Optimization of thermal response test equipment and evaluation tools

Camille Simondon
Abstract

Nowadays Ground Source Heat Pumps (GSHP) are widely used to provide heating and/or cooling as well as domestic hot water in commercial and residential buildings. The Swedish GSHPs market is the first one in the European Union with more than 378,000 units installed until 2010 according to the Swedish Heat Pump Association (SVEP).

This thesis focuses on the improvement of a Thermal Response Test (TRT) apparatus available at KTH Royal Institute of Technology – Energy Technology Department. This equipment aims at improving Borehole Heat Exchanger (BHE) design in terms of size. Its key purpose is to evaluate two main BHE properties: the ground thermal conductivity and the borehole thermal resistance.

A new command software is developed in order to control the TRT equipment and run TRT measurements. This new software is developed using Python as programming language and replaces an older program which needed LabVIEW to run. The TRT command software designed in this thesis provides the user with a simple and user-friendly interface to control each device of the equipment. Measurements are exported and saved to files which can be open with both Microsoft Excel and the analysis tool also developed in this thesis.

The stand-alone evaluation tool can be used to analyse TRT and/or DTRT measurements. This analysis tool helps the user to compute large amount of data with few data manipulation and low computation time. Model parameters and TRT/DTRT measurement can be imported from files into it and different fitting settings are available to run the optimization, i.e. account for baseline variations.
(early activities in the borehole, different optimization periods, analysis during thermal recovery of
the ground, single/multi-sectional analysis along the depth, among others).

This report covers a theoretical description of TRT experiments and its models, the objectives of such
a project and the development of the control and evaluation tools.

Keywords: Borehole Heat Exchanger, Ground Source Heat Pump, Distributed Thermal Response Test,
Python, Evaluation Tool
Acknowledgements

I first would like to thank José Acuña, my supervisor during this thesis, for the fantastic opportunity he offered me to work in KTH – Energy Technology department. He straightaway put his trust in me and my work by giving me a great challenge to address. He always took time to answer my questions even when he was busy. His advice and remarks were always very valuable.

I would also like to thank Kalle for his technical skills and help during this thesis. I also thank the people from KTH – Energy Technology department I had the chance to discuss with during the project or fika.

I also thank all the friends with whom I shared the office with during this thesis and whom I had fun with: Alexander, Marine, Arthur, Marc, Michel, Willem, Luca, Davide, Marcus, Louis, Johann, Louis, Florian, GianMarco and probably others.

Last but not least, I also thank my family for supporting me during this exciting journey abroad, for their patience and unfailing understanding in my studies. Thanks to my father Serge, my mother Gabrielle and a very particular gratitude to Aurélie for her constant support and encouragement.
Abbreviations

BHE  Borehole Heat Exchanger
BTES  Borehole Thermal Energy Storage
COP  Coefficient of Performance
DAQ  Data Acquisition System
DTRT  Distributed Thermal Response Test
GSHP  Ground-Source Heat Pump
LSA  Line-Source Approximation
TRT  Thermal Response Test

Nomenclature

\( \dot{m} \)  Mass flow  \( \text{kg/s} \)
\( c \)  Volumetric heat capacity  \( J/(m^3.K) \)
\( C_p \)  Specific heat capacity  \( J/(kg.K) \)
\( Q \)  Injection power  \( W \)
\( q \)  Heat flux  \( W/m \)
\( R \)  Thermal resistance  \( (m.K)/W \)
\( R_b \)  Borehole thermal resistance  \( (m.K)/W \)
\( r_b \)  Borehole radius  \( m \)
\( t \)  Time  \( s \)
\( T_b \)  Borehole wall temperature  \( ^\circ C \)
\( T_g \)  Undisturbed ground temperature  \( ^\circ C \)
\( T_{in} \)  Temperature at the inlet of the borehole heat exchanger  \( ^\circ C \)
\( T_m \)  Mean temperature difference between inlet and outlet fluid  \( ^\circ C \)
\( T_{out} \)  Temperature at the outlet of the borehole heat exchanger  \( ^\circ C \)
\( w \)  Volumetric flow rate  \( m^3/s \)
\( \alpha \)  Thermal diffusivity  \( m^2/s \)
\( \gamma \)  Euler’s constant  \( \approx 0.5772 \)
\( \Delta T \)  Temperature difference from undisturbed ground temperature  \( ^\circ C \)
\( \lambda_g \)  Ground thermal conductivity  \( W/(m.K) \)
\( \rho \)  Density  \( kg/m^3 \)
Table of Contents

Abstract .................................................................................................................................................. ii

Abbreviations .......................................................................................................................................... v

Nomenclature ........................................................................................................................................... v

Table of Contents ................................................................................................................................. viii

Index of Figures ........................................................................................................................................ x

Index of Tables ......................................................................................................................................... xi

1. Introduction ......................................................................................................................................... 1

  1.1. Thermal resistance and ground thermal conductivity ................................................................. 2

  1.2. Thermal Response Test .................................................................................................................. 4

      1.2.1. TRT principle and objectives ................................................................................................. 4

      1.2.2. TRT apparatus ...................................................................................................................... 5

  1.3. TRT analysis and evaluation tools ................................................................................................. 7

      1.3.1. Analytical models .................................................................................................................. 8

         1.3.1.1. Infinite Line Source ........................................................................................................... 8

         1.3.1.2. Cylinder Line Source ....................................................................................................... 11

         1.3.1.3. Beier’s model .................................................................................................................... 12

  1.4. TRT procedure .............................................................................................................................. 13

  1.5. Objectives ....................................................................................................................................... 16

2. Methodology ............................................................................................................................................. 17

  2.1. TRT equipment ............................................................................................................................. 17

  2.2. Programming language: Python ................................................................................................... 19

  2.3. TRT command software ................................................................................................................ 19
2.3.1. Data acquisition and command software presentation ........................................ 19
2.3.2. First Thermal Response Test ........................................................................... 24
2.4. TRT/DTRT measurement evaluation tool ......................................................... 26
   2.4.1. Tool presentation ......................................................................................... 26
   2.4.2. Results comparison ................................................................................... 29

4. Conclusion ........................................................................................................... 33

5. Future work ......................................................................................................... 34

References .............................................................................................................. 36
**Index of Figures**

Figure 1: Horizontal closed-loop ground heat exchanger .......................................................... 1
Figure 2: vertical closed-loop ground heat exchanger ............................................................... 1
Figure 3: U-tube BHE geometry .................................................................................................. 2
Figure 4: coaxial (pipe-in-pipe) BHE geometry ........................................................................ 2
Figure 5: Thermal resistance fundamental in borehole heat exchanger ..................................... 3
Figure 6: Thermal Response Test unit (Gehlin, et al., 2003) ........................................................ 6
Figure 7: Circulating fluid temperatures during late-time trend in TRT (Beier, 2011) .............. 8
Figure 9: Temperature profile in the ground and seasonal temperature variations (Ericsson, 1985) . 14
Figure 10: Circulating fluid temperature during TRT (Acuña, 2010) ........................................ 15
Figure 11: TRT equipment available at KTH – Energy Technology department ...................... 17
Figure 12: schematic of the TRT equipment (Kamarad, 2012) .................................................. 17
Figure 13: EasyIO30P DAQ card in its electric box ................................................................. 18
Figure 14: user interface, TRT control panel in LabVIEW (Kamarad, 2012) ............................ 18
Figure 15: TRT equipment control software overall structure .................................................. 20
Figure 16: TRT command software – command tab ................................................................. 21
Figure 17: TRT command software – Graph output tab ............................................................ 23
Figure 18: fluid mean temperature during the whole TRT in KTH lab ..................................... 25
Figure 19: flow rate and injected heat during the whole TRT in KTH lab ................................. 26
Figure 20: TRT/DTRT analysis tool overall structure ............................................................... 27
Figure 21: TRT/DTRT analysis software – input parameters tab ............................................. 27
Figure 22: TRT/DTRT analysis software – output results tab .................................................. 29
Figure 23: Ground thermal conductivity optimization on section 1 ....................................... 30
Figure 24: Borehole thermal resistance optimization on section 1 ........................................... 30
Figure 25: Raspberry Pi computer ......................................................................................... 34
Index of Tables

Table 1: accuracy error of exponential integral approximation ................................................................. 9
Table 2: communication protocol for each communication unit ............................................................... 20
Table 3: TRT equipment sensors communication port .............................................................................. 22
Table 4: $\lambda_g$ comparison with (Acuña, et al., 2009) ........................................................................ 31
Table 5: $R_6$ comparison with (Acuña, et al., 2009) ................................................................................ 31
1. Introduction

Geothermal energy is by definition the energy stored in the form of heat beneath the earth’s surface. This renewable energy is nearly infinite (extracted heat is small compared to Earth’s heat content) and is not depending on climatic conditions. This energy can be found at different temperature levels in the ground depending mainly on local geology and depth. The worldwide technical potential for geothermal electricity is estimated to be 12,500 TWh/year according to (International Energy Agency, 2011) while only 223 TWh were estimated to be produced in 2012 (Ren21, 2013). These figures highlight the huge potential for electricity production coming from geothermal energy.

In case geothermal heat does not match the application heat requirement, additional heat may be needed and ground-source heat pumps (GSHPs) can be used to raise the temperature to the required level. GSHPs are systems composed of three main parts: the ground side in which heat is either taken or stored, the heat pump itself and the building side which is heated or cooled. Primary fluid is used in the building side whereas another fluid, called secondary fluid, is circulating in the borehole heat exchanger, i.e. the ground side. Nowadays, ground-source heat pumps technology, also known as “shallow geothermal technology”, is widely used to provide heating and/or cooling as well as domestic hot water in commercial and residential buildings. GSHPs come in two general configurations: horizontal subsurface loops and vertical borehole heat exchangers (BHEs), as shown in Figure 1 and Figure 2 respectively. In the latter case, GSHP make use of the stable temperature of the ground (temperature level depending on the geographical location) up to 200 meters depth in order to extract heat from the ground, respectively store heat into the ground.

![Figure 1: Horizontal closed-loop ground heat exchanger](image1)

![Figure 2: vertical closed-loop ground heat exchanger](image2)

Ground-source heat pumps are now the fastest growing application of direct geothermal use, with about 4.5 million GSHPs sold worldwide since 2005 of which 770,000 units only in 2011 mainly in Italy, France and Sweden (European Heat Pump Association, 2013). Moreover, the total installed
capacity was 15,400 MW_{thermal} for GSHPs in 2009 (U.S. Department of Energy, 2009) while they account for 49% of overall geothermal heat production applications (International Energy Agency, 2011).

GSHPs are normally connected to the ground through a pipe loop commonly called borehole heat exchanger. The U-pipe configuration is the most common BHE used in many installations. The U-pipe is placed in a vertical borehole where a filling material is added between the U-tube and the borehole wall (Figure 3). This filling material can be either grout or ground-water and is most of the time required by governments to prevent contaminants from travelling along the vertical borehole. Besides, in this configuration the secondary fluid travels downs and then upwards through two equal tubes linked together at the bottom of the borehole. Another usual configuration is the coaxial type. It consists of a central pipe inserted into a larger tube (external pipe) creating an annular flow channel between them (Figure 4). Note that several coaxial BHE configurations exist, depending on the pipes geometry: pipe-in-pipe, multi-pipe or multi-chamber.

1.1. Thermal resistance and ground thermal conductivity

For borehole thermal energy storage (BTES) design purposes, especially when it comes to large BHE systems, it is necessary to know some important parameters such as geological thermal properties, system dimensions and configurations. These geological parameters are key factors in the design process and can be divided into the ground thermal conductivity and the borehole thermal resistance:

- The ground (or soil) thermal conductivity $\lambda_{gr}$, expressed in $W/m.K$, is the capacity of the ground to conduct heat. It mainly depends on the ground properties.
• The borehole thermal resistance $R_b$, expressed in $m.K/W$, which is the thermal resistance between the borehole wall and the circulating fluid, characterizes the capacity of the borehole to resist the heat flow. It depends on the filling material among others parameters. Additionally, the borehole thermal resistance must be as low as possible to get a small temperature difference between the fluid and the ground.

The total ground thermal resistance $R_T$ is expressed as the sum of the ground thermal resistance $R_g$ and the borehole thermal resistance $R_b$ (1):

$$R_T = R_g + R_b$$  \hspace{1cm} (1)

The borehole thermal resistance results in the sum of the thermal resistance of the fluid circulating inside the pipe $R_f$, the wall pipe thermal resistance $R_{pipe}$ as well as the filling material thermal resistance $R_{bhw}$ (2):

$$R_b = R_f + R_{pipe} + R_{bhw}$$  \hspace{1cm} (2)

The pipe is usually made of polyethylene with an average thermal resistance of 0.4 $m.K/W$.

This sum of thermal resistances is illustrated in Figure 5.

![Figure 5: Thermal resistance fundamental in borehole heat exchanger](image-url)
It can also be added that the temperature between the fluid in the pipe \(T_f\) and the borehole wall \(T_b\) is connected with the borehole thermal resistance \(R_b\) as well as the specific heat transfer rate \(q\) (W/m) as stated (3):

\[
T_f - T_b = R_b \cdot q
\]  
(3)

This equation underlines the proportionality that exists between the heat transfer rate and the temperature difference between the heat carrier fluid and the borehole wall. As this temperature difference is expected to be as low as possible, a small thermal borehole resistance value is suitable for design for a given a specific heat transfer rate.

Moreover, it can be introduced the ground diffusivity \(\alpha\) (expressed in \(\text{m}^2/\text{s}\)) as the relation between the ground capacity to conduct the heat and its capacity to store energy (4):

\[
\lambda = \rho \cdot C_p \cdot \alpha
\]  
(4)

where \(C_p\) is the specific heat capacity (expressed in \(\text{J/kg} \cdot \text{K}\)) and \(\rho\) is the density (expressed in \(\text{kg/m}^3\)).

The filling material plays an important role in the borehole thermal resistance. It usually has a high value in order to encourage the heat transfer between the ground and the circulating fluid. Although it is the case with bentonite and concrete, the ground-water has a low thermal conductivity. However natural convection occurs inside when ground-water is used as filling material which enhances the heat transfer between the heat exchanger and the surrounding ground. In Sweden the latter is widely promoted and used because of the ground geology, mainly made of hard crystalline rock, which keep the risks for contamination normally low.

In order to evaluate these ground properties, a well-known method has been developed for several years and is now used worldwide, the Thermal Response Test (TRT).

1.2. Thermal Response Test

1.2.1. TRT principle and objectives

Thermal Response Test (TRT) is an indirect method mainly used to get new knowledge about the thermal properties of the ground, i.e. estimate mean values for two ground thermal properties around the borehole, thanks to the study of the fluid temperature evolution versus the time during
measurements in-situ. The main outcomes of a TRT are the ground thermal conductivity and the borehole thermal resistance.

TRT measurements are carried out in order to obtain the thermal response data, i.e. the temperature development in the borehole at a certain energy injection rate. In order to measure these parameters, different sensors are used (see section 1.2.2 TRT apparatus).

The borehole thermal resistance and the ground thermal conductivity may present local variations along the borehole depth. That is why, in order to improve conventional TRT, the optical fibre technology can be applied to collect more precise information on the real temperature profiles in the borehole. While thermal response test logs the inlet and outlet fluid temperatures, the distributed thermal response test (DTRT) carries out a profile of the temperature at a local level in the borehole using distributed temperature sensing (DTS). This technique is studied in details in (Fujii, et al., 2006) and (Acuña, 2013) and has proved to be accurate and reliable compared to the local geological and ground information.

Accurate estimation of the ground thermal conductivity and the borehole thermal resistance is essential since it has a huge impact on prediction of the heat transfer rates for the design of GSHP systems. Thereby, it also affects the efficiency of the borehole and the size of the installation, i.e. the heat pump’s coefficient of performance (COP), and thus its payback time. Economic impact of overestimating the borehole thermal resistance is studied by (Marcotte, et al., 2008). As explained previously, the borehole resistance is a key parameter for standard sizing method and that is why it may lead to overdesign, under-estimation of the profitability of the geothermal project and substantial loss of profit.

1.2.2. TRT apparatus

A typical thermal response test apparatus consists of a circulation pump, an electric heater, a water tank (used for purging and as an expansion tank), a data acquisition system as well as measurement equipment: at least two temperature sensors in order to log the inlet and outlet flow temperatures and a flow meter (Figure 6).
The first measurement device for thermal response testing was built at Royal Institute of Technology KTH, Sweden, in 1983 by two thesis students together with Palne Mogensen. The method used allows calculating the thermal resistance between the secondary working fluid and the borehole wall as well as the thermal conductivity (Mogensen, 1983). A decade later, similar types of equipment were built quite simultaneously in Sweden and the USA. In 1996, the Swedish response test apparatus, called “TED”, was developed at Luleå University of Technology (Eklöf, et al., 1996). Based on this first TRT apparatus, similar and improved test units were later developed in several other countries around the world.

Even though the construction of TRT may seem quite simple, some recommendations should be taken as stated in IEA (Energy Technology Network) ECES Annex 21\(^1\) which has studied and collected a large amount of information about TRTs worldwide. One of the goals of IEA ECES Annex 21 is to define a standard TRT procedure, so-called best practice TRT manual, in order to initiate a worldwide TRT standard for TRT measurements. Thus, accurate and reliable comparison between results gathered is made possible. Concerning the TRT equipment, the heater has to be able to supply a steady heat load and to allow several thermal load steps. Moreover, the circulating pump should allow flow rate changes in order to adapt the test to different boreholes and designs. Furthermore, all devices and pipes have to be thermally isolated in order to minimize the influence of ambient temperature and pipes have to be as short as possible in order to avoid load fluctuation when

running the system. All these recommendations are made in order to keep the influence of the ambient temperature, and the undesirable heat provided to the circulating fluid, as low as possible.

### 1.3. TRT analysis and evaluation tools

The easiest way to estimate both soil thermal conductivity and borehole thermal resistance is to use the mean of the measured inlet and outlet temperatures of the circulating fluid as a representative fluid temperature along the entire ground loop (5).

$$T_m = \frac{T_{in} + T_{out}}{2}$$

(5)

Although it is the most convenient method, this assumption is also not rigorous. As a matter of fact it implicitly assumes that the heat transfer rate is uniform along the length of the borehole which is considered as an unrealistic hypothesis. Moreover the use of $T_m$ may lead to an over-estimation of the borehole resistance $R_b$ (Marcotte, et al., 2008).

Proposing an alternative to the mean temperature approximation, Marcotte and Pasquier assume a fluid temperature variation at power $p$, $|\Delta T(x)|^p$, varies linearly within the U-tube between $|\Delta T_{in}|^p$ and $|\Delta T_{out}|^p$. Here $\Delta T$ represents the temperature difference from the undisturbed ground temperature, $T_g$, which is obtained thanks to pre-circulating fluid into the borehole during the first hours of the TRT. The vertical temperature profile is then given (6):

$$|\Delta T(x)| = \left\{ |\Delta T_{in}|^p + \frac{x}{2L} \cdot (|\Delta T_{out}|^p - |\Delta T_{in}|^p) \right\}^{1/p}$$

(6)

Note the variable $x$ represents the position along the full pathway in the U-tube from inlet to outlet connections. Eq. (6) provides the same result as the mean temperature approximation for a $p$ value equals to 1. Marcotte and Pasquier recommend using $p \rightarrow -1$, based on comparisons with numerical models of a borehole. Vertical temperature profiles are obtained plotting the temperature along the borehole vs. depth. It gives the possibility to compare different methods: mean temperature difference, $p$-linear approximation, as well as numerical methods.

For a better calculation of borehole resistance, (Marcotte, o.a., 2008) recommend the use of the so-called $p$-linear average temperature along the U-tube. This average temperature is obtained from integration from 0 to $L$, along the U-tube path, of (6) to give (7):

$$|\Delta T_p| = \left. \frac{p \cdot (|\Delta T_{in}|^{p+1} - |\Delta T_{out}|^{p+1})}{(1 + p) \cdot (|\Delta T_{in}|^p - |\Delta T_{out}|^p)} \right|$$

(7)
The best results are obtained with $p \to -1$ as it fits closely the transient-state fluid temperature computed with the numerical model.

Temperature evolution versus logarithmic time during a TRT is shown in Figure 7. A comparison of the mean temperature difference and the “p-linear” approximation is also plotted. When the temperature as a function of the logarithmic time is linear is called the late-time trend. This late-time slope of the inlet fluid temperature, the outlet fluid temperature and the mean temperature are all the same.

![Figure 7: Circulating fluid temperatures during late-time trend in TRT (Beier, 2011)](image)

There is also another approach of the p-linear approximation in which the borehole wall temperature $T_b$ is used as reference instead of the undisturbed ground temperature $T_g$ (Du, et al., 2011) and (Lamarche, et al., 2010). The p-linear approximation developed in (Du, o.a., 2011) shows best result using $p \to 0$ for single U-tube configuration. Nonetheless the borehole wall temperature is usually not measured and then these equations will not be treated with more details.

1.3.1. Analytical models

1.3.1.1. Infinite Line Source
(Mogensen, 1983) is the first who applied the line source model to estimate the borehole thermal resistance. This Infinite Line Source (ILS) model reduces the borehole geometry to a vertical ground heat exchanger drilling to an infinite line source and surrounded by an infinite homogeneous ground.
This model is widely used because of its simplicity and rapid results. According to (Carslaw, et al., 1959), the equation for temperature $T$ at radial distance $r$ from a line source and with a constant heat injection (or extraction) rate $q$ can be written as stated in (8):

$$T_m(r, t) = \frac{q}{4. \pi. \lambda_g} \left[ -Ei\left( -\frac{r^2}{4. \alpha_g. t} \right) \right]$$  \hspace{1cm} (8)

In (8) the symbol $Ei$ represents the exponential integral function as defined in (9):

$$\forall x > 0, Ei(-x) = - \int_x^\infty \frac{e^{-t}}{t} dt$$  \hspace{1cm} (9)

The natural logarithm approximation applied in (9) leads to (10):

$$\forall x > 0, Ei(-x) \approx \ln\left(\frac{1}{x}\right) - \gamma$$  \hspace{1cm} (10)

where the term $\gamma$ (Euler’s constant) $\approx 0.5772$. In (10), the lower the $x$ value, the better the approximation. Eq. (8) thus becomes (11):

$$T_m(r, t) \approx \frac{q}{4. \pi. \lambda_g} \left[ \ln\left(\frac{4. \alpha_g. t}{r^2}\right) - \gamma \right]$$  \hspace{1cm} (11)

As explained before, this approximation is accurate only if the term $\frac{r^2}{4. \alpha_g. t}$ has a low value, or in other words, the term $\frac{\alpha_g. t}{r^2}$ has a high value. This error in approximation is summarized for different $\frac{\alpha_g. t}{r^2}$ values in Table 1 below. The condition means that the accuracy of this approximation increases as the ground thermal diffusivity $\alpha_g$ gets higher i.e. the velocity of the thermal front reaches further beyond the borehole wall.

**Table 1: accuracy error of exponential integral approximation**

<table>
<thead>
<tr>
<th>$\frac{\alpha_g. t}{r^2}$ value lower than</th>
<th>10.0</th>
<th>5.0</th>
<th>2.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.034</td>
<td>0.022</td>
<td>0.014</td>
<td>0.007</td>
<td></td>
</tr>
</tbody>
</table>

The fluid temperature is found by adding the line-source temperature evaluated at the borehole radius ($r = r_b$) and the effect of the borehole thermal resistance $R_b$ in order to take into account the temperature difference between the working fluid and the borehole wall i.e. effect of the thermal resistance between the fluid inside the pipe and the borehole wall (Ingersoll, et al., 1948) (12):
where $T_g$ is the undisturbed ground temperature.

Using (12), the time dependency can be separated (13):

$$T_m(r_b, t) = \frac{q}{4.\pi.\lambda_g} \left[ \ln \left( \frac{4.\alpha_g.t}{r_b^2} \right) - \gamma \right] + q.R_b + T_g$$

Therefore, it allows separating the logarithmic time dependency in (13) in the form:

$$T_f(t) = k \cdot \ln(t) + m$$

with $k$ being the slope of the curve and $m$ the ordinate at the origin. It means that application of equation (14) to the late-time trend is used in order to determine the ground thermal conductivity $\lambda_g$ (15):

$$\lambda_g = \frac{q}{4.\pi.k} = \frac{Q}{4.\pi.k.L}$$

where $Q$ is the heat input rate, $k$ is the late-time slope and $L$ is the length of borehole. The $k$ value can be easily determined by plotting the temperature response on a semi-logarithmic scale (temperature vs. logarithmic of time) as illustrated by Figure 5.

Knowing the ground thermal conductivity $\lambda_g$ and solving for $R_b$ in (12) is now possible and produces (16):

$$R_b = \frac{T_m(t) - T(r_b, t)}{q}$$

$$= \frac{1}{q} \cdot (T_m(r_b, t) - T_g) - \frac{1}{4.\pi.\lambda_g} \left[ \ln \left( \frac{4.\alpha_g.t}{r_b^2} \right) - \gamma \right]$$

(16)

Note that this equation is valid only when the thermal process within the borehole is under steady-flux condition.

If the pipes are symmetrically placed in the borehole, (12) can be expressed in terms of the soil and borehole resistances as (17):

$$T_m(r_b, t) - T_g = \frac{Q}{L} \cdot (R_s + R_b)$$

(17)

where
1.3.1.2. Cylinder Line Source

The Cylinder Line Source (CLS) model assumes the borehole as a cylinder surrounded by homogeneous ground and having constant heat flux across its periphery (Carslaw, et al., 1959). Besides the ground loop heat exchanger is considered as a single coaxial pipe with an equivalent diameter of the two pipes of U-pipe exchanger. The ILS model is considered as a simplification of the cylinder line source model. The following equation describes the cylindrical source solution (19):

\[ T(r, t) = \frac{q}{\lambda_g} \cdot G(z, p) = \frac{q}{\lambda_g} \cdot G \left( \frac{\alpha_g t}{r_b^2}, \frac{r}{r_0} \right) \]  

Being \( G(z, p) \) is the cylindrical source function as described by (Ingersoll, et al., 1954) (20) and (21):

\[ G(z, p) = \frac{1}{\pi^2} \int_{0}^{\infty} f(\beta) \, d\beta \]  
\[ f(\beta) = (e^{-\beta^2 z} - 1) \cdot \frac{J_0(p, \beta) \cdot Y_1(\beta) - Y_0(p, \beta) \cdot J_1(\beta)}{\beta^2 [J_1^2(\beta) + Y_1^2(\beta)]} \]  

In above equation, \( J_0, J_1, Y_0 \) and \( Y_1 \) are Bessel functions of the first and second kind.

The general equation can be written as presented in (28):

\[ T_p(t) = \frac{q}{\lambda_g} \cdot G(z, p) + q \cdot R_b + T_0 \]  

(Carslaw, et al., 1959) developed a model based on cylinder source theory, in which solutions are obtained varying boundary conditions for regions bounded by cylinder geometry. The borehole heat exchanger is represented as a cylinder filled with a backfill material and the fluid temperature for larges value of the time or a small radius can be determined with the following approach cylinder theory (23):

\[ T(t) = T_g + \frac{Q}{4 \pi \lambda_g H} \cdot \left( 2h + \ln 4 \cdot \frac{t}{C} - \frac{4h - \alpha}{2 \cdot \alpha_1} \cdot \frac{\alpha_1 - 2}{2 \cdot \alpha_1} \cdot \ln 4 \cdot \frac{t}{C} \right) + \ldots \]  

where

\[ R_s = \frac{1}{4 \pi \lambda_g} \cdot \ln \left( \frac{4 \alpha_g t}{y \cdot r_b^2} \right) \]  

(18)
1.3.1.3. **Beier’s model**

(Beier, et al., 2012) developed a model of borehole heat transfer in case of U-pire BHE configuration. It considers the heat transfer between the fluid circulating in each pipe and the undisturbed ground as well as the influence between the two pipes. This model allows a calculation of the borehole thermal resistance but does not provide more information about the ground thermal characteristics. It also calculates the fluid temperature profile along the BHE.

From an initial energy balance on each pipes (one from where the fluid enters and one from where the fluid exits the borehole), the model introduces several dimensionless variables and parameters to produce the dimensionless equations (26):

\[
\begin{align*}
\frac{dT_{D1}}{dz_D} &= N_{12}(T_{D2} - T_{D1}) - N_{s1}T_{D1} + N_{s1}T_{Ds} \\
\frac{dT_{D2}}{dz_D} &= N_{12}(T_{D2} - T_{D1}) + N_{s2}T_{D2} + N_{s2}T_{Ds}
\end{align*}
\]  

Then it applies known boundary conditions to solve these two first-order differential equations and finally calculates the vertical temperature profile at a given time under the above assumptions according to (27):

\[
\begin{align*}
T_{D1}(Z_D) &= C_1 e^{a_{12}Z_D} + C_2 e^{a_{21}Z_D} + a_1 + a_{11}Z_D + a_{12}Z_D^2 + a_{13}Z_D^3 \\
T_{D2}(Z_D) &= C_3 e^{a_{31}Z_D} + C_4 e^{a_{41}Z_D} + a_2 + a_{21}Z_D + a_{22}Z_D^2 + a_{23}Z_D^3
\end{align*}
\]  

with \(C_1, C_2, C_3\) and \(C_4\) being four dimensionless parameters depending on others dimensionless constants \(N_{12}, N_{s1}\) and \(N_{s2}\) as described in (28), (29), (30) and (31). The constants written as \(a_i\) and \(a_{ij}\) are listed in (Beier, et al., 2012).

\[
C_3 = \frac{[N_{s1} + N_{12} + a_1]}{N_{12}} C_1 
\]  

\[
N_{12} = \frac{L}{w_c R_{12}} = \frac{L}{m_c R_{12}} = \frac{L}{w_p C_p R_{12}}
\]
Previous studies indicate that one symmetric assumption may be done in order to simplify this model keeping good results (Yang, et al., 2010). It can be assumed that the two U-tube legs are located in symmetric positions from the centre of the borehole. In this situation, $R_{b1}$ equals $R_{b2}$ and $\lambda_{g1}$ equals $\lambda_{g2}$ which leads to $N_{s1}$ equals $N_{s2}$.

With the temperature profiles given by (27) and by integrating along the vertical borehole taking into account the thermal resistances, the heat transfer rate is found (32):

$$Q_D = \int_0^1 (T_{D1} - T_{Ds})dz_D + \frac{N_{s2}}{N_{s1}} \int_0^1 (T_{D2} - T_{Ds})dz_D$$  \hspace{1cm} (32)

Moreover, it is known from (Beier, 2011) that the dimensionless heat input rate $Q_D$ can be expressed as (33):

$$Q_D = \frac{Q(R_{b1} + \lambda_{g1})}{(T_{in} - T_s)L}$$  \hspace{1cm} (33)

Finally, substituting the temperature profiles for the dimensionless temperatures into the heat transfer rate equation gives (34):

$$Q_D = C_5 + C_6 + C_7$$  \hspace{1cm} (34)

where $C_5$, $C_6$ and $C_7$ are three dimensionless constants explained in (Beier, et al., 2012).

Eq. (33) can be applied at any specific time during the late-time trend period. A similar model using a transient heat transfer model and including the earlier time is developed in (Beier, 2014).

The heat input rate $Q$ and temperatures $T_{in}$ and $T_s$ are measured values, the borehole length $L$ is a known geometric parameter. Then the ground thermal conductivity $\lambda_{g1}$ is estimated from the slope of the late-time temperature trend as explained in (15). Eq. (18) provides estimation for $R_s$ based on the ground thermal conductivity.

### 1.4. TRT procedure

Good estimation of the undisturbed ground temperature is necessary for a correct design of the ground heat exchanger. (Ericsson, 1985) states that the deeper the borehole is, the higher the
undisturbed ground temperature will be due to the geothermal gradient. (Acuña, 2010) has shown with different measured temperature profiles that this statement is not always true in reality. As a matter of fact it highly depends on the buildings above the ground which insulate the ground from outdoor air temperature variations and impose a different boundary condition at the ground level, often providing a heating effect to the ground. Moreover seasonal variation is observed up to 15 meters below ground surface because of seasonal ambient air temperature change (Figure 8).

According to (Gehlin, et al., 2003), undisturbed ground temperature $T_g$ can be measured in two different ways. Both methods require the borehole to be at thermal equilibrium with the surroundings before a thermal response test.

One commonly used method is circulating the heat carrier fluid of the borehole heat exchanger through the whole borehole for about half an hour before the heater is switched on for the test. During this period, called the pre-circulating period, the temperature along the whole borehole becomes almost constant and is then used as an estimation of the average borehole temperature. However, even though no heat is injected by the heater, some heat gain will always be observed in the system because of the pump work. That is why the pre-circulation period should not last too long, especially if the borehole is not deep enough.
Figure 9 illustrates this pre-circulating period: in the beginning (80 to 90 hours), the fluid circulates through the whole borehole without any heat injection. From this period, the undisturbed ground temperature can be determined.

The average fluid temperature between the inlet and outlet temperatures (yellow curve in Figure 9) at the ground surface level can be computed in different ways: the arithmetic average $T_m$ or for example using the “p-linear” average $|\Delta T_p|$. While the former assumes that the heat transfer rate along the borehole is constant (often leading to an overestimate of the local borehole thermal resistance), the latter may sometimes fit better with the average fluid temperature.

Following the pre-circulating period, the heat injection period into the borehole starts during which the fluid is constantly heated and circulates through the borehole. It is also possible to run TRTs by extracting heat, as suggested in (Mogensen, 1983). Heat extraction tests have the advantage of keeping low levels of free convection in groundwater-filled boreholes.
1.5. Objectives

This Master thesis has three main objectives.

1. Reparation of the pump in the TRT equipment: Some problems with the thermal response test apparatus needed to be fixed in order to be used for field measurements. Replacement parts must be ordered for the pump and, after reparation, it must be put back into the TRT system and incorporated in the control software.

2. Development of a new optimized control software for the TRT equipment: the existing control software presented by (Kamarad, 2012) needs LabVIEW to be able to run. A new program developed in Python will be created instead. This new program would be as far as possible user-friendly and easy to be run on any available computer. It should help to control the TRT apparatus and its devices in the same way the LabVIEW programs already does. This step will start by creating a simple ON/OFF button for each component of the TRT system without any major control strategies. The ideal final goal of doing such software would be to make it run on a really small and simple computer\(^2\) integrated with the TRT system unlike the LabVIEW program, almost independently and remotely controlled.

3. Development of a stand-alone TRT evaluation tool: this tool would be able to import TRT and DTRT measurements and compute the key parameters of the BHE in a simple way, with few data manipulation and user-friendly interface. It should provide different options, such as optimization settings and models selection.

\(^2\) A single-board computer (such as Raspberry Pi computer, http://www.raspberrypi.org/) is one possible solution.
2. Methodology

2.1. TRT equipment

The TRT equipment considered in this thesis is the one available at KTH – Energy Technology department which was built by (Kamarad, 2012) (Figure 10).

![Figure 10: TRT equipment available at KTH – Energy Technology department](image)

The equipment available at KTH consists of a pump, an electric heater and an actuated ball valve. There are also several sensors: three temperature sensors (ambient, inlet and outlet), two pressure sensors (differential and absolute) and one flow meter. The schematic of the TRT equipment is shown in Figure 11.

![Figure 11: schematic of the TRT equipment (Kamarad, 2012)](image)
In order to communicate with the different devices and sensors on the TRT bench, a data acquisition system (DAQ) card linked to the TRT apparatus is used. The Master thesis done by (Kamarad, 2012) is an example of how this can be done. It this case, it uses a EasyIO30P IO-30P-ME controller as DAQ card unit (see Figure 12).

![Figure 12: EasyIO30P DAQ card in its electric box](image)

The remote control software was originally done with LabVIEW and was used to monitor and control the TRTs (see Figure 13). This user interface is replaced by the new Python-based command program developed here.

![Figure 13: user interface, TRT control panel in LabVIEW (Kamarad, 2012)](image)
2.2. Programming language: Python

Python\(^3\) is a free open-source code which allows easy modification and improvement. It is a powerful high-level programming language and since it is also cross-platform, it can run on almost any operating system (Windows, Linux/Unix, OS/2 and Mac). It is freely available to download and install. Besides, many libraries can be imported into Python. These libraries are developed to add features to Python such as communication protocols, charts and diagrams or mathematical equations as well.

Moreover, the interface itself is based on Tkinter, the standard Python Graphical User Interface (GUI). Tkinter gives the opportunity to create simple widgets such as labels, buttons or checkboxes and many more. All these modules allow any advanced interface to be created.

2.3. TRT command software

The main objective of the new command software is to be more independent of licensed programs such as LabVIEW, which was previously required to run the old command program. This new program must use Python in order to be run on any computer, with any operating systems and with low resource requirements.

2.3.1. Data acquisition and command software presentation

The first step in designing such software is to define the communication protocol used by each communication unit of the TRT equipment (see Table 2). Two different communication protocols are used: Modbus Serial RTU and Modbus TCP/IP for the pump control unit and DAQ unit, respectively. Both protocols can be implemented into Python using PyModbus\(^4\) library, a full Modbus protocol implementation.

The protocol describes the way the communication is done between the command program and the equipment controlled through the communication unit. Moreover, the computer running the command software must be linked to the communication unit using the right interface. It uses a USB-RS485 converter cable for the pump control unit and an Ethernet cable for the DAQ unit (with a Wifi connection to a wireless router in between).

---

\(^3\) More information can be found at [http://www.python.org/](http://www.python.org/).

The control software allows a full control of each device of the TRT equipment and a sensor reading with real-time display. The fluid properties can also be defined so as to compute the injected heat during the thermal response test (this feature should be developed further in order to account for the temperature dependent fluid properties). All the measurements are auto-saved in a folder in order to keep the measured data in case the software crashes. The overall structure of the software is shown in Figure 14.

![Figure 14: TRT equipment control software overall structure](image)

The one-window interface is made of two tabs with several panels. The first tab is used to control the TRT equipment (see Figure 15) and the second tab is used to see the real-time graph output when a test is performed.
Figure 15: TRT command software – command tab

In the first tab, the top left panel is dedicated to the equipment control. It allows the user to turn the pump ON and OFF and set a flow rate. Then the software will automatically try to match the real flow rate given by the flow meter and the set flow rate by adjusting continuously the pump speed. The actuated ball valve can be turned ON and OFF, as well as opened at any given opening percentage. Finally, the electric heater can also be turned ON and OFF and the heating power can be chosen in the range from 2.0 to 9.0 kW. The time interval at which the sensors are updated can be defined by the user.

The bottom left panel deals with the circulating fluid and its properties for the borehole considered. The user can choose between several built-in fluids and their properties (density $\rho$ and specific heat capacity $C_p$). These values are assumed constant and are used to compute the injected heat $Q$ in the borehole during the test knowing the measured volumetric flow rate $w$ and the temperature difference between the outlet and the inlet (35):

$$Q = \rho \cdot C_p \cdot w \cdot (T_{out} - T_{in})$$  \hfill (35)

The idea is to include an automatic function in order to account for the temperature dependency of the density and specific heat, and even include a flow control strategy which keeps the flow constant when the fluid viscosity changes with temperature. This has been left as a suggestion for future work.

The last panel on the right-hand side shows all the output from the TRT equipment. At the top, events and potential warning messages are displayed to report on the TRT equipment state. For
instance, each time there is a change in the heating power or the set flow rate, a message is displayed in this event text box. At the bottom, the sensors panel gathers all the information from the sensors on the bench. It contains the two pressure sensors (absolute and differential pressures), the real flow rate in the system and the three temperature sensors (output, input and ambient temperatures). In order to get the sensor value, a specific DAQ communication port is read as shown in Table 3.

Table 3: TRT equipment sensors communication port

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Reference</th>
<th>Communication port (DAQ unit)</th>
<th>Output value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (x3)</td>
<td>PT1000</td>
<td>9 – 11 – 13</td>
<td>~ 800 – 1,500 Ω</td>
</tr>
<tr>
<td>Pressure (x2)</td>
<td>GE UNIK 5000 absolute and differential pressures</td>
<td>339 – 341</td>
<td>0 – 10 V</td>
</tr>
<tr>
<td>Flow meter (x1)</td>
<td>Brunata HGP-SIV 15-40 and HGP 15-40-07</td>
<td>735</td>
<td>Pulse counter (0.1 l/pulse)</td>
</tr>
</tbody>
</table>

The DAQ card has a built-in function to convert the output value from the PT1000 sensor from resistance (in ohm) to temperature (in degree Celsius). Regarding to the pressure sensors, they deliver a 0-10 V analogue signal which is converted linearly in accordance with the pressure range from 0 to 5 bars. The flow rate value is sent to the DAQ card by pulses. Each pulse represents a certain amount of fluid going through the flow meter: the volume is set to 0.1 l/pulse in this case. The flow rate is calculated using the pulse accumulator which counts the number of pulses and the update time \( t_{\text{update}} \) at which the sensor is read (36):

\[
w = \frac{\text{pulse count}}{10 \cdot t_{\text{update}}}
\]

(36)

The second tab is used to show real-time graphs of the sensors when a test is carried out (Figure 16).
This tab is made of 3 different charts on top of each other. The top chart shows the ambient, inlet and outlet temperatures versus time. The chart in the middle shows the set flow rate and the real flow rate on the left y-axis and the calculated injected power on the right y-axis versus time. The last chart at the bottom shows the differential and absolute pressures versus time. Each chart is updated every time a new data point is logged. The time elapsed between two measurements is defined by the user with the update time in the first tab. Moreover, there is an indication of the number of measurement points in the bottom right corner. It provides the user with useful information for how large the measurement files are.

When a thermal response test is carried out with this command software, it activates an auto-save feature. A new folder is created in the working directory, i.e. the directory where the command program is located. The default name of this folder is the date (with YYMMDD format) of the test. In this folder, each time a new measurement is done a new file with all the measurements is created and saved. This file is a plain-text file using the .CSV file format extension (semicolon as a delimiter between fields). It is made of 9 columns, one of each parameter saved: time (hour), injected power (Watt), measured temperature (degree Celsius), inlet temperature (degree Celsius), outlet temperature (degree Celsius), ambient temperature (degree Celsius), flow rate (l/s), absolute pressure (bar) and differential pressure (bar). The measured temperature saved in this file is calculated with the arithmetic mean of the measured inlet and outlet temperatures as presented in (5). This file can be opened with Microsoft Excel and with the TRT evaluation tool which has also
been developed. This auto-save feature is essential to make sure that even if the software crashes or something wrong happens, all the measurements done up to the crash are still available.

Additionally, besides the measurement file, a log file is also automatically saved every time a parameter of the test is changed in the first tab. For instance when the set flow rate or the heating power is changed by the user, a log file using the .TXT file format extension is saved in the same folder as the measurement files. This file helps the user to know what variable was changed or what happened at specific instants when a thermal response test is carried out. This log file is auto-saved in the same folder as the folder used for the measurements.

2.3.2. First Thermal Response Test

In order to assess the stability and the usability of this new command software, a Thermal Response Test was carried out in KTH lab.

The experimental setup was composed of the TRT equipment linked to a water tank in order to simulate the borehole. A laptop computer was also used with Python and the TRT command software installed as well as the needed libraries to make the command software run. It was linked to the pump control unit using the USB-RS485 converter and connected to the DAQ unit through the Wifi from the wireless router.

Figure 17 and Figure 18 show the TRT which was carried out with the TRT equipment in KTH. During the first hour the program is running without any fluid circulation, followed by 2 hours of fluid pre-circulation (without heat injection besides the circulation pump contribution) where the temperature in the water tank becomes almost constant. At the end of the pre-circulation, about 2.5 hours of relatively constant heat injection into the water tank followed, concluded by about 3.5 hours of thermal recovery with fluid circulation.

The fluid volumetric flow rate was set to 0.20 l/s and the heating power was set to 3.0 kW.

Figure 17 shows the temperature response versus the elapsed time. At the beginning of the test, without fluid circulation, the inlet and outlet temperatures are different. When the pump is turned on, the inlet and outlet temperatures become relatively equal although they are not constant over the pre-circulation period. As it can be seen, between 1.0 and 3.0 hours of the test, the temperatures slightly decrease. This is because of a previous use of the TRT installation: the circulating fluid stored in the tank was still warm from a previous test and is then somewhat cooling down. After 3.0 hours, the electric heater is turned on. The inlet and outlet temperatures are then rapidly rising during the
whole period. After 2.5 hours of heat injection, the electric heater is turned off with the fluid circulation still happening. During this recovery phase, the fluid cools down.

Figure 17: fluid mean temperature during the whole TRT in KTH lab

Figure 18 shows the evolution of the flow rate (in blue, on the left y-axis) and the injected heat (in red, on the right y-axis) during the same laboratory test. At the beginning, there is no flow rate and after 1.0 hour, the pump is turned on with a wet flow rate of 0.20 l/s. The real flow rate is slightly lower, in the range from 0.19 to 0.20 l/s. The injected heat is more or less equal to zero except during the heating phase. During this period, it varies from 2.6 to 2.9 kW although it should be closer to 3.0 kW as set in the electric heater parameters. This difference can be explained because of the constant values of the density and specific heat capacity used for the calculation of the power although the real temperature of the circulating fluid is changing over the time. Moreover the real flow rate has a main influence on the injected heat. Also, there may be a slight thermal loss in the equipment between the inlet and outlet point.
2.4. TRT/DTRT measurement evaluation tool

2.4.1. Tool presentation

The stand-alone TRT/DTRT evaluation tool developed in this thesis aims at improving the data analysis by providing a simple and user-friendly interface. As a matter of fact, both TRT and DTRT measurements generate a lot of data to analyse, thus the software appears as a good solution to compute this large amount of data. It helps reducing the data manipulation hence it also reduces the overall evaluation time.

The determination of the ground thermal conductivity $\lambda_g$ and the borehole thermal resistance $R_b$ is carried out by calculating the temperature difference between the fluid and the undisturbed ground as a function of time. A computer program subsequently minimizes the squared error between calculated and measured values by adjusting $\lambda_g$ and $R_b$ parameters. The program allows the user to choose between the Infinite Line Source model (ILS) (Ingersoll, et al., 1948) and the Infinite Cylinder Source model (ICS) (Carslaw, et al., 1959) that evaluate the temperature response after time $t$ of a step change in supplied heat power $q$. Such program was first used in (Acuña, et al., 2009) for analysing one borehole section at the time, and has been further developed in Microsoft Excel using Visual Basic for Applications (VBA) by Palne Mogensen. Now, it is able to evaluate the whole borehole depth after a few mouse clicks.

The tool developed takes model parameters and TRT/DTRT measurements files as input for the calculation. It allows the user to choose different optimization modes and models. In case of DTRT
measurement, different sections with specific fitting settings can be chosen for the computation. The main outputs from this analysis tool are the borehole thermal resistance, the ground thermal conductivity and the delta temperature response plotted versus time. Besides, model parameters can be changed and saved easily. The overall structure of the program is shown in Figure 19.

The one-window interface is made of two tabs: the first one for data input and the second one for results output once the computation is done. The data input is separated into three main parts: model parameters, TRT or DTRT measurements and model calculation (Figure 20).
Model parameters are the parameters required to run the calculation. The input file is a text file using the .TXT file format extension which contains one parameter per line (ground volumetric capacity, borehole diameter, borehole length and section length for instance). It also gives initial guess values for ground thermal conductivity and borehole thermal resistance which are later used in the optimization process.

Data file contains the measurements performed with the TRT or DTRT apparatus. The input file is a plain-text file using the .CSV file format extension (semicolon as a delimiter between fields). In case of TRT data, it contains three columns: the first one for the time, the second one for the power input and the last one for the measured temperature. In case of DTRT data, it contains the temperature and power measured for each section versus the time. Each of these parameters is stored in a different column of the file. It may have as many sections, i.e. as many columns, as the borehole is made of.

The program allows the user to define different fitting settings independently for each section of the borehole: it can be specified time range for optimization, undisturbed ground temperature, length and baseline rise values specific for each section. The baseline rise (expressed in $K/H$) accounts for the previous use of the borehole if the borehole has not reached an undisturbed state when carrying out a new thermal response test. Once the model parameters and measurements are loaded into the software, it is possible to run the optimization on either one or the other parameter while keeping the other constant. Another approach consists in evaluating both parameters at the same time and a fourth one is to run the calculation providing both parameters and computing the time-step response based on them. The computation may be run with ILS model.

Figure 21 shows an example of output results for a borehole section. In this case, the borehole thermal resistance is evaluated during the heating phase, i.e. between 106 and 138.5 hours, for section 8. The program provides the user with a line graph of the measured temperature and the computed temperature versus time. It also gives key parameters computed for the section considered.
Once the computation is done, the tool allows the user to export both the final computed results and the computed delta temperature response to CSV files. This file can be open using Microsoft Excel, for instance.

### 2.4.2. Results comparison

In order to assess the performance and accuracy of this new analysis tool, real DTRT measurements were used and compared to results obtained in (Acuña, et al., 2009). Same DTRT measurements and model parameters were taken in the computation process. In a first place, the rock thermal conductivity is evaluated during the recovery phase, neglecting the first 10 to 20 hours. This phase provides the best information about the rock thermal conductivity. As a matter of fact, the heat injection is stopped and there are no radial temperature gradients in the borehole, thus the borehole fluid and the ground have the same temperature. The borehole is therefore a better representation of the surrounding ground during this recovery phase, allowing the evaluation of the rock thermal conductivity. The ground thermal conductivity is evaluated during the late-time of the recovery phase (time range between 150 and 164.5 hours in this case) as shown in Figure 22 with section 1 considered.
Once this step done, the borehole thermal resistance is then computed during the heating phase using the ground thermal conductivity previously found as an input value. In this case the evaluation is done in the time range between 106 and 138.5 hours (see Figure 23).

This analysis tool allows the possibility to run the optimization on either one specific section or on all sections one after the other automatically, hence reducing the need for intervention from the user. The same protocol was repeated for all sections of the borehole in order to compute the specific and optimized values for each section. Table 4 and Table 5 below give the final error difference between
the computed results from the analysis tool and from (Acuña, et al., 2009), for each section and for respectively the ground thermal conductivity and the borehole thermal resistance.

Table 4: $\lambda_g$ comparison with (Acuña, et al., 2009)

<table>
<thead>
<tr>
<th>Borehole section</th>
<th>$\lambda_g$ (W/K.m)</th>
<th>Absolute difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Acuña, et al., 2009)</td>
<td>Simondon</td>
</tr>
<tr>
<td>1</td>
<td>3.160</td>
<td>3.148</td>
</tr>
<tr>
<td>2</td>
<td>2.820</td>
<td>2.811</td>
</tr>
<tr>
<td>3</td>
<td>2.980</td>
<td>2.972</td>
</tr>
<tr>
<td>4</td>
<td>2.670</td>
<td>2.657</td>
</tr>
<tr>
<td>5</td>
<td>2.850</td>
<td>2.848</td>
</tr>
<tr>
<td>6</td>
<td>2.980</td>
<td>2.967</td>
</tr>
<tr>
<td>7</td>
<td>3.310</td>
<td>3.305</td>
</tr>
<tr>
<td>8</td>
<td>3.620</td>
<td>3.609</td>
</tr>
<tr>
<td>9</td>
<td>2.600</td>
<td>2.612</td>
</tr>
<tr>
<td>10</td>
<td>3.370</td>
<td>3.362</td>
</tr>
<tr>
<td>11</td>
<td>3.500</td>
<td>3.504</td>
</tr>
<tr>
<td>12</td>
<td>3.270</td>
<td>3.287</td>
</tr>
<tr>
<td>Average</td>
<td>3.094</td>
<td>3.090</td>
</tr>
</tbody>
</table>

Table 5: $R_b$ comparison with (Acuña, et al., 2009)

<table>
<thead>
<tr>
<th>Borehole section</th>
<th>$R_b$ (K.m)/W</th>
<th>Absolute difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Acuña, et al., 2009)</td>
<td>Simondon</td>
</tr>
<tr>
<td>1</td>
<td>0.071</td>
<td>0.071</td>
</tr>
<tr>
<td>2</td>
<td>0.068</td>
<td>0.068</td>
</tr>
<tr>
<td>3</td>
<td>0.057</td>
<td>0.056</td>
</tr>
<tr>
<td>4</td>
<td>0.054</td>
<td>0.054</td>
</tr>
<tr>
<td>5</td>
<td>0.058</td>
<td>0.058</td>
</tr>
<tr>
<td>6</td>
<td>0.064</td>
<td>0.063</td>
</tr>
<tr>
<td>7</td>
<td>0.057</td>
<td>0.057</td>
</tr>
<tr>
<td>8</td>
<td>0.055</td>
<td>0.054</td>
</tr>
<tr>
<td>9</td>
<td>0.078</td>
<td>0.078</td>
</tr>
<tr>
<td>10</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>11</td>
<td>0.059</td>
<td>0.059</td>
</tr>
<tr>
<td>12</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>Average</td>
<td>0.0618</td>
<td>0.0615</td>
</tr>
</tbody>
</table>
As it can be observed, results obtained with the stand-alone analysis software developed are very close to the one from (Acuña, et al., 2009). The error difference for ground thermal conductivity ranges between 0.06 and 0.51% and the error difference when averaging all the sections is 0.13%. The error difference for borehole thermal resistance ranges between 0.00 and 1.82% and the error difference when averaging all the sections is 0.40%. These results prove the accuracy of the software to provide reliable computed values.

Nonetheless these very close results there is still a small difference, especially in the ground thermal conductivity optimization. This can be explained by the difference in the way Python and Excel VBA do the calculation, particularly on iterations loops. It may be possible to improve the analysis tool in order to get even more close results by looking further into the code.

Finally, this analysis tool is also extremely time-efficient and computes the final results for the 12 sections of the borehole in less than 2 minutes. The computation time is in the same order of magnitude as the computation time with the Excel macro, but the overall evaluation time is significantly reduced thanks to the reduction in data manipulation from the user.
4. Conclusion

The three objectives of this thesis are entirely fulfilled.

First of all, the TRT equipment available at KTH – Energy Technology department is fully working. The pump has been fixed with new gaskets and no more leakages were experienced when running it.

Then, two new Python-based programs were successfully developed and designed.

The command program allows a full control of the TRT equipment available at KTH. The previous command program using LabVIEW is no more needed. The new program provides the user with a simple and user-friendly interface so as to control each device from the TRT equipment independently. Different settings for the thermal response test can also be defined in an easy way. The command program also offers the possibility to monitor the test running with real-time updated graphs. The auto-save function creates regularly measurement files so as to allow keeping the measurement carried out no matter what could happen with the program. These files can be open with Microsoft Excel. Small-scale tests were successfully carried out in the lab using the command software.

The stand-alone analysis tool is a very useful and powerful tool to import measurement files from both TRT and DTRT equipment. It helps to compute the key parameters of the BHE in a simple way with few data manipulation from the user. Parameters and measurement can be imported from files. The measurement file chosen can be the one created with the command program. The program allows the user to choose between different fitting and optimization settings. It gives clear and quick graphs and results. The computed values and graphs can be exported to a file and opened in Microsoft Excel.
5. Future work

Although the three objectives defined are met, some improvement to each of these objectives can be done.

The next step to improve the TRT equipment is to replace the old laptop computer running the command software by a smaller computer such as the Raspberry Pi. A Raspberry Pi (see Figure 24) is a low-cost credit-card sized computer that can be plugged into a computer screen and a keyboard. This very small type of computer runs on Linux-based operating system and is powerful enough to run the command software developed in this thesis. The reasons why the old laptop computer should be replaced are that it takes a lot of space in the electric box and it uses a lot of power and electricity which are not necessary.

![Raspberry Pi computer](image)

Figure 24: Raspberry Pi computer

In order to properly run the TRT command software, this new Raspberry Pi needs to be linked to be TRT equipment in the same way the old laptop computer was. It means the USB-RS485 converter and the Wifi connection to the wireless router need to be set up. The Raspberry Pi has 2 USB ports so there is no problem for the USB-RS485 converter connection. In order to access the internet, the user can choose between using an Ethernet cable linked to the DAQ card and setting up the connection through a 3G USB key to the wireless router. Once this is done and with some configuration, the Raspberry Pi can be accessed from any computer with internet access without any physical interaction. This would allow a full and easy remote control of the TRT equipment when running real on-field measurements. It would be possible to run and monitor thermal response tests without the need to be physically present.

The new command software designed now allows the user to have a full control of the TRT equipment. A way to improve it is to change the fluid thermal properties used in the injected heat calculation. As a matter of fact the accuracy of the calculated injected heat can be enhanced by
taking the real fluid temperature into account for the fluid thermal properties. As of now, the fluid properties used for calculation are those corresponding to water fluid at 25°C and they are kept constant during the whole test although the real fluid temperature is changing with time. In order to update the fluid thermal properties with the temperature variation, the appropriate equations should be found and used in the software. Besides this function, a flow control strategy could also be included in the software in order to keep the flow constant when the fluid viscosity changes with the temperature.

Besides this fluid thermal properties calculation tool and flow control strategy, it is also possible to improve the way the auto-save function works in the software. As of now, a new measurement file is created each time the sensors are updated and saved in a default folder. In case of a failure of the computer (either a usual laptop computer or a credit-card sized computer such as the Raspberry Pi), the measurement files saved would not be available any more. A simple solution is to set the default folder in the cloud using any file hosting service with cloud storage. The files would then be synchronized and could be available from any computer anywhere in real time, even if the computer installed with the TRT equipment crashes or shuts down.

Finally the analysis tool also works properly although some improvements can be done. First of all, many other models could be investigated and eventually added into the tool. The Infinite Line Source and the Cylinder Line Source are already implemented. However, the latter one does not provide good results and further investigation should be provided to this model. In addition to these two models, g-functions, Finite Line Source and Beier model among others could be other possibilities.

Furthermore the command software computes the mean temperature estimator using the mean of the measured inlet and outlet temperatures as mean temperature estimator. As explained previously, the p-linear estimator provides better results and should be used instead. Then the p-linear estimator could be added to the analysis tool in order to improve the reliability of the computed results.
References


