground water flow measurements

<table>
<thead>
<tr>
<th>Run</th>
<th>ground water level [m] before pouring</th>
<th>tank weight after pouring [Kg]</th>
<th>poured volume [liters]</th>
<th>Pipe length [m]</th>
<th>time [sec]</th>
<th>water flow [l/min]</th>
<th>Injection P [friction loss]</th>
<th>Average flow Qp [l/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.17</td>
<td>1.36</td>
<td>7.81</td>
<td>8</td>
<td>177.9</td>
<td>2.633</td>
<td>not included</td>
<td>4.61</td>
</tr>
<tr>
<td>2</td>
<td>9.29</td>
<td>1.06</td>
<td>8.23</td>
<td>8</td>
<td>204.3</td>
<td>2.417</td>
<td></td>
<td>4.61</td>
</tr>
<tr>
<td>3</td>
<td>4.36</td>
<td>1.49</td>
<td>7.71</td>
<td>8</td>
<td>191.1</td>
<td>2.347</td>
<td></td>
<td>4.61</td>
</tr>
<tr>
<td>4</td>
<td>9.23</td>
<td>0.9</td>
<td>8.33</td>
<td>8</td>
<td>229.3</td>
<td>2.180</td>
<td></td>
<td>4.61</td>
</tr>
<tr>
<td>5</td>
<td>9.12</td>
<td>0.77</td>
<td>8.35</td>
<td>8</td>
<td>237.6</td>
<td>2.109</td>
<td></td>
<td>4.61</td>
</tr>
</tbody>
</table>

It can be see in Table 3-1 that the estimated value for the amount of water passing out through the cracks at the specific overpressure per unit time was 2,337 l/min. This flow is considered relatively low.

3.3 Ground water flow logging in energy wells

Localizing and measuring the ground water movements around energy wells is a useful method for characterizing the borehole. By measuring ground water flow one can localize cracks/fissures located at different depths and hence determine where significant heat transfer changes occur. This happens due to the fact that the flow changes abruptly at the points where there exist cracks and the local heat transfer coefficient increases due to the higher water velocities around the borehole heat exchanger.

One way for logging ground water flows in boreholes consists of pumping the ground water out of the borehole and thus creating a water flow from the surrounding fissures to the borehole.

At some point while pumping out water from the borehole, one could possibly find a balance between out pumped flow and the natural incoming flow into the well by keeping the water level stable. The flow of the water that is being pumped out is an indication of how much ground water flow there is. In other words, the flow pumped out will be equal to the ground water flow into the hole as long as the ground water level is kept constant. Moreover, one can simultaneously log the flow along the borehole length in order to discover at which specific points in the boreholes the water is flowing in. This gives a direct analogy to crack location.

3.3.1 The flow Logging equipment from Geosigma

The Swedish company Geosigma AB, specialized in soils, rocks and water, has developed special equipment for flow logging in boreholes. One of these basically consists of a metal cylindrical probe with a propeller located in its inner part. Figure 3-7 shows a picture of this equipment.

The measurement is done by sending down the equipment at a known velocity and registering the rotation of the propeller which happens due to the presence of ground water flow. This is then related to the flow conditions at the different depths.

It can be observed in Figure 3-7 that the equipment has a rubber disk at the end. This disk can be changed according to the borehole diameter and it is used in order to avoid that the ground water flows around the probe, i.e. the idea is that all the water flows through the propeller so the logging
becomes as exact as possible. Besides this, the white bands located parallel to the metal cylinder are used to center and steer the instrument into the borehole. Their size is also chosen depending on the borehole diameter.

The Geosigma’s flow logging instrument can be used in boreholes down to 46 mm in diameter and has a measuring minimum velocity value of 0.3 m/min which corresponds to a minimum flow of approximately 0.7 l/min in a 56 mm borehole. The probe length is 1.3 meters and its diameter (without the steering bands nor the rubber disk) is 43 mm.

The equipment does not only consist of the probe. In addition, other components are necessary. One of them is a submersible pump which can be used for pumping out the ground water from the borehole in order to provoke ground water flow. The submersible pump looks as the one shown in Figure 3-9. The flow pumped out from the borehole is also registered with a flow meter as the one shown in Figure 3-8.

This montage has a valve arrangement which allows sending water back to the borehole when necessary. Finally, all the data is registered in a logger. Other secondary equipment is used for installing the different equipment parts. These can be observed in Figure 3-10.
When the equipment is installed into the borehole, it looks as shown in Figure 3-11.

It can be seen in Figure 3-11 that there are several cables going into the borehole. These carry the signal from the measurements done with the probe propeller and also for giving electrical power to the submerged equipment. The black and the while hoses are for pumping the water out and into the borehole respectively.

A sketch of the whole system is shown in Figure 3-12.
3.3.2 Study case of flow logging

The flow logging equipment from GEOSIGMA has been used in a borehole installation which is part of a research project called “Efficient use of geothermal wells for heat pumps” at The Royal Institute of Technology, Sweden.

The studied borehole is 260 m deep and has a diameter of 140 mm. The ground water flow into the borehole resulted to be approximately 0.4 l/min after decreasing the ground water level by 35 meters.

The test started at the ground water level by trying to register any possible flow through the borehole. However, no flow was detected and the water level was reduced 22 m. At this point, the borehole did not present any significant ground water flow during an approximate period of one hour and the water level was finally reduced by 35 m with respect to its original level. At this point, although the current flow was very low (0.4 l/min), a logging process was carried out as shown in Figure 3-13.

The minimum flow value which allows finding anomalies (fractures, fissures, cracks) around the borehole for this equipment is 2 l/min and therefore, no anomalies were localized during the test. However, the results show that, at the interval between 190 – 200 m there is a possible small increase in the borehole diameter.

3.4 The Possiva flow logging equipment

The possiva flow logging equipment is a measurement instrument developed by a company called PRG-Tec Oy with the intention of determining the positions and flow rate in flow yielding fractures in boreholes. This instrument is based on a difference flow meter principle which consists of measuring at limited sections of the boreholes in stead of measuring the total cumulative ground water flow along the borehole.
According to (Mikael Sokolnicki 2007), the incremental changes of flow along the borehole are generally easy to be missed since they are very small. The Possiva Flow meter can solve this problem by using rubber disks at two ends of measuring probe in order to isolate the measurement area from the upper and lower part of the ground water with respect to the measurement instrument, as shown in Figure 3-15.

There are four rubber disks at the upper end of the section and normally six at the lower end of the section. The distance between rubber disks is about 4 cm for the four lowermost rubber disks and about 6 cm for the two uppermost ones. Centralisers are used to keep the tool and rubber disks in the middle of the borehole (Jan-Erik Ludvigson 2002).

The ground water flowing from fissures located between the upper and lower rubber bands passes through a section where the flow sensors are located. The flow along the borehole (flowing vertically) outside the isolated test section passes through a bypass pipe and is discharged at the upper end of the instrument.

The possiva flow meter can be used to measure the flow in and out of the borehole. The measuring principle uses a thermal pulse and/or thermal dilution methods for determining the flow. This is done by the use of thermistors which track the dilution of a thermal pulse and the transfer of the thermal pulse with moving water.

The instrument can be used for boreholes with diameters of 56, 66 and 76 mm and the length of the measuring section can vary according to what is needed to be measured. The flow range is between 6 and 300000 ml/hr with ± 10% accuracy (Mikael Sokolnicki 2007).
4 Determination of borehole geometrical characteristics

It is known from previous chapters that the thermal performance of the bedrock as an energy source for vertical energy wells might vary based on:

1. The energy need and type of building, type of distribution system in the house, and energy utilization regimes taking place in the building.

2. The ground water level of the site.

3. The ground thermal properties

4. The temperature of the ground

5. The borehole geometry

The first three factors have already been explained in previous chapters of this report and point number 4 is presented in chapter 5. In addition to that, this section deals closely with point number 5, the borehole geometrical characteristics and the different ways that there are to describe them in detail from the geometrical point of view.

As a start, it is of relevance to mention that there is a standard called Normbrunn-97, made by the Geological Survey of Sweden SGU which presents the regulations to be followed in Sweden when drilling energy wells for heat pumps. It includes several parts regarding the planning of the borehole, the drilling equipment, the usage of the well, the placing of the collector, and the duties and obligations of each activity (SGU 1997).

Generally, two steps have to be obeyed. The first step requires that a steel pipe must be introduced at the same time when drilling the first part of the hole. This pipe thickness is meant to be at least 5 mm and it has to be tightened into the ground rock so that any inflow of surface water or water in the top soil is prohibited. Figure 4-1 shows a borehole with its corresponding steel pipe. Its total depth measured from the surface area must be 6 meters.

Afterwards, the steel pipe can be tightened with the help of cement. This avoids the falling of rock pieces and superficial water down into the hole, and eases the installation of the collector.

The second step deals with the drilling of the hole through the rock until the desired depth. The drilling equipment must include a compressor, piping and hoses approved by previous inspections. The well must, if possible, be located at least four meters away from the house walls.
A typical energy well for heat pump usage is normally described by its geometrical characteristics and the ground water level conditions. The diameter (normally between 100 and 150 mm) and its depth (between 120 m and 250 m depending on the above mentioned factors) are the most common parameters used when describing boreholes. However, as it has been stated along this report, it is of importance to be able to describe energy wells in detail when doing research projects.

There exists an instrument called C-ALS “Cavity auto-scanning laser system” (see Figure 4-2) which can be inserted into a borehole for scanning its different geometrical properties along the depth. It measures the three-dimensional shape of the wells and ensures a complete 360° covering of the borehole. It also has a digital compass as well as sensors which enable it for accurate positioning and orientation inside the well.

Figure 4-2. C-ALS cavity scanning system (MDL 2007)

One geometrical parameter of great importance is the borehole radius. It was explained in chapter 2 that the thermal resistance of a borehole is dependent to its radius and to the BHE characteristics. The thermal resistance of two boreholes with different radius but, identical BHEs, identical thermal and ground water conditions, would be lower in the borehole with lower diameter. This is because the values of the logarithmic temperature distribution associated with radial conduction become lower since the BHE pipes sit closer to the borehole wall.

Regarding the borehole length, it is known that the general bedrock temperature gradient is positive (as shown in Figure 1-1). Therefore, it would be logical to believe that the boreholes reach the planned depth after being drilled and thus a temperature in the bottom of the well can be predicted. However, these is not always possible due to deviations of the drill directions which make that the real borehole depth after drilling end up many meters higher than expected, and therefore with a slightly lower temperature.

In addition, the thermal influence between two boreholes is proportional to the distance between them, i.e. if two boreholes are close to each other; the thermal performance in one of them might be influenced by the other. The bedrock temperature profile could therefore be altered if several boreholes, drilled close to each other, with different heat extraction regimes are simultaneously used.

It is usually desired to address the boreholes towards a known direction in order to guarantee that they will not be so close to each other at a certain depth under the ground surface level and also to prevent a risk of crossing two boreholes while drilling the well.

Due to the relevance of these aspects regarding energy wells for heat pumps, the following section explains how these borehole deviations occur and describes some method for measuring it.

4.1 Borehole deviation measurements

Drillers usually desire to plan the drilling direction in advance, in order to assure that the holes do not approach or influence each other. It is difficult to control deviations of the wells with respect to the planned direction and the borehole might take a slightly different direction as compared with what was expected as shown in Figure 4-3.

Figure 4-3. Drilling deviated boreholes
A borehole deviation might principally be due to possible presence of fractures or rock failures at
certain depths. The cracks can suddenly change the drill orientation and guide it towards its own
planes. The rock natural conditions and the expected borehole depth also influence since the degree
of deviation might proportionally increase with the borehole depth. Other factors are associated
with the drilling method and equipment, i.e. the type of drill and drill accessories, rotation velocity,
uncontrolled or excessive push down, the driller experience, and the initial position of the drilling
hammer (Ingetrol 2004).

The determination of type of equipment that can be used in order to measure a borehole deviation
depends on the desired measurement accuracy, the test duration and usage difficulty. Different
measurements carried out in the same borehole will always provide slightly different results, but
they should all converge to a most probable value. The deviation measurements are normally car-
ried out by registering, among others, two main parameters:

- **Dip angle**: inclination between 0 and +/- 90°
- **Azimuth angle**: direction - between 0 and 360°, relative to the direction of the magnetic
  north.

With these two parameters, the Cartesian position parameters x, y and z, are calculated at each
measurement point.

What follows is a presentation of different products and methods used to carry out borehole devia-
tion measurements. At the end, a study case with real measurements will be presented.

### 4.1.1 The Flexit instruments

Flexit is a Swedish company that designs and sells specialized instruments for different types of
geological surveys. This section presents two of their instruments used to measure borehole devia-
tions:

The first one is called **FLEXIT GyroSmart**, which uses the gyroscope principle. A gyroscope is a
device that can be used to do angle rate measurements based on the Coriolis force effect.

A FLEXIT GyroSmart is built as a digital butterfly gyroscope (see Figure 4-4) that consists
of two wings which are forced to vibrate in antiphase motion out a plane to which they are
interconnected. The amplitude of the out of plane vibration is directly proportional to the
applied rate.

To finish, the output rate signal is measured by a second set of electrodes located underneath
the wings.

The micro gyroscopes enable the GyroSmart to do measurements in zones of magnetic anomalies
for a complete and precise mapping of boreholes. The accuracy of the instrument is 0.2° for the dip
angle and 0.5° for the azimuth angle in the worst case scenario. It is battery operated for 9 hours of
continuous operation and it has a storage capacity of 512 MB. The communication between the
GyroSmart and the storage instrument is synchronized via wireless.
The second instrument can be of two types, \textbf{FLEXIT SingleSmart}, and \textbf{FLEXIT MultiSmart}. They orientate themselves after the earth magnetic field when they are introduced in the borehole. They both have two parts: StoreIT (shown in Figure 4-5) and SensIT (shown in Figure 4-6).

![Figure 4-5. StoreIT](image)

![Figure 4-6. The SensIT probe](image)

The sensIT is sent down into the borehole covered with a pressure barrel which protects it from high pressure and against shock with the bedrock; whiles the StoreIT pocket pad stays up at surface level. These two parts are synchronized so that, by running the SensIT to the depth of interest, one can record the exact time and measured parameters at a certain location. The StoreIT can store up to 890 sets of measurements (shots) including their time, date, borehole reference and depth. Everything is controlled from the StoreIT.

The difference between the SingleSmart and the MultiSmart instrument depends on the features of the SensIT since it can work on two different modes, single shot and multi-shot type, respectively.

In the \textit{Single shot} case, the measurement is made at a certain position each time that the equipment is located at the measurement point. One must take down the equipment to interest point and the borehole direction is then determined by puzzling all the measurements carried out along the depth. On the other hand, \textit{multi-shot} equipment makes several sequential measurements as the equipment is going down and the borehole’s trajectory simultaneously pictured, i.e. it makes a survey in one run taking a measurement every five seconds. However, only the points for which it recorded a depth (commanded from the StoreIT) are saved in the StoreIT and the rest are discarded.

It is important to mention that all the Flexit smart tools are sent down into a brass pressure barrel on at least 3 m of non-magnetic rods and that none of them has cable nor requires any initial orientation. Their easiest error scenario could occur due to linear, radial or rotational movement of the SensIT probe while it takes a reading down in the borehole, but this is easily controlled by the instrument thanks to a 3D accelerometer that measures the gravity field strength in three orthogonal directions so that the reliability of the overall measurement can be checked. If the measurement point is not reliable, the software suggests the user to erase the shot.

Thanks to borehole deviation measurements, it is possible to take early actions to keep a borehole straight since a hole can be redirected in order to reach the planned target and depth.

\subsection*{4.1.2 The MDL rod boretrak instrument}

There is also an instrument called \textit{MDL rod boretrak} which surveys the borehole deviation by using lightweight rods which are aligned and continuously connected by a common axis in hinge form. It works under a different principle than the common equipments, i.e. it is a non magnetic and non gyro instrument. Figure 4-7 shows the MDL rod boretrak equipment sold by the Canadian company TEC, Thomas Engineering LTD.
The first rod, better known as measurement head, is made of stainless steel. It has a diameter of 37 mm and weighs 2.5 Kg. It has a sensor that calculates the borehole deviation from the vertical direction by means of inclinometer sensors located in it. The output from the sensors is compiled in a logger and then transfer to a computer for post processing. The accuracy of the measurement is 0.1°. The rest of the rods weight 0.7 Kg each and are made of carbon-fiber. They permit lowering the equipment into the borehole by adapting its shape to it (MDL 2007) as shown in Figure 4-8.

The C-ALS equipment presented previously is used in the same way as the MDL rod boretrak by attaching it to the rods in stead of the measuring head.

4.1.3 Study case of deviation measurement

This section presents the results of borehole deviation measurements that have been done as part of a research project at The Royal Institute of Technology KTH. In this case, the borehole deviation was measured in three boreholes which distance between each other is approximately 5 meters, as illustrated in Figure 4-9.

The depth of the three boreholes is 260 meters and the diameter is 140 mm.

The measurements were done with a Flexit MultiSmart instrument which was sent down into each borehole with a wire which has a length counter so the exact location of the instrument can be known (see Figure 4-10). Measurement points were taken every 10 meters for a total of 26 measurement points. The following parameters were measured for each borehole:

- Depth of the measurement point
- Dip angle at the measurement point
- Azimuth angle at the measurement point
From this data, the coordinates \(x, y, z\) for each measurement point were calculated and presented in tables for each borehole.

The measurement results were presented both in a tabulated and graphical way. A two dimensional plot is shown in Figure 4-11 taken from the original report made by the company TGB borrteknik AB, who carried out the measurements.

![Figure 4-10. Sending down the Flexit instrument](image1)

![Figure 4-11. Results from borehole deviations (TGB 2007)](image2)

The horizontal and vertical axis (Figure 4-11) express the borehole deviation in the \(x\) and \(y\) directions [in meters] at each measurement point. It can be seen that the boreholes ended up far away from the vertical direction, specially borehole number 6 which total deviation in the vertical axis indicates more than 90 meters deviation.
A three dimensional plot of these points has been done (see Figure 4-12) in order to visualize this situation in a better way.

The expected depth of the wells was 260 meter. However, it can be observed in Figure 4-12 that boreholes 4, 5 and 6 ended 9,65; 13,12 and 20,91 meters away from the planned depth.

Figure 4-13 shows a picture of the instrument that was used during these deviation measurements.
4.2 The Borehole Protocol

Directly after a driller makes a borehole, it is a duty to write what is called borehole protocol and hand it to the SGU in order for them to register the well in their database. Figure 4-14 shows a copy of the borehole protocol form. This document includes information about the location of the well, the drilling method used, the type of rock, the ground water level, the steel pipe dimensions, and any other extra notes that the driller might want to mark.

![Figure 4-14. Borehole protocol form](image_url)
5 Temperature measurement techniques in energy wells for heat pumps

As it has been presented in the previous chapters, several parameters must be considered in order to follow up in detail the thermal performance of an energy well installation for heat pumps. E.g. groundwater flow, ground thermal properties, etc. However, it is of great importance to also monitor the borehole and secondary fluid temperature at different depths in order to be able to draw a complete picture of what happens under the ground regarding heat transfer. This chapter presents two different methods for carrying out these temperature measurements, using thermocouples and using optic fiber cables.

The former method is very attractive since it is a technique for measuring the secondary fluid by direct contact with the thermocouple. It consists of perforating the pipe wall with a thermocouple wire in order to achieve a temperature measurement in the inner part of the collector pipes. The technique can be used for punctual temperature measurements at a determined depth.

The second method consists of using distributed temperature sensing (DTS) technology which requires the use of fiber optic cables and a special reading instrument. This technique offers many advantages from the accuracy point of view and permits continuous and simultaneous temperature readings every one meter along the whole cable length.

The focus is, as mentioned, on measuring the temperature of the secondary fluid circulating into the BHE and on the filling material side, as shown in Figure 5-1 and Figure 5-2.

Figure 5-1. Location of measurement points in the secondary fluid
5.1 Temperature measurements in energy wells using Thermocouples

5.1.1 The thermocouple principle
The thermocouples working principle is called “the Seebeck Effect”, which states that if a circuit consists of two dissimilar metals and two connecting junctions between them are made and exposed to different temperatures, a current is induced in the circuit. Then, with a volt-meter in the circuit, an electric potential proportional to the temperature difference can be detected.

The Seebeck effect is the main parameter indicating the temperature values during a temperature measurement with thermocouples. However, there are also two other effects which only are considered as uncertainties in the measurement; these are called the Peltier and the Thomson Effect.

The measurement techniques with thermocouples developed in this chapter are done with thermocouples type T. In this case, the two metals that enable the Seebeck Effect to occur are copper (positive wire) and constantan (negative wire).

5.1.2 Temperature measurements in energy wells with thermocouples
The application of thermocouples in real geothermal wells can be used for measuring the temperature of the filling material of the borehole and also for the secondary fluid circulating into the BHE. Due to its relevance for thermal performance analysis of fluid flow in collector pipes and to its degree of complexity, this section is focused on the latter case. This type of measurement can be relatively more problematic since it might require perforating the collector wall at the point of interest and it would be strictly necessary to ensure the tightness of the insertion point. Otherwise, there would be a ground water pollution threaten.

Previous studies have been made locating the thermocouple on the outside of the BHE wall and covering it with a thin layer of aluminum foil, followed by 2 cm thick insulation. This method has been strongly questioned since the experiment results showed values which reliability is still doubted.

Therefore, this section presents some measurement techniques than ensure direct contact between the thermocouple and the fluid.

Another aspect of relevance when measuring the secondary fluid temperature is the position of the thermocouple inside the pipe. A wrong location of the measurement point could cause a flow dis-
turbance as well as the reading of the wrong temperature value. Nevertheless, measuring the temperature at any point inside the pipe ensures a more reliable reading when comparing with the external thermocouple location.

5.1.3 The experiments for the development of the new measurement technique

For measuring the secondary working fluid temperature at different depths of the borehole installations, several insertion methods of a thermocouple through a PEM 40 x 2,4 mm pipe were tested in order to evaluate their water tightness. The thermocouple is of the type “quick disconnect stainless steal” with code TMQSS-M050U-150, supplied by Omega Engineering.

The first initiative for these techniques was taken by (Nowacki 2007) who proposed to experiment the following options:

- **Insertion of pre-heated thermocouple through the pipe wall:** It consisted on heating a 0,5 mm thermocouple wire through direct contact of the wire with an electric resistance, followed by an angled insertion through the pipe wall. The perforation is done without difficulty since the plastic melts as the thermocouple wire penetrates. The hypothesis of the method states that the plastic would tie up as it solidifies, allowing water tightness in the thermocouple insertion point. Figure 5-4 illustrates an already made insertion of this type.

![Figure 5-4. Thermocouple wire inserted through pipe wall](image)

- **Insertion of a rivet or a conic screw:** This method consisted of locating a rivet into a previously made hole through the pipe wall and subsequently locating and attaching a thermocouple wire into the rivet’s middle point using Epoxy. Conic screws were also inserted through the pipe wall to evaluate their tightness. These two methods are illustrated in Figure 5-5.

![Figure 5-5. Rivet and conic screw inserted through pipe walls](image)

Later on, (Palm 2007) proposed an improvement to the first initiative:

- **Angled insertion of thermocouple with subsequent melting of pipe material over the perforated point:** This was carried out by covering the perforation area with pipe material in order to create an extra pipe layer in the insertion surroundings and thus ensure a higher degree of tightness. It was done by vigilant melting of pipe material around the insertion point and subsequently letting it solidify until it becomes part of the original pipe.
Moreover, (Broberg 2007) proposed two last methods. They consisted of the following:

- **Thermocouple located between pipe connection with an Electro socket**: Making a cross-sectional cut of the collector pipe at the point where the thermocouple is to be located, it is possible to place the thermocouple wire in between the two pipe parts by coupling them with the help of an electro socket as shown in Figure 5-7.

- **Thermocouple insertion through a hole with subsequent protection with shrinking hose**: A hole (2 mm in diameter) was drilled through the pipe wall following by the insertion of the thermocouple wire through it. The insertion point was lastly covered with a shrinking hose (a hose that reduces its diameter under the effect of high temperatures) in order to tighten it. Figure 5-8 shows a picture of the shrinking hoses before they are melted.

All these methods were tested at the laboratory of Applied Refrigeration and Thermodynamics at the Royal Institute of Technology, Sweden. The experiments were carried out as follows:

1. After performing the different insertion methods, the pipe sample was pressure tested with water using the pressure tester shown in Figure 5-9.
2. If the pipe sample resulted to be tight in step 1, it was then temperature cycled 5 times between -30°C and room temperature (approx. 24°C) in order to consider possible pipe contractions and elongations due to temperature changes.

3. Pressure test with water once again after temperature cycling

4. If step 3 succeeded, the pipe sample was finally pressure tested with water + air inside the pipe. This ensures that the measurement point is completely safe under any circumstances in the real installation.

5.1.4 The test results

The experiment presented above resulted to be very successful and the three last proposals were all tight after the pressure tests.

When applying the angled insertion of the thermocouple through the pipe wall (without subsequent melting of pipe material), two perforation samples resulted to be water tight at a pressure of 12 bar and six insertion points presented leakages at pressures around 4 bar. However, just a few of them was tight during the test with pressurized air and water. This method does not guarantee that there would not be leakages.

Regarding the test with the rivets and conic screws, the whole assembly (5 rivets and 3 conic screws) was water tight and presented no leakages during the first pump test even under pressure equal to 10 bar. The conic screws perforations stayed water tight during the whole test, however, after cycling the pipe sample between -30°C and room temperature (24°C), all the rivet insertion points presented leakages at 7 bar. In all the cases, these leakages took place through the borderline between the rivet and the plastic pipe and not through the Epoxy assembly of the thermocouple and the rivet's middle hole.

The method by melting extra pipe material after inserting the thermocouple wire resulted to be 100% successful after 10 trials. No leakages appeared at 10 bar pressures along the whole test. Figure 5-10 shows a picture a thermocouple assembly at a real borehole installation. This assembly was done by angled insertion of the thermocouple wire, followed by covering the area with extra melted pipe material and finally protected with a shrinking hose.

![Figure 5-10. Completed thermocouple assembly](image)

The same successful resulted from the experiments with the electro socket. No leakages appear even at pressures of 10 bar. Figure 5-11 shows a picture of the cross section of the electro socket welded area with an inserted thermocouple wire.

![Figure 5-11. Picture of the cross sectional welding of an electro socket](image)

Furthermore, shrinking the hose on top of a drilled hole with an inserted thermocouple resulted to be water tight. It was therefore decided to use it as a security factor in connection with the other methods, i.e. shrinking the hose after melting extra pipe material on top of the insertion point, and using the shrinking hose to cover the electro socket after the connection is done.
5.2 Temperature measurements in energy wells using Distributed Temperature Sensing (DTS)

The technology consists of passing information through an optical fiber cable in the form of light. The cable is normally enclosed in an arrangement of a core, a cladding and the light which is guided to and from a measurement zone where the light is modulated by the measured variable of interest and returned along the same optical fiber to a detector at which the optical signal is interpreted.

Figure 5-12 shows a sketch of a typical DTS system. It can be observed a computer system (the DTS instrument) which is installed in a suitable monitoring location and connected to a length of optical fiber cable which is installed along an installation of interest. This figure is a perfect illustration for understanding the application of this technology in the ground source heat pumps field just imagining that the pipeline in the figure represents the energy well or the borehole heat exchanger.

What makes the optical fiber sensors attractive in this application is that they can measure at distributed point configurations, which means that they measure constantly along the fiber cable and this represents a huge advantage when comparing with thermocouples since only one cable is needed to measure at several points. The main benefits of this technology are:

- Their immunity to electromagnetic fields within the sensor system and within the feed and return signals
- The capacity of distributed measurements of temperature and position continuously over long distances using a single fiber cable as sensing element
- The sensor can be used in hazardous environments.
- High accuracy.

These benefits make the optical a very suitable instrument for temperature measurements in energy wells where the working environment is under the ground. Obtaining an accurate temperature profile from the borehole heat exchanger and filling material by only installing one or two cables definitely attracts the attention of researchers within this field.

Regarding the drawbacks of this technology one can mention the economic aspect. The optic fiber cables themselves are inexpensive. However, the cost of the DTS reading instrument is very high and is directly proportional to the equipment’s resolution. However, DTS systems are cost effective since one sensor can collect data that is spatially distributed whilst a conventional sensing system require to locate a thermocouple for each point of interest.

5.2.1 The fiber optic working principle

The shifts in temperature along the cable are sensed by introducing a light signal into a fiber and then the optical path length within the fiber is modulated or modified by the temperature. The physical phenomena capable of imposing this modulation can be varied (Webster 2000) and they can include linear and non-linear effects. In the linear case, the input optical frequency is the same as the output optical frequency.

On the other hand, the non-linear effects include fluorescence and Raman and Brillouin scattering which are usually observed within the fibers themselves. In this case, the input and the output optical frequencies are not the same since the light is absorbed within a material and re-emitted as a dif-
ifferent optical wavelength from the observed point. This is how the temperature values are read at different points in the cable. The punctual temperature values will determine the difference in optical wavelengths between the input and output signal.

The Raman and Brillouin backscatter are temperature sensitive. Brillouin lines become impractical, but the Raman signal with its two elements (the stokes and anti-stokes) can be filtered from the backscattered light and finally interpreted by the DTS instrument. Figure 5-13 illustrates the backscatter spectrum.

The effect has its origin in the frequency distribution of scattered light caused when the energy of an incident photon modifies the state of a molecule. This modification might increase or decrease the vibration state of the molecule resulting in a difference between incident and emitted frequency. This relationship is uniquely associated with temperature and can not be influenced by other external parameters. The type of scattering will therefore be defined by the temperature. Figure 5-14 illustrates the backscattering process happening within a DTS system.

DTS systems can be configured to automatically detect a break in the sensor fiber and report the location of the identified break. In order to avoid any loss of data, one can configure the sensor fiber in a loop where the fiber can switch to single ended measurement from both ends. This is normally recommended since offers the advantage of switching the measurement direction and comparing the media values of both configurations which should be the same. In case of a break, the DTS system can be set up to single ended operation.

5.2.2 Performance parameters
Actual DTS systems can be characterized in accordance to temperature, time, and length resolutions. Different denominations can be used to describe the performance parameters. According to (Schlumberger 2002), the parameters are divided in spatial range, spatial resolution, sampling interval, temperature resolution, and measurement time.
**Spatial resolution** is a parameter that indicates the distance between the 10% and 90% points of a step temperature change which happens at a point of the sensor fiber. Figure 5-15 illustrates this parameter. If there is a hot spot which width is lower than the spatial resolution, the measured temperature is lowered by approximately the ratio between the hot spot width and the spatial resolution.

![Figure 5-15. Spatial resolution of a fibre optic](image)

The **sampling interval** is the distance between each measurement point and it determines the total number of measurements.

The **spatial range** refers to the maximum length for which the performance specification is maintained.

The **temperature resolution** is represented by the standard deviation of the temperature measured values.

Time resolution is the specified time interval to acquire and present a complete temperature profile of one DTS loop to a certain temperature resolution. It includes the time for acquisition of the backscatter signal, digitalizing and processing.

A compromise among all the previous parameters defines the performance of a DTS system, e.g. evaluating a system that has 1 K temperature resolution, time resolution of 1 min, sampling interval of 1 meter and a total interrogation length of 2 kilometres; one could improve the capacity of this system to much more distance if the time resolution and sampling interval is increased and/or the temperature resolution is reduced.

### 5.3 Study case using thermocouples and DTS systems for temperature measurements in energy wells

From the same project as the previous study cases were presented, two of the research boreholes have been instrumented with thermocouples and optic fiber cables for temperature measurements both in the ground water and in the secondary fluid side. This section exemplifies the measurement techniques previously described by presenting the instrumentation of one of these two boreholes that is 260 meters deep and it is equipped with a Single U PE 40x2,4mm pipe collector.

The first measurement instrument to be installed in the collector was the inner optic fiber cable. Figure 5-16 and Figure 5-17 show pictures of the cable installation process.

![Figure 5-16. Inserting DTS cable into the BHE](image)

In addition, five thermocouples of the type “quick disconnect” and code TMQSS-M050U-150 from Omega Engineering were
melted in through the tube wall on both collector pipes in order to measure the secondary fluid temperature. This was done following the method “Angled insertion of thermocouple with subsequent melting of pipe material over the perforated point” followed by protecting the insertion points with a shrinking hose. Figure 5-19 shows some pictures while installing the thermocouples. The location of the insertion points are at 15 m, 55 m depth under the surface level and one right after the collector bottom (260 m deep). This is sketched in Figure 5-18.

![Figure 5-18. Location of thermocouples in the BHE](image)

After the thermocouples are installed in the pipes, they are connected with thermocouple cables of the type “T Thermocouple Wire” and code TT-T-24-TWSH-SLE from Omega Eng., which take the signal all the way up to the control room at the ground surface level. These cables are carefully identified and mounted VP – pipes in order to protect them from robust touch against the borehole wall during the BHE installation. The connection of thermocouples with the cables is protected with Epoxy in order to avoid possible contact with the ground water.

![Figure 5-19. Installing the thermocouples in the BHE](image)

Simultaneously, a fiber optic cable was installed at outer surface of the BHE in order to measure the ground water temperatures.
Figure 5-22 shows the borehole heat exchanger with all the thermocouple and fiber optic cables coming out from the borehole and going into a yellow pipe which takes them into a control room where the reading equipment is located together with the heat pumps. The reading equipment consists of the following equipment which is also shown in Figure 5-24:

- A data logger
- A temperature box where each of the thermocouples are connected to the logger through a circuit with an internal reference temperature (J₂) as shown in Figure 5-23. The measurement points in the borehole are represented by (J₁).
- A DTS for emitting and processing the laser light signal that travels through the optic fibre cables (includes its own screen and keyboard)
- A computer with screen for control of the measurements from the data logger.

Figure 5-23. Circuit for each of the thermocouples in the temperature box (Palm 2007)
6 Conclusions

- In order to ensure an efficient use of the ground energy, borehole characterization procedures need to be done during research projects prior to a vertical ground source heat pump installation. Additionally, appropriate temperature measurement techniques must be used so a detailed and reliable heat transfer monitoring can be done.

- Bedrock thermal property judgement can be classified within theoretical, laboratory or field measurements (in situ); and generally, this is carried out by: looking at geological tables and charts for the place of interest, making laboratory and field measurements of rock samples, making a thermal response test in situ by using the installed BHE, making a thermal response test while drilling a borehole, calculating the properties based on the rock composition.

- The simplest method to estimate the ground thermal properties is by the use of average values from geological maps. Nevertheless, there might be variations of up to 20% from the average value depending on the type of rock.

- Mineral composition analysis can be done at the laboratory by putting a rock sample in contact with a heat generating probe and analysing its transient response. The conductivity is determined by controlling the sample temperature profile versus time.

Measuring the rock thermal properties in the laboratory as well as in the field could sometimes not be 100% objective since the bedrock is vulnerable to its relation with possible natural changes in the borehole surroundings. However, if this time dependent variables can be evaluated in a relevant way, the laboratory and practical measurements should be prioritized before calculation measurements.

- In situ measurements of borehole thermal properties are a better approximation to the reality in view of the fact that many ideal assumptions are made when making mathematical models.

- There is a method for carrying out the thermal response while drilling the borehole which consists of analyzing the heat transferred in the rock during the drilling activities. This method allows obtaining the conductivity along the borehole depth instead of an average value for the whole well. However, it does not give a value for borehole thermal resistance and therefore it is not possible to analyze the thermal performance of different borehole heat exchangers.

- During a thermal response test, a fluid is circulated through the borehole heat exchanger and a constant heat power is supplied or extracted so that the fluid is heated/cooled in a controlled way. The measured variables are the supplied heat, the outdoor temperature, the secondary fluid flow, and the borehole incoming and outgoing temperatures. The mean fluid temperature is plotted against the logarithm of time and the measured points fall on a straight line which slope is then used to determine the thermal conductivity of the rock and then the thermal resistance can also be calculated.

- A method to estimate the ground water flow in a borehole is to insulate the borehole from its upper part with a packer and then inject water through the packer registering how long it takes for the water to flow down. The packer is inserted into the borehole until the desired depth and then filled with gas in order to tighten itself to the borehole wall.
By pumping out water from a borehole and finding a balance between the out pumped flow and the natural incoming flow into the well by keeping the water level stable, it is possible to predict the flow of ground water through into the well. Simultaneously the flow along the borehole length can be logged with a cylindrical probe with a built in propeller made by the Swedish company Geosigma AB, which rotation rate depends on the water flow at a certain depth. This gives a direct analogy to crack location around the borehole.

There is an instrument called Possiva flow meter ideal for locating cracks around the borehole. It consists of a probe that is sent down into the well and is based on a difference flow meter principle that consists of measuring at limited sections of the boreholes in stead of measuring the total cumulative ground water flow along the borehole. It uses rubber disks at two ends of the measuring probe in order to isolate the measurement area from the upper and lower part of the ground water with respect to the measurement instrument so that an exact horizontal flow value can be determined.

A borehole deviation might principally be due to possible presence of fractures or rock failures at certain depths that can suddenly change the drill orientation and guide it towards its own planes. The rock natural conditions and the expected borehole depth also influence since the degree of deviation might proportionally increase with the borehole depth. Other factors are associated with the drilling method and equipment, i.e. the type of drill and drill accessories, rotation velocity, uncontrolled or excessive push down, and the driller experience.

A FLEXIT GyroSmart is an instrument built as a digital butterfly gyroscope that can do deviation measurements in zones of magnetic anomalies for a complete and precise mapping of boreholes.

A FLEXIT SingleSmart and MultiSmart borehole deviation measurement instruments orientate themselves after the earth magnetic field.

The deviation measurements are normally carried out by registering the dip angle (inclination between 0 and +/- 90°) and the Azimuth angle (direction - between 0 and 360°). With these two parameters, the Cartesian position parameters x, y and z, are calculated at each measurement point.

It is of great importance to monitor the borehole and secondary fluid temperature at different depths in order to be able to draw a complete picture of what happens under the ground regarding heat transfer.

Two temperature measurement techniques using thermocouples which can be used for punctual temperature measurements at the inner part of the collector were developed. The first one consists of an angled insertion of thermocouple with subsequent covering the perforated point with pipe material by vigilantly melting of plastic and letting it solidify until it becomes part of the original pipe. The second method consists of locating the thermocouple between an Electro socket pipe connection.

Distributed temperature sensing technology uses fiber optic cables and a special reading instrument in order to offer many advantages from the accuracy point of view. It permits continuous and simultaneous temperature readings every one meter along the whole cable length. It is a very suitable method for temperature measurements in energy wells where the working environment is under the ground. It permits obtaining an accurate temperature profile from the borehole heat exchanger and filling material by only installing one or two cables definitely attracts the attention of researchers within this field.
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