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Response testing and evaluation of groundwater-filled boreholes

Development and validation of a new calculation tool

Master's Thesis in Sustainable Energy Systems

HELENA NAKOS

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Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Ground source heat pump, GSHP, systems are an interesting alternative in the energy sector compared to other heating and cooling systems due to the fact they are considered to be energy efficient technologies. The use of GSHP systems, in comparison to the use of more conventional cooling and heating systems, could result in a decrease of emissions according to the U.S. Environmental Protection Agency, EPA.

The design of a ground source heat pump system will depend on the ground thermal properties. These properties include ground thermal conductivity, borehole thermal resistance and the undisturbed temperature of the ground. These properties are commonly estimated from *in-situ* thermal response tests, TRTs. Numerous methods have been developed to evaluate the experimental data obtained from thermal response tests.

This Master's Thesis presents a comparison of some of the commonly used methods for the evaluation of ground thermal properties. A new method has also been presented to evaluate experimental data obtained from TRTs. The method is based on mathematical models developed by Javed and Claesson and considers the thermal capacities, resistances and properties of all the borehole elements. The new method has been programmed in the software MATLAB and has been compared to the existing methods. The evaluation of these methods have been performed using experimental data obtained from different *in-situ* TRTs. The TRTs have been performed both for single and multiple injection rates, in increasing and decreasing injection modes. The estimated ground thermal properties have then been used to model a GSHP system where the size of the system obtained from the different methods have been compared to each other. The GSHP systems have been modeled in the software, Earth Energy Designer, EED.

The results show that the existing methods give similar results when the evaluation is performed for single injection rates. This is also true for the new method. The multiple injection rates in increasing mode gave similar results as the values estimated from the single injection rates. The multiple injection rate performed in decreasing mode showed that the existing methods give inconsistent results of the ground thermal properties. The new method however, gave more consistent results. The EED calculations showed that the borehole lengths obtained from the new method can be compared to the existing methods already used today and that the borehole length variations between the methods do not vary more than 10 % from each other. Javed *et al.* observed that uncertainties of this magnitude can be expected in this type of comparisons.

The analysis in this Master's Thesis have showed that the new TRT evaluation approach can be compared to the existing methods already used today. The new method show good evaluation properties for multiple injection rates compared to the existing methods since they can have problems with the evaluation of groundwater-filled boreholes. Besides the results of the comparison a software tutorial is presented of the new evaluation method.

Keywords: Borehole heat exchanger, Borehole thermal resistance, Ground source heat pump, Ground thermal conductivity, Groundwater-filled borehole, Thermal response test.

Contents

Preface

This report presents the Master's Thesis on response testing and evaluation of groundwater-filled boreholes, where a new calculation tool has been developed and validated. The Master's Thesis was performed during 2011 at Chalmers University of Technology at the Division of Building Services Engineering.

I would like to thank my supervisor, Saqib Javed and the Division of Building Services Engineering at Chalmers University of Technology, for the support and expertise throughout the thesis.

Göteborg October 2011
Helena Nakos

Abbreviations

COP	Coefficient of performance, defined as the useful heat produced by the heat pump compared to the work needed by the heat pump.
EED	Earth Energy Designer.
FD	Finite Difference (as in finite difference numerical method).
GLHEPRO	Ground Loop Heat Exchanger Pro.
GPM	Geothermal Properties Measurement.
GSHP	Ground Source Heat Pump.
LSM	Line Source Method.
MIR	Multiple Injection rate.
TEP	Thermal response test Evaluation Program.
TRT	Thermal Response Test.

1 Introduction

Sustainable energy systems play an important role towards reaching a sustainable future since the energy sector is one of the most important emission sources[13]. Technologies providing high efficiency combined with low or no environmental impact are highly desirable. One rapidly growing system in the energy sector is the ground source heat pump, GSHP, system. The U.S. Environmental Protection Agency, EPA, has called these systems, *"the most energy efficient technologies available"* and states that the use of fossil fuels could be significantly reduced by using GSHP systems instead of the more conventional systems, resulting in a decrease of emissions[21]. For this reason, these systems are an interesting alternative in the energy sector compared to other heating and cooling systems.

The reason for the GSHP system being attractive from an environmental point of view is because it uses the ground as a heat source or a heat sink for heating or cooling buildings with a certain energy demand. The temperature in the ground remains nearly constant after a certain depth and is not affected by seasonal changes. This technology is not totally emission free, it still needs electricity to run the heat pump and other auxiliary equipment. However, the system has a high coefficient of performance, COP, around 3-5[18] and the amount of electricity needed is lower compared to other systems.

The design of the GSHP system can be performed in different modeling softwares. These softwares need specifications on the building's energy demand, the performance of the heat pump and the ground thermal properties. The heat pump performance data is available from manufacturers and the building's heating and cooling demands can be determined using building energy analysis software. One factor of significant impact on the overall design of GSHP systems are the ground thermal properties. The ground properties are often estimated using *in-situ* TRT. The better the ground properties can be estimated the more economically feasible the system can be made. At present the existing methods used to estimate ground thermal properties use many simplifications and assumptions when determining the ground thermal properties of ground thermal conductivity and borehole thermal resistance. One of the optimisation possibilities of designing a GSHP system lies in improving the techniques for estimating ground thermal properties.

1.1 Purpose

The design of a ground source heat pump system depends on the ground thermal properties. These properties include ground thermal conductivity, borehole thermal resistance and the undisturbed temperature of the ground. These properties can vary for different geographic locations and are hence calculated from an *in-situ* thermal response test, when designing a large-sized GSHP system.[14]

By estimating these properties, the limitations of ground heat transfer are identified which are then used to determine the amount of boreholes needed for a certain building energy demand. These systems are often over designed and more boreholes are used than what is needed. Thus a good estimation of the ground thermal properties is important for the thermal efficiency of a GSHP system and its economic feasibility.[9]

Numerous methods have been developed to evaluate the experimental data obtained from a thermal response test. The most commonly used methods have been developed to evaluate grouted boreholes(i) but in Sweden the boreholes are groundwater-filled[14]. In grouted boreholes the heat transfer is due to conduction. This is also the case for groundwater-filled boreholes but in these types of boreholes the heat transfer is also influenced from convective flow. The convective heat transfer in the groundwater-filled bore-

(i)Explanation of a grouted borehole can be found in Section 2.1.

holes arise from temperature differences in the groundwater inside a borehole. The temperature differences are developed due to the heat injection that the borehole is induced to. This will result in the volume expanding or decreasing creating density differences in the water. The density difference will create movement of the water. The more denser part will start to sink and the less dense water will rise, the convective flow that is created will result in better heat transfer through the borehole.[11] This limitation of the current methods, developed to evaluate grouted boreholes accounting only for conductive heat transfer, render room for development in this field.

1.2 Scope

This Master's Thesis aims at the development of a new method to evaluate thermal response tests conducted on groundwater-filled boreholes. The new method will consider the thermal capacities, resistances and properties of all the borehole elements and is hence expected to be valid even for short test durations. This can reduce the required duration for which the thermal response tests need to be conducted.

1.3 Overview of method

The new method to evaluate thermal response tests will be based on mathematical models that will consider a wide range of ground thermal properties for borehole evaluation. The new method will be validated using existing methods and a series of *in-situ* thermal response tests. In addition a literature study is conducted to get a better overview on the subject.The programming language, MATLAB is used to program the new method.

To better understand the limitations of the existing methods, a comparison is made between the methods. These methods are then compared to the developed new method. The comparison is made using experimentally measured data from a series of *in-situ* TRT performed with various heat injection rates. Various heat injection rates have been used since the influence the convective heat flow has on the heat transfer will depend on the size of the heat injection rate. By using different heat injection rates the existing methods can be assessed on how they are affected when evaluating groundwater-filled boreholes. The obtained ground thermal properties have then been used to model a GSHP system. A comparison is performed between the obtained sizes of the systems that would be necessary to have for a certain building energy demand.

The new method and some findings of this Master's Thesis are also reported in a scientific paper[16] which has been accepted for publication in ASHRAE Transactions[1].

2 Theory

This chapter describes the fundamental theory needed in this thesis. The first section introduces the ground source heat pump system. The sequent section gives an overview of the theory and construction of a thermal response test. The following sections describe the existing methods used for evaluation of ground thermal properties. The last section of this chapter introduces the theory for the development of the new method that will be used for the evaluation of ground thermal properties.

2.1 Ground Source Heat Pumps

Ground source heat pumps are commonly used today since they have proven to be an efficient way of heating or cooling buildings by using the ground as a heat source or a heat sink[2]. This is accomplished by drilling holes in the ground, so called boreholes, where a U-pipe is inserted into the borehole. In the U-pipe a fluid is circulated which exchanges heat with the surroundings. Between the U-pipe and the borehole commonly some type of grouting material is introduced. The type of grouting material differs for different countries and locations and is used to increase the heat transfer between the circulating fluid and the ground. In Sweden the groundwater is used instead of a grouting material[14]. Figure 2.1 shows an overview of the construction of a borehole.

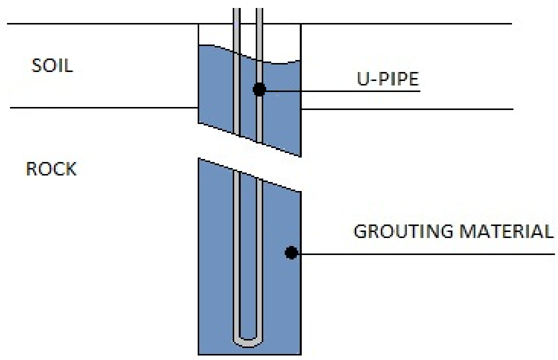

Figure 2.1 Overview of a borehole.

The cost of a ground source heat pump system is strongly related to the required borehole length, resulting in a desire to install the minimum length possible for a certain demand[2]. The increased cost in proportion to the boreholes length is due to the high cost of drilling equipment and especially if different equipment needs to be used for one borehole[18]. The cost is also dependent on how efficient the GSHP system is. The efficiency is dependent on the temperature gradient of the ground since, at the top layer the ground temperature is sensitive to seasonal changes and changes with time. Deeper in the ground the temperature is less sensitive to these changes and as a result a more constant temperature can be assumed[9]. A sufficient long borehole will thus be considered to exchange heat at a constant temperature. For this reason the system will be considered to remain efficient through the year. A system that would exchange heat with fluctuant temperatures would have an efficiency that would vary depending on the climate. During the year the system could have both high and low efficiencies. For this reason it would be considered to be less efficient than a system that exchanges heat with the part of the ground not affected by seasonal changes.[18] Thus a compromise is often necessary between the optimal length providing the most efficient heat exchange and optimal length that gives the minimum cost of the GSHP system.

To be able to accomplish good design criteria and to evaluate a GSHP's capacity, accurate estimations need to be done on the ground thermal properties.

2.2 Thermal Response Test

A thermal response test, TRT, is conducted to estimate ground thermal properties. Since these properties change for different geographic locations, the tests are performed locally where one wishes to install a GSHP system. Figure 2.2 shows a representation of the TRT setup used in this Master's Thesis.

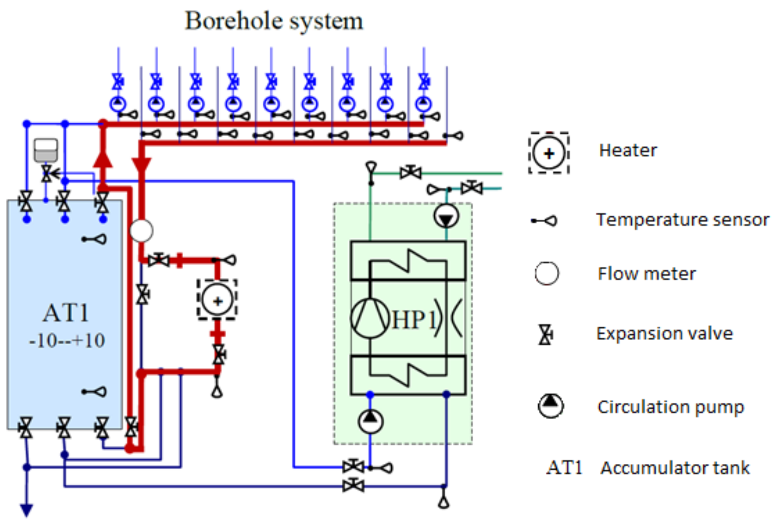

Figure 2.2 Setup of a thermal response test in heat injection mode. (Javed[14])

The solid bold red lines show the flow of the fluid. The fluid is circulating in the boreholes passing a heater which is used to heat up the fluid so that it can inject the heat into the ground. There are temperature sensors located before and after the boreholes and before and after the heater. A flow meter is positioned before the heater. The flow can be changed by means of variable speed circulation pumps, installed for each borehole or by the degree of opening or closing the flow regulating valves located at the boreholes. This is important since turbulent flow is wanted in the U-tube. By having turbulent flow inside the U-tube a low thermal resistance is ensured thus providing a better heat exchange.

There are different ways one can perform TRTs. They can be conducted in heat injection mode as shown in Figure 2.2, they can also be conducted in heat extraction mode or by using fluid at a constant temperature. The two last tests are shown in Figure 2.3.

Most commonly TRTs are performed in heat injection mode for ground property estimations. The reason for this is that it can reduce the effects of external factors that can influence the measurements easier compared to other methods[14]. This has also been the method used in this Master's Thesis.

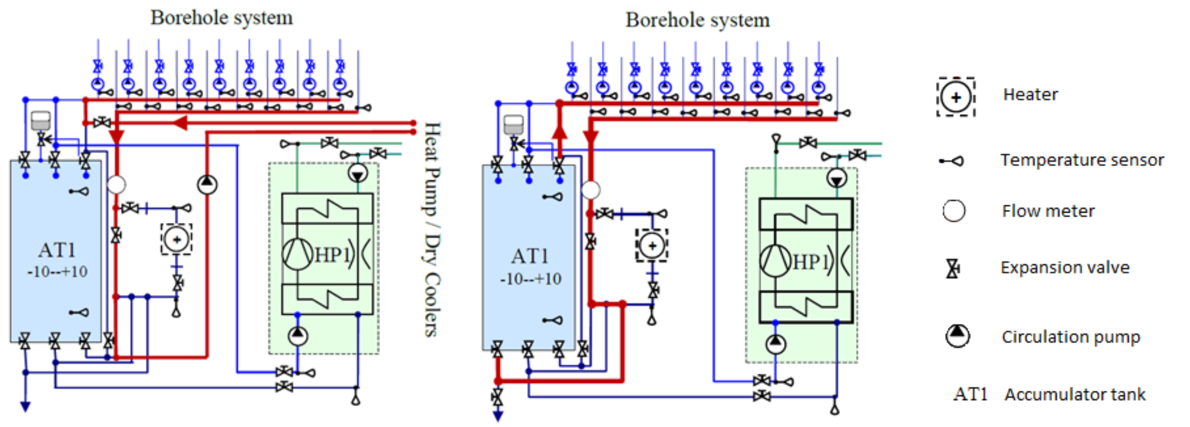

Figure 2.3 Setup of a thermal response tests. The figure to the left shows a TRT in heat extraction mode and the figure to the right shows a TRT with constant input temperature using the accumulator tank 1. (Javed[14])

For the test procedure the undisturbed ground temperature is the first property of the ground to be estimated. There are two methods that can be used to measure the undisturbed ground temperature. The first method, which is most common, is performed by circulating the fluid inside the U-pipe without any heat being injected to the borehole. This is done until the circulating fluid reaches a steady temperature. The measurements are conducted for approximately 20-30 minutes. If the test was to continue for a longer time the measurements would start to get affected by the circulating pumps, since they add heat to the fluid. However, even during this short test time the temperature is influenced of the heat from the circulation pump.

For the second method, the fluid is left in the undisturbed borehole loop for a number of hours. During this time the temperature of the fluid in the loop reaches thermal equilibrium with the surrounding temperature of the ground. Then the pumping starts, without any heat being injected to the borehole and the fluid that have reached thermal equilibrium in the loop exit the borehole. The inlet and outlet temperature of the fluid is measured during the test. By knowing the flow rate, velocity and loop length the time the fluid in the U-tube will take to exit the borehole can be calculated. In this way a better approximation of the undisturbed ground temperature can be found, this is the method used in this Master's Thesis.

The thermal response test continues by injecting a known power into the borehole, most commonly at a constant injection rate. The inlet and outlet temperatures of the fluid are then measured at constant intervals of 5-10 minutes for a minimum of 50 hours. Measurements are also performed on the power input and the flow rate of the fluid. By using analytical or numerical mathematical models the ground thermal conductivity and the borehole thermal resistance can then be evaluated.

When the ground thermal properties are found, calculations can be performed on how many and how deep boreholes are needed to satisfy a certain building energy demand. These calculations are usually performed with softwares such as Earth Energy Designer, EED[7] and Ground Loop Heat Exchanger Pro, GLHEPRO[20].

2.3 Line Source Approximation Method

The line source approximation method, LSM, is the most commonly used method for evaluation of thermal response test data. The line source approximation method can be used both as a direct and a parameter estimation method for estimating ground thermal properties from TRTs. The most accepted use of this method has been derived by Gehlin[10] and is most used due to its simplicity. In this method the borehole is considered as an infinitely long heat source in homogeneous ground. A thermal resistance is introduced as a relation of the heat flow from the circulating fluid to the borehole wall. This thermal network is illustrated in Figure 2.4. Further the heat injection rate is assumed to be constant.

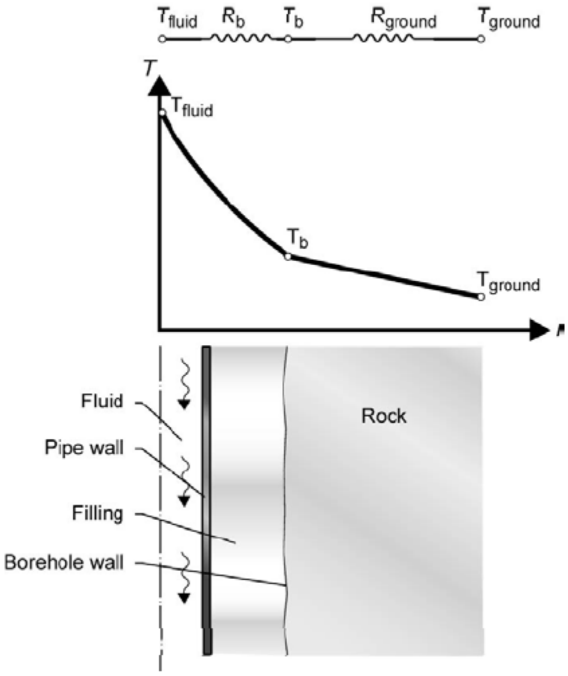

Figure 2.4 Thermal netwok considered in the LSM. (Gehlin[10])

The approximation, presented in Equation 2.1, is used to estimate the mean temperature of the fluid. The parameters are defined in Table 2.1.

$$T_f = \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4at}{r^2}\right) - \gamma\right) + T_0 + R_b q. \tag{2.1}$$

Table 2.1 Definition of the parameters used in Equation 2.1.

Parameter	Definition
a	The ground thermal diffusivity [m^2/s]
q	The injected heat rate [W/m]
r	Borehole radius [m]
R_b	Borehole thermal resistance [(mK)/W]
t	Time [s]
T_0	The undisturbed temperature of the ground [°C]
γ	Euler's constant [-]
λ	The ground thermal conductivity [W/(mK)]

Equation 2.1 can be written in a linear form since the heat injection is considered to be constant and becomes thus,

$$T_f = k\ln(t) + m \tag{2.2}$$

where T_f is the mean temperature of the fluid and the inclination, k, is defined below,

$$k = \frac{q}{4\pi\lambda}. \tag{2.3}$$

For the direct line source approximation method the fluid temperature is plotted against the logarithmic time to determine the inclination k. From the inclination it is possible to calculate the ground thermal conductivity which in its turn is used to calculate the borehole thermal resistance. The borehole thermal resistance is calculated using Equation 2.4 by Beier and Smith[4].

$$R_b = \frac{1}{4\pi\lambda}\left(\frac{T_f - T_0}{k} - \ln\left(\frac{4at}{\gamma\ r^2}\right)\right). \tag{2.4}$$

As mentioned previously one of the assumptions made in this method was that the power input was considered to be constant, meaning that this method will not be accurate for varying power inputs. This assumption provides the method with an uncertainty since the power usually fluctuates over time due to different power intensities. This is one of the drawbacks with this method.

In this Master's Thesis the line source method with parameter estimation technique has been used. The method uses a step response technique where the minimum square difference between the measured temperature and the calculated temperature is sought for a certain time interval. The power input is divided into stepwise increments since the power is not constant during the whole test[10]. The power steps are then used to calculate the temperature by using the principle of super-positioning. The temperature response from each step is summarised to get the temperature response as a function of time. The method uses the guess values of the ground thermal conductivity and the borehole thermal resistance until the values that give the minimum errors are found.

For both the direct and parameter estimation line source methods it is recommended to use the values for times larger than 15 hours since results prior to this give high residual errors. The line source methods do not account for the local heat transfer inside the borehole. The ground thermal conductivity and borehole thermal resistance will be estimated using fewer values when some of the data from the TRTs are discarded. The amount of data used in the evaluation will affect the results since more data that can be used the better the accuracy of the ground thermal conductivity and borehole thermal resistance will be.

2.4 Geothermal Properties Measurement

Geothermal properties measurement, GPM, is a software which determines the ground thermal properties from TRTs, by using parameter estimation techniques. The method has been developed by Shonder and Beck[3]. In the software an input file consisting of the average fluid temperature, heat injected to the borehole and the time intervals for the heat injection, is used. The values from the input file are matched to those obtained from the parameters estimated by the program. The parameter estimation is conducted using the

Gauss method of minimisation between the calculated data and the measured data to find the minimum sum of square errors.

A one dimensional numerical heat transfer model is used with the parameter estimation technique. The two pipes of the U-tube are modeled as a single pipe with an equivalent diameter. A thin film around the equivalent pipe diameter is introduced to account for the heat capacity of the pipes and the fluid. Figure 2.5 shows the one-dimensional approximation. The variables used are presented in Table 2.2.

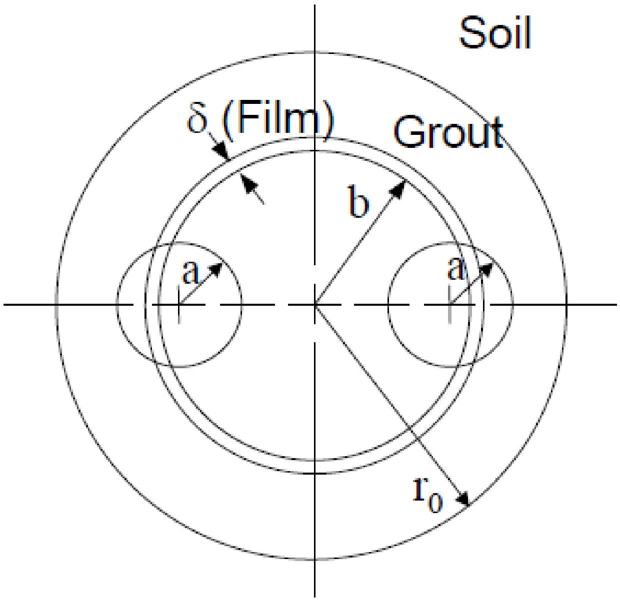

Figure 2.5 One-dimentional approximation of a borehole. (Shonder and Beck[3])

Table 2.2 Definition of the parameters used in Figure 2.5.

Parameter	Definition
a	The inner radius of the pipe [m]
b	The equivalent pipe radius [m]
r_0	The radius of the borehole [m]
δ	Film thickness [m]

The pipe is assumed to be hollow so that no thermal capacity is accounted for. All resistance is in the thin film. For this assumption the equivalent pipe radius can be calculated from Equation 2.5[3] where r_u is the outer radius of the pipe.

$$r_p = r_u\sqrt{2} \tag{2.5}$$

The numerical model used in the GPM takes into account the transient heat conduction in the borehole and thus becomes insensitive to varying heat injections. This is a good feature since the power is rarely constant and fluctuates due to different power intensities.

A factor that can be constraining is that the time intervals in the input file needs to be constant, not making it possible to derive the ground thermal properties from varying time intervals. This method is only meant to evaluate TRTs on grouted boreholes. Also the method performs the optimisation for the whole test duration. If a multiple injection rate, MIR, TRT is to be evaluated one can not choose for which times the ground thermal conductivity and borehole thermal resistance should be evaluated and optimised for.

2.5 Finite Difference Numerical Method

This numerical method, described by Ghelin[10] and Gustafsson *et al.*[11], uses an explicit one-dimensional finite difference numerical method to evaluate the ground thermal properties.

Like the previous methods the borehole is considered to have a U-pipe where the two pipes in the borehole are approximated as one equivalent pipe. Inside the pipe the fluid is circulating and outside the pipe the borehole is filled with a grouting material. The borehole thermal resistance that is introduced to account for the thermal relation between the circulating fluid and the borehole wall is calculated using Equation 2.6,

$$R_b = R_{bhf} + \frac{R_{pipe}}{2} \tag{2.6}$$

$$\text{where } R_{pipe} = \frac{1}{2\pi\lambda_{pipe}} \ln\left(\frac{r_{p_o}}{r_{p_i}}\right). \tag{2.7}$$

R_{pipe} is the thermal resistance between the fluid and the borehole filling material and R_{bhf} is the thermal resistance between the filling material and the borehole wall. In Equation 2.7, λ_{pipe} is the pipe thermal conductivity, r_{p_o} is the pipe outer radius and r_{p_i} is the pipe inner radius. The thermal resistance R_{bhf}, is divided into two parts, R_{fl-bhf} and $R_{bhf-bhw}$. R_{fl-bhf} is the thermal resistance for the heat flow between the outer surface of the U-pipe and the borehole filling temperature. $R_{bhf-bhw}$ is the heat flow resistance between the borehole filling temperature and the borehole wall. These values are calculated from Equation 2.8 and 2.9,

$$R_{fl-bhf} = (1-x)R_{bhf} \tag{2.8}$$

$$R_{bhf-bhw} = xR_{bhf}. \tag{2.9}$$

The value of x depends on the number of U-tubes inserted in the borehole. This model has divided the radial direction of the borehole into 18 cells starting from the center of the borehole. The first cell has been introduced to model the volume and thermal mass of the circulating fluid. The next cell represents the filling material in the borehole and the rest of the cells are introduced to model the surrounding ground. The heat conductance is divided into three parts. The two first parts are dependent on the thermal resistance. The thermal resistance is divided into two parts given from Equation 2.8 and Equation 2.9. These equations represent the two first cells and for this reason the two first parts of the heat conductance calculations also represent the heat conductance in the two first cells. The third part of the heat conductance represents the heat conductance in the surrounding ground using the following cells. For this reason the heat conductance of the ground is calculated between two cells in the radial direction. The three parts are,

1. A heat conductance between the fluid and the borehole filling shown in Equation 2.10.

2. A heat conductance between the borehole filling and the borehole wall shown in Equation 2.11.

3. A heat conductance in the radial direction shown in Equation 2.12.

$$U_{fl_{bhf}} = \frac{1}{\frac{R_{pipe}}{2} + R_{fl-bhf}} \tag{2.10}$$

$$U_{bhf_{bhw}} = \frac{1}{\frac{\ln(\frac{\mathrm{rm}}{\mathrm{r}})}{2\pi\lambda} + R_{bhf-bhw}} \tag{2.11}$$

$$U_{ground} = \frac{2\pi\lambda}{\ln(\frac{r_m}{r_m - \Delta r})}. \tag{2.12}$$

In Equations 2.11 and 2.12, r_m is the mean radius of two cells at different radial distances from the borehole center. r is the borehole radius, λ is the soil thermal conductivity and Δr is the difference between two cells at different radial distances from the borehole center.

The ground thermal conductivity and borehole thermal resistance is finally calculated using a parameter estimation technique that is carried out by minimising the difference between the calculated and experimentally measured temperatures of the fluid. This difference is minimised by changing the model's input values of the ground thermal conductivity and the borehole thermal resistance. The optimisation uses a nonlinear least squares optimisation technique.

2.6 New Evaluation Method

A new method has been developed to evaluate ground thermal properties from TRTs. The new method considers all properties of the borehole, such as the thermal capacities, resistances and properties of all the borehole elements in the Laplace domain.[15]

This only simplification this method is using of the borehole model, is to assume that the two pipes in the borehole is instead one pipe and thus considering the borehole to have one equivalent diameter. In Figure 2.6 the resulting geometry of the borehole and its related boundary conditions are shown. The definitions of the parameters used in the figure can be seen in Table 2.3.

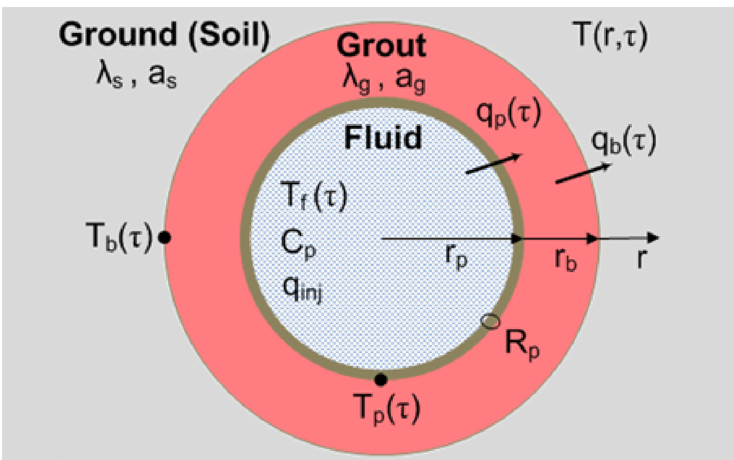

Figure 2.6 Resulting borehole geometry of the new method.(Javed[14])

Table 2.3 Definitions of the parameters used in Figure 2.6.

Parameter	Definition
a_g	The thermal diffusivity of the grout [m^2/s]
a_s	The thermal diffusivity of the soil [m^2/s]
C_p	The thermal capacity of the fluid [J/(mK)]
$q_b(\tau)$	The heat flux from the grout to the surrounding ground [W/m]
q_{inj}	Heat flux [W/m]
$q_p(\tau)$	Heat flux of the heat transfer from the pipe to the outer surface of the grout [W/m]
r	Radial distance [m]
r_b	The radius of the borehole [m]
r_p	Pipe equivalent radius [m]
R_p	The thermal resistance of the pipe [(mK)/W]
$T(r,\tau)$	The temperature at radius,r and time, τ [°C]
$T_b(\tau)$	The temperature of the borehole outer boundary [°C]
$T_f(\tau)$	The temperature of the fluid[°C]
$T_p(\tau)$	The temperature of the pipe outer boundary [°C]
λ_g	The thermal conductivity of the grout [W/(mK)]
λ_s	The thermal conductivity of the soil [W/(mK)]

The heat transfer can be presented as a thermal network, from which the temperature of the fluid in the Laplace domain can be derived. The full equations and definitions of the mathematical model, the Laplace transforms and the thermal network is presented by Javed and Claesson[14] [15].

From the expressions provided by Javed and Claesson[15], the temperature of the fluid is given by,

$$T_f(t) = \frac{2}{\pi} \int_0^\infty \frac{1 - e^{-u^2 \frac{t}{t_0}}}{u} L(u) \mathrm{d}u \tag{2.13}$$

$$T_f(0) = 0, \ \frac{\mathrm{d}T_f}{\mathrm{d}t} \to 0, \ t \to \infty. \tag{2.14}$$

The term $L(u)$ is,

$$L(u) = Im \frac{-q_{inj}}{C_p \dfrac{-u^2}{t_0} + \dfrac{1}{R_p + \dfrac{1}{\overline{K}_p(u) + \dfrac{1}{\overline{R}_t(u) + \dfrac{1}{\overline{K}_b(u) + \overline{K}_s(u)}}}}}. \tag{2.15}$$

The terms of the conductances and their inverse, the resistances, expressed in ordinary Bessel functions are given by Equations 2.16 - 2.20,

$$\overline{K}_s(u) = \frac{1}{\overline{R}_s(u)} = \frac{2\pi\lambda_s p_s u[J_1(p_s u) - iY_1(p_s u)]}{J_0(p_s u) - iY_0(p_s u)} \tag{2.16}$$

$$\overline{K}_t(u) = \frac{1}{\overline{R}_t(u)} = \frac{4\lambda_g}{J_0(p_p u)Y_0(p_b u) - Y_0(p_p u)J_0(p_b u)} \tag{2.17}$$

$$\overline{K}_p(u) = \frac{1}{\overline{R}_p(u)} = \frac{0.5\pi p_p u[J_1(p_p u)Y_0(p_b u) - Y_1(p_p u)J_0(p_b u)] - 1}{\overline{R}_t(u)} \tag{2.18}$$

$$\overline{K}_b(u) = \frac{1}{\overline{R}_b(u)} = \frac{0.5\pi p_b u[J_1(p_b u)Y_0(p_p u) - Y_1(p_b u)J_0(p_p u)] - 1}{\overline{R}_t(u)} \tag{2.19}$$

$$p_p = \frac{r_p}{\sqrt{a_g t_0}},\ p_b = \frac{r_b}{\sqrt{a_g t_0}},\ p_s = \frac{r_b}{\sqrt{a_s t_0}}. \tag{2.20}$$

For time varying heat injection rates the temperature of the fluid can be calculated by superimposing the step response. The temperature of the fluid is thus found from Equation 2.21,

$$T(t) = \sum_{n=1}^{N_{tst}} (q_n - q_{n-1}) T_f(t - tst_n) + T_0. \tag{2.21}$$

q_n is the power injected into the borehole, t is the time for when the temperature was measured and tst is the time for when the power input changed. T_f is the fluid temperature calculated from the integral in Equation 2.13 and T_0 is the undisturbed ground temperature.

The thermal resistances of the pipe and the grout are calculated from the Equations 2.22 and 2.23 respectively.

$$R_p = \frac{1}{2\pi\lambda_p} \ln \frac{r_p}{r_p - d_{pw}} \quad \left[\frac{mK}{W}\right] \tag{2.22}$$

where d_{pw} is the thickness of the pipe,

$$R_g = \frac{1}{2\pi\lambda_g} \ln \frac{r_b}{r_p} \quad \left[\frac{mK}{W}\right]. \tag{2.23}$$

The pipe thermal capacity per unit length is calculated from Equation 2.24,

$$C_p = 2\pi r_i^2 \rho_f c_f f \quad \left[\frac{J}{mK}\right] \tag{2.24}$$

where f is a factor of the amount of fluid inside the loop in comparison to the amount of fluid outside the loop. The borehole thermal resistance is calculated from Equation 2.25,

$$R_b = \frac{R_p}{2} + R_g. \tag{2.25}$$

Except for using Equation 2.25 to calculate the borehole thermal resistance there is another approach to calculate this property. Starting from Equation 2.26 and rewriting it as shown in Equation 2.27 the borehole thermal resistance can be found.

$$T_f = T_b + R_b q \tag{2.26}$$

$$R_b = \frac{T_f - T_b}{q} \tag{2.27}$$

T_b is the mean temperature at the borehole radius r_b.

Claesson and Javed[8] have developed a method to calculate the mean temperature of the borehole using Equation 2.28 and then superimposing the step response using Equation 2.29.

$$T_{ls}(r_b, t) = \frac{q}{4\pi\lambda_s} \int\limits_{\frac{1}{\sqrt{4a_s t}}}^{\infty} e^{-r_b^2 s^2} \frac{I_{ls}(Hs, Ds)}{Hs^2} \mathrm{ds} \tag{2.28}$$

$$T_b(t) = \sum_{n=1}^{N_{tst}} (q_n - q_{n-1}) T_{ls}(t - tst_n) + T_0 \tag{2.29}$$

In Equation 2.28, $I_{ls}(Hs, Ds)$ is the error function calculated from Equation 2.30. In these equations H is the borehole depth and D is the starting depth of the borehole.

$$I_{ls}(Hs, Ds) = 2ierf(Hs) + 2ierf(Hs + 2Ds) - ierf(2Hs + 2Ds) - ierf(2Ds) \tag{2.30}$$

The error function is obtained from Equation 2.31 and Equation 2.32,

$$ierf(X) = Xerf(x) - \frac{1}{\sqrt{\pi}}(1 - e^{-X^2}). \tag{2.31}$$

$$erf(x) = \frac{2}{\sqrt{\pi}} \int\limits_0^x e^{-v^2} \mathrm{dv} \tag{2.32}$$

There are also different theories on how the equivalent pipe diameter should be calculated depending on the type of borehole. For a grouted borehole Equation 2.33[22] and Equation 2.34[14] can be used.

Grouted borehole:

$$r_p = \sqrt{r_o s} \tag{2.33}$$

or,

$$r_p = r_o\sqrt{2} \tag{2.34}$$

where s is the shank spacing, which is the distance between the two pipe centers.

In the case of a groundwater-filled borehole Equation 2.35 should be used which has been shown by Gustafsson and Westerlund[12] to give the most accurate results.

Ungrouted borehole:

$$r_p = 2r_0. \tag{2.35}$$

In Equation 2.22 the thickness of the pipe, d_{pw}, is needed. However, as mentioned previously it is assumed that the borehole has an equivalent pipe radius. In the calculations of the equivalent pipe radius the actual radius of the pipe is used. If one uses the pipe outer radius an equivalent pipe outer radius is calculated and if one uses the pipe inner radius an equivalent pipe inner radius can be calculated. This means that by assuming that the two pipes in the borehole have one equivalent diameter, the pipe thickness should also be assumed to be an equivalent pipe thickness. This equivalent pipe thickness should be used in the equations instead of the real thickness of the pipes. This has been accounted for in this Master's Thesis and Equations 2.36, 2.37 and 2.38 have been used depending if the borehole is grouted or groundwater-filled.

Grouted borehole:

$$d_{pw} = \sqrt{r_o s} - \sqrt{r_i s} \tag{2.36}$$

or,

$$d_{pw} = \sqrt{2}(r_o - r_i) \tag{2.37}$$

Ungrouted borehole:

$$d_{pw} = 2(r_o - r_i) \tag{2.38}$$

The new method will here on be referred to as TRT evaluation program, TEP. The mathematical models used in the TEP make this model an attractive new method since it can be used both with varying time intervals and with varying power inputs.

3 Method

This chapter accounts for how the evaluation of the existing methods was conducted. The final section in this chapter gives a description of the new method and how it was constructed and evaluated.

3.1 Ground thermal properties estimation

The existing methods chosen to be used for the evaluation of the ground thermal properties are the LSM, the method used in the GPM software and a numerical method based on a finite-difference, approach, all described in Chapter 2. Other methods used for ground property estimations from TRTs were not included in this study due to time restrictions on this Master's Thesis. Further not all methods are available for usage even though it would be interesting to include them in the evaluation. For these reasons the most commonly used methods were chosen with an exception of the FD numerical method.

Since the methods use different assumptions on the borehole design and different calculation techniques for the ground thermal properties, the results on the ground thermal conductivity and the borehole thermal resistance will vary for each method. To evaluate the methods and to determine the effect each method has on the design of a ground source heat pump system needed for a certain building energy demand, the methods have been used in different scenarios of heat injection in the TRTs. The results of the ground thermal conductivity and borehole thermal resistance have then been used in the software EED[7]. With this software different systems were designed and the obtained size of the systems were compared to each other.

For the evaluation, experimental data from TRTs conducted in controlled laboratory conditions have been used. The glsTRTs that have been performed are:

1. TRT using single heat injection rates.
   - Single injection rate of 67 W/m. A representation of this scenario can be viewed in Figure 3.1.
   - Single injection rate of 140 W/m. A representation of this scenario can be viewed in Figure 3.2.
2. TRTs using multiple injection rates, MIR:
   - Increasing injection rates, where the heat injection was first kept at a constant level for a certain time and then increased to a higher level. The first injection rate was 67 W/m and the second injection rate was 140 W/m. A representation of this scenario can be viewed in Figure 3.3.
   - Decreasing injection rates, where the power input was first kept at a constant level and then decreased to a lower level after a certain time. The first injection rate was 140 W/m and the second injection rate was 67 W/m. A representation of this scenario can be viewed in Figure 3.4.

With these different tests conducted on groundwater-filled boreholes the estimation of the ground thermal properties will be highly responsive to the heat injection rates used. The convective heat transfer in the borehole will be higher for high values of heat injection and will be lower for lower values of heat injection. Gustafsson and Westerlund[11] have showed that for groundwater-filled boreholes, in a solid bedrock, when the injection rate increases the ground thermal conductivity can be constant over longer periods of time and that the borehole thermal resistance decreases. While for a borehole surrounded by fractured bedrock the ground thermal conductivity increases and the borehole thermal resistance stays constant.[11]

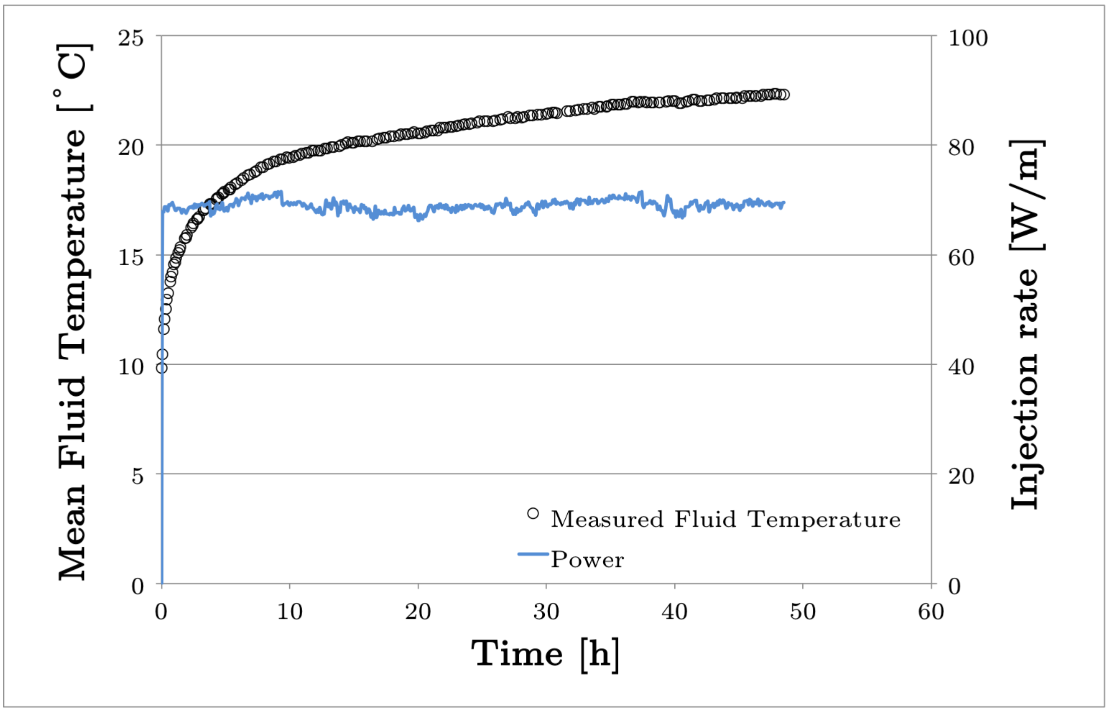

Figure 3.1 Single injection rate of 67 W/m. The power and mean temperature of the fluid is plotted over time.

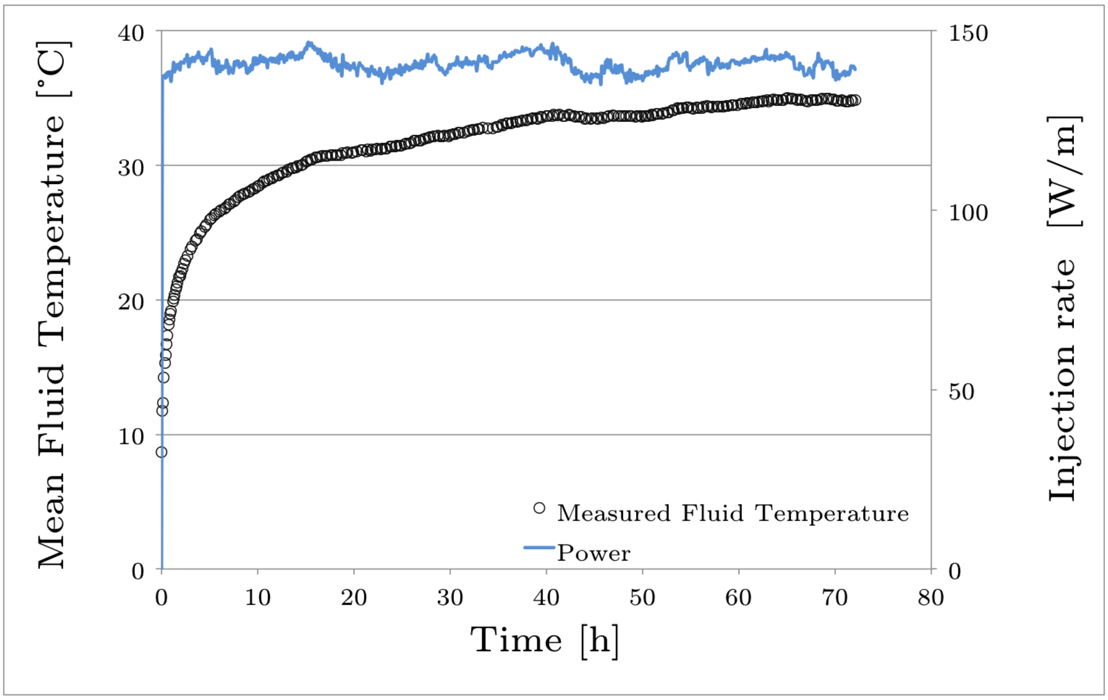

Figure 3.2 Single injection rate of 140 W/m. The power and mean temperature of the fluid is plotted over time.

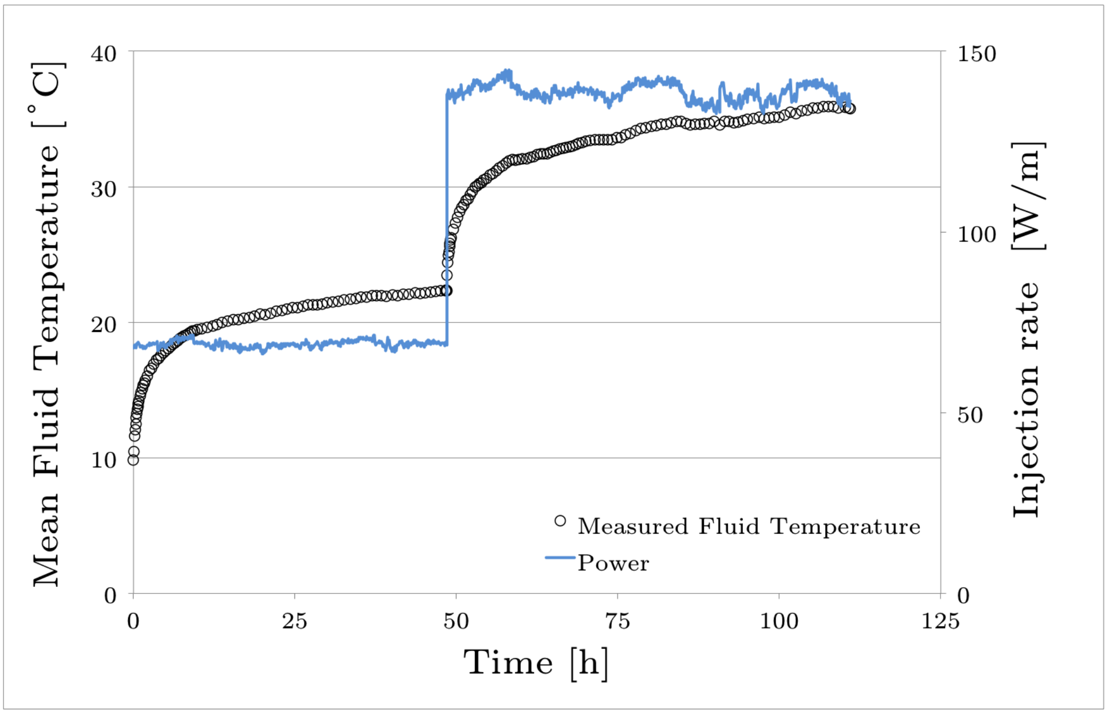

Figure 3.3 Increasing heat injection. First injection rate of 67 W/m and second injection rate of 140 W/m. The power and mean temperature of the fluid is plotted over time.

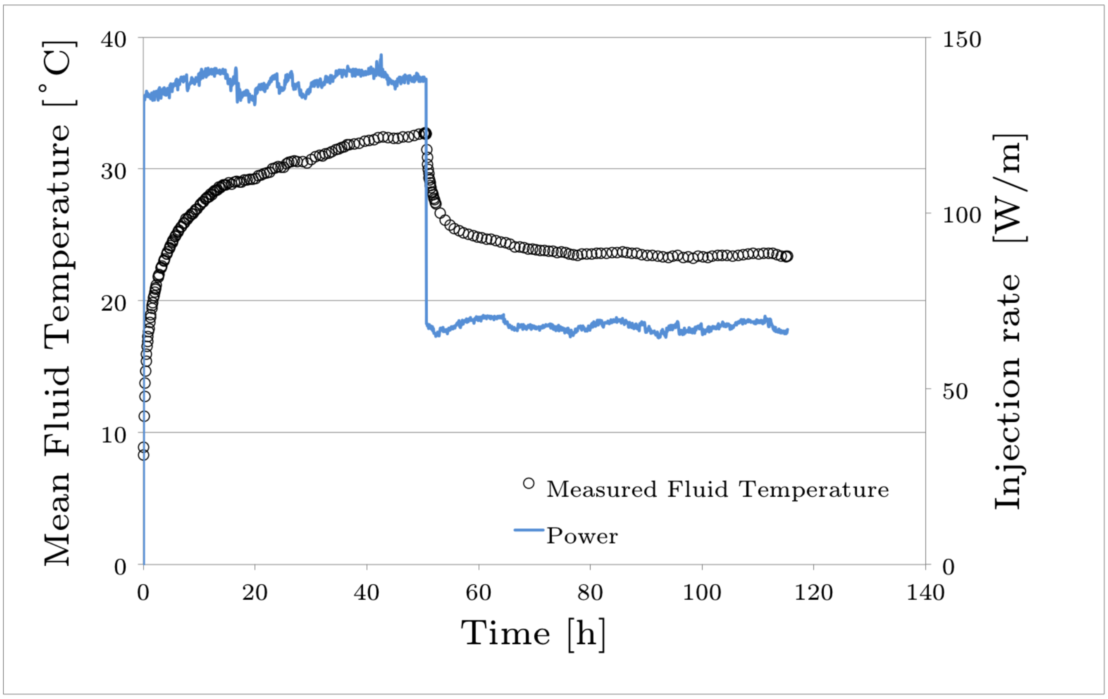

Figure 3.4 Decreasing heat injection. First injection rate of 140 W/m and second injection rate of 67 W/m. The power and mean temperature of the fluid is plotted over time.

The experimentally measured data from the different cases of TRTs were used in the methods to estimate the ground thermal conductivity and the borehole thermal resistance. Two sub-cases were made for the TRTs that were performed using MIR. The sub-cases were constructed so that the possibility to chose for which values of the measured data the optimisation was to be performed for. The sub-cases were:

1. Including all the measured data in the calculations but choosing to do the optimisation for the first injection rate only.
2. Including all the measured data in the calculations but choosing to do the optimisation for the second injection rate only.

The sub-cases were performed for the LSM and the FD numerical method. For theLSM the first 15 hours were excluded since the method is not accurate for times shorter than 15 hours[10]. The second sub-case could not be performed using the GPM software so for this optimisation the second injection rate was neglected.

Further, for the evaluation of the methods, a TRT setup by Beier *et al.*[5] has been used were all the values of the ground properties have been measured independently and are thus known. From this TRT the measured temperature of the fluid, time for data logging and the heat input was given as well as the ground thermal properties. Two different tests were provided, one where the injection rate was constant and one where the injection rate was turned off in the middle of the test and then restarted. These tests will be referred to as Beier test 1 and Beier test 2 respectively.[5] A representation of the Beier test 1 can be viewed in Figure 3.5 and representation of the Beier test 2 can be viewed in Figure 3.6.

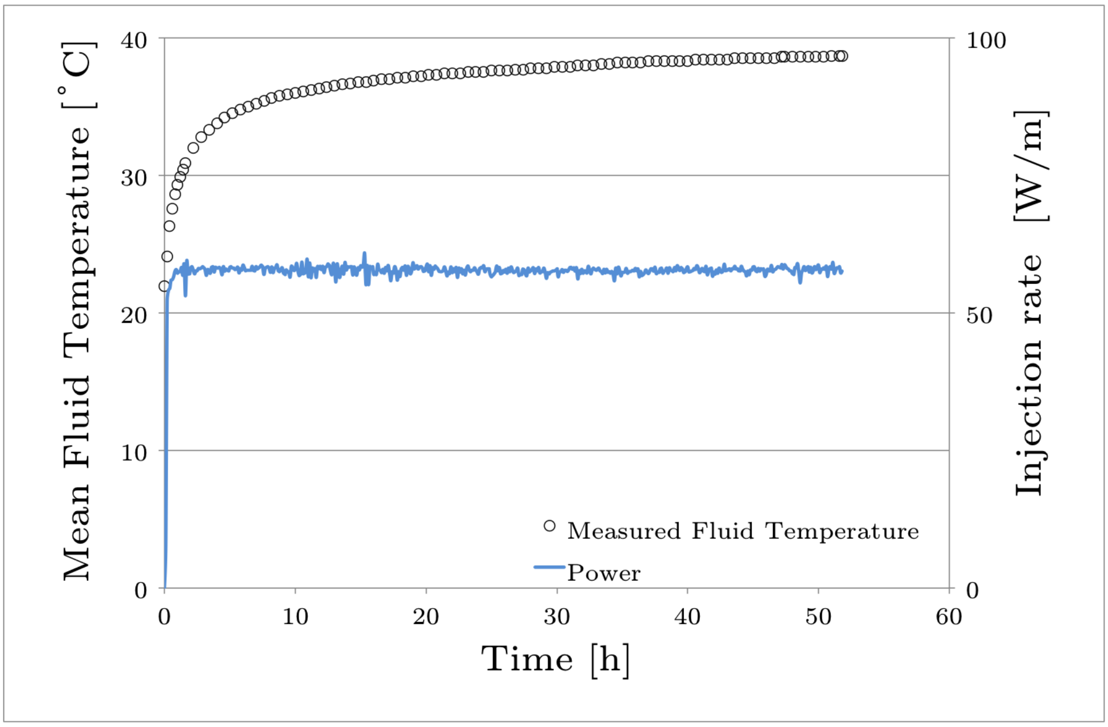

Figure 3.5 A representation of the Beier test 1. The power and mean temperature of the fluid is plotted over time.

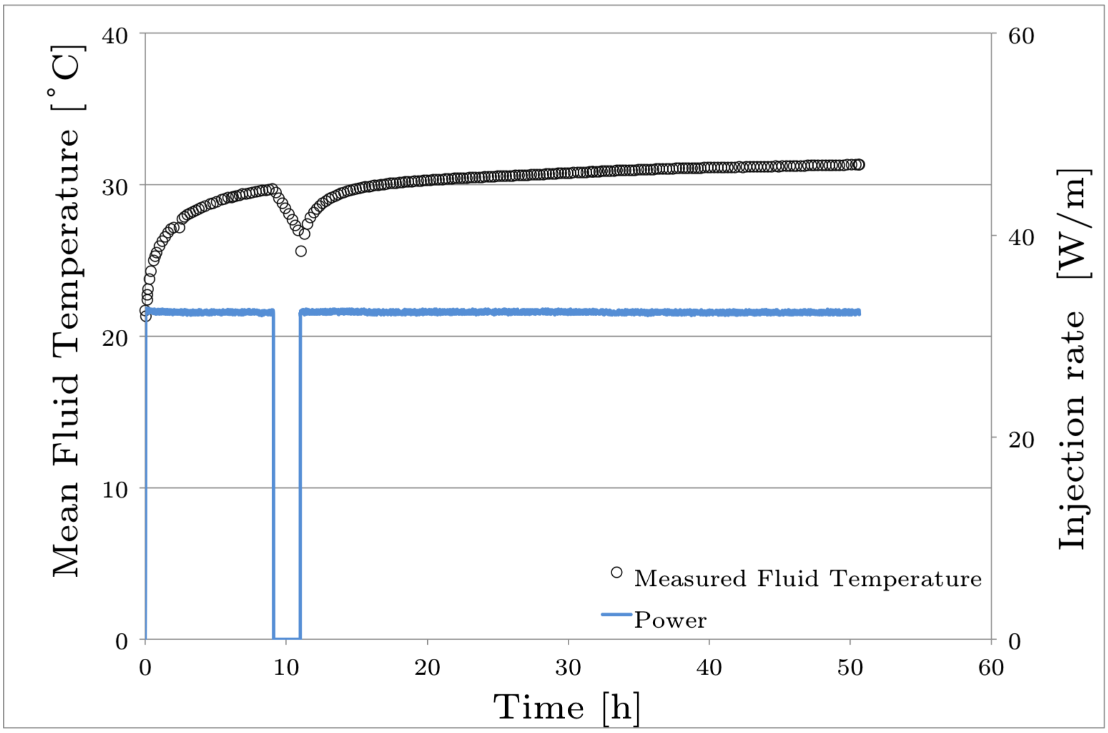

Figure 3.6 A representation of the Beier test 2. The power and mean temperature of the fluid is plotted over time.

An overview of the input data needed for each method can be viewed in Table 3.1.

Table 3.1 Input data necessary for each method.

Input parameter	LSM	GPM	FD numerical method
Borehole diameter	x	x	x
Active borehole length	x	x	x
Time for when the measured data was recorded	x	x	x
Undisturbed ground temperature	x	x	x
Power input for each time	x	x	x
Measured mean temperature	x	x	x
(Volumetric) Heat capacity of soil	x	x	x
(Volumetric) Heat capacity for the grout or groundwater	-	x	x
Inner radius of the U-pipe	-	x	x
Outer radius of the U-pipe	-	-	x
Heat capacity for the fluid inside the U-pipe	-	-	x
Thermal conductivity of the U-pipe	-	-	x

3.2 Evaluation of the obtained ground properties

To evaluate the existing methods, the ground properties obtained from the simulations mentioned in Section 3.1, are used to model a GSHP system for a certain building energy demand. The model is obtained from the system design software EED[7].

In EED the monthly cooling loads, heating loads and peak loads are specified combined with the thermal conductivity and borehole thermal resistance estimated from the measured data of the TRTs. When the simulation is performed the program provides different configurations of boreholes, depth and construction one can choose from.

The energy loads needed in the EED can be taken from real cases where the building energy demand is known. This would give a more realistic case of the size of the GSHP system needed. Such cases were not provided for this Master's Thesis and a synthetic load profile was used instead to simulate the building energy demand. With the synthetic load profile different scenarios can easily be created. In this Master's Thesis two scenarios have been created, one extreme scenario where the cooling demand is dominating and one scenario where the heat and cooling demand is balanced over one year. From these scenarios the monthly loads and peak loads are obtained and are used in EED. The scenarios have been generated by Equation 3.1 developed by Pinel[19] presented by Bernier *et al.* in[6].

$$
\begin{aligned}
Q(x) = {} & f(x;A,B,C) + (-1)^{\mathrm{floor}\frac{F(x-B)}{8760}} \mathrm{abs}(f(x;A,B,C)) \\
& + D(-1)^{\mathrm{floor}\frac{F(x-B)}{8760}} \mathrm{signum}\left(\cos\left(\frac{F\pi(x+G)}{4380}\right)+E\right)
\end{aligned} \tag{3.1}
$$

where

$$
\begin{aligned}
f(x;A,B,C) = {} & A\sin\left(\frac{\pi(x-B)}{12}\right)\sin\left(\frac{F\pi(x-B)}{8760}\right) \\
& \cdot\left[\frac{168-C}{168} + \sum_{i=1}^{3}\frac{\left(\cos\left(\frac{i\pi C}{84}\right)-1\right)\sin\left(\frac{i\pi(x-B)}{84}\right)}{i\pi}\right].
\end{aligned} \tag{3.2}
$$

The parameters used in Equation 3.1 are presented in Table 3.2 and in Table 3.3.

Table 3.2 Parameters used in Equation 3.1.

Input Data	Description
abs	The absolute value
floor	The largest integer less than or equal to the number considered
Q	Heat load
signum	Plus or minus 1 according to the sign of the expression evaluated (if expression >0 then +1; if expression <0 then -1)
x	Time variable

Table 3.3 Values for the parameters used in Equation 3.1 provided by Pinel[19].

Parameter	Description
A	2000 amplitude
B	1000 asymmetric profile; 2190 symmetric profile;
C	80
D	0.01
E	0.95
F	4/3 asymmetric profile; 2 symmetric profile
G	2190 asymmetric profile; 0 symmetric profile

The synthetic load profile was implemented in the software, MATLAB. The model from Pinel[19] accounts only for one borehole of approximately 100 meters. In this project A was changed to account for multiple boreholes. This change was performed to simulate a realistic GSHP size to be used in the EED. For the symmetric curve the variables are shown in Table 3.4.

Table 3.4 Variables for the symmetric curve.

Parameter	Description
A	128000
B	2190
C	80
D	0.01
E	0.95
F	2
G	0
x	0-8760 hours

Figure 3.7 below shows the symmetric load profile obtained from these equations.

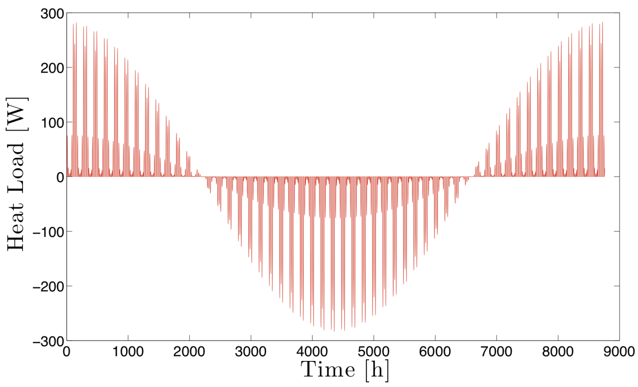

Figure 3.7 Balanced load profile.

For the asymmetric curve the variables are shown in Table 3.5.

Table 3.5 Variables for the asymmetric curve.

Parameter	Description
A	128000
B	1000
C	80
D	0.01
E	0.95
F	4/3
G	2190
x	0-8760 hours

Figure 3.8 below shows the asymmetric load profile obtained.

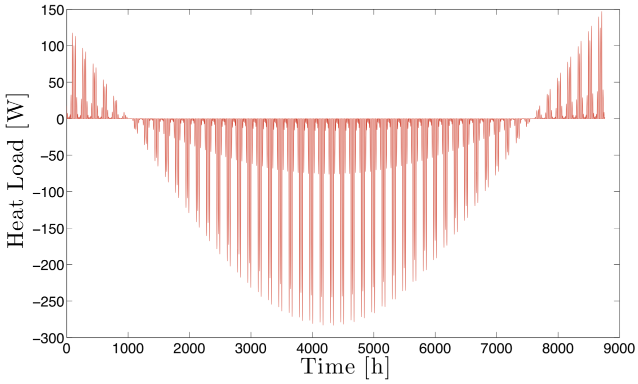

Figure 3.8 Cooling-dominated load profile.

As mentioned previously different configurations of boreholes are presented in the EED from which the most suitable can be chosen. For each scenario the same configuration of boreholes were chosen for the balanced case and the same configuration were chosen for the cooling-dominated case. In this way the evaluation can be performed on how the GSHP system's size changes using the ground properties obtained from the different methods.

3.3 New Method Development

The theory from Section 2.6 has been used to develop a new method to evaluate the ground thermal conductivity and the borehole thermal resistance from TRTs. The method has been implemented into the software, MATLAB.

In the theory different equations could be used for calculations of the equivalent borehole diameter and borehole thermal resistance depending on the type of borehole one wishes to evaluate. To determine what set of equations that would give the best results in the optimisation the measured data from the Beier test 1 and Beier test 2 have been used since all the properties were known. The estimated ground thermal conductivity and borehole thermal resistance have then been compared to the measured values to find which equations would be best to use. The results from the comparison to find the best set of equations can be seen in Section 4.1.

The final program uses an optimisation technique to determine the minimised square errors between the calculated temperature of the fluid and the measured temperature of the fluid. To find the actual thermal conductivity and the borehole thermal resistance, starting values of the ground thermal conductivity and the grout thermal conductivity are guessed. By guessing these values the fluid temperature can be calculated. The calculated fluid temperature is then used to calculate the difference between this temperature and the measured temperature. If the difference is high the program updates the guessed values until the minimum error is reached.

In the program it will be possible to choose any time period of the total test duration to be used for the estimation of the ground thermal conductivity and borehole thermal resistance.

After the equations were chosen and the new solution implemented in MATLAB the model was used to estimate the ground thermal conductivity and the borehole thermal resistance using the same scenarios as the ones used with the existing methods described in Section 3.1. The values were then evaluated using the EED[7] software as described in Section 3.2.

4 Results

The results from the evaluation of the existing methods used for estimating ground thermal properties, as well as the results from the new method are presented in this chapter. The first section presents the results obtained from the new method for the search of the equations that would be the best to use. How the new method was modeled is also presented in the first section. The following sections presents the results from the different cases used to obtain values of the ground thermal conductivity and borehole thermal resistance from all the methods. The final section in this chapter presents the results from the modeling of the GSHP system in the EED[7].

4.1 Model development and choice of equations for the new evaluation method

Described in Section 3.3 was how the method development of the new method was performed and evaluated. The new method was based on the theory presented in Section 2.6 from which the estimation of the ground thermal properties were to be performed by a model programmed in the software MATLAB.

In Section 2.6 different equations were presented for the calculation of the equivalent pipe radius and the borehole thermal resistance. To choose which equations would be best to use, the results of the ground thermal properties obtained from the different equations were compared to a reference case. The reference case used for this evaluation was the Beier test 1 and test 2 since all the values and properties were known.

The measured data used in the evaluation was divided into different cases. For the Beier test 1, one test-run was performed, where all the data were included in the calculations. For the Beier test 2, two different test-runs were performed. The first evaluation was made including all the measured values and the second evaluation was made by excluding the first 20 hours. Between the first 20 hours the power was turned off. As mentioned in the theory this would give uncertainties on the results for some models since they can not handle power fluctuations. This is done to evaluate how well the model handles these type of power fluctuations and to see which equation would provide most accurate results in these cases.

To use Equation 2.27 to calculate the borehole thermal resistance, the values used for the temperature of the fluid and the temperature at the borehole radius, r_b, need to have a linear relationship. But if the two temperatures are plotted against time one can see that this is not the case for all the values. Thus not all values can be used in the calculation of the borehole thermal resistance and some of the values need to be excluded. For the Beier test 1 the first 20 hours were excluded and for the Beier test 2 the first 33 hours were excluded to ensure that the measured data used would be approximately linear.

The results from the Beier test 1 performed for all data can be seen in Table 4.2 and Table 4.1. The results from the Beier test 2 performed for all data can be seen in Table 4.4 and Table 4.3 and the results from excluding the first 20 hours to calculate the ground properties can be seen in Table 4.6 and Table 4.5. The known data of importance from the Beier tests that the calculated values are compared to, are:

1. The soil thermal conductivity that was equal to 2.7 W/(mK)

2. The grout thermal conductivity that was equal to 0.73 W/(mK)

3. The borehole thermal resistance that was equal to 0.18 (mK)/W

Table 4.1 Results of the ground thermal conductivity and grout thermal conductivity obtained from the new method using the Beier test 1. All experimentally measured data are included.

Equation used to calculate the equivalent pipe radius	Ground thermal conductivity [W/(mK)]	Grout thermal conductivity [W/(mK)]
$r_p = \sqrt{r_o s}$ (2.33)	2.712	1.114
$r_p = r_o\sqrt{2}$ (2.34)	2.549	2.605
$r_p = 2r_0$ (2.35)	2.493	1.774

Table 4.2 Results of the borehole thermal resistance obtained from the new method using the Beier test 1. All experimentally measured data are included. The first 20 hours of the calculated temperatures have not been included in the calculation of the borehole thermal resistance using Equation 2.27.

Equation used to calculate the equivalent pipe radius	Borehole thermal resistance using Equation 2.27 [(mK)/W]	Borehole thermal resistance using Equation 2.25 [(mK)/W]
$r_p = \sqrt{r_o s}$ (2.33)	0.147	0.128
$r_p = r_o\sqrt{2}$ (2.34)	0.140	0.101
$r_p = 2r_0$ (2.35)	0.138	0.098

The ground thermal conductivity obtained from the Beier test 1, are in the range of 2.49 - 2.71 W/(mK). Equation 2.33 provided the closest values to the measured values known in the Beier tests. The borehole thermal resistance obtained from Equation 2.27 are in the range of 0.134 - 0.147 (mK)/W and the values obtained using Equation 2.25 to calculate the borehole thermal resistance are in the range of 0.098 - 0.128 (mK)/W. Equation 2.33 used to calculate the equivalent pipe radius in combination with Equation 2.27 used to calculate the borehole thermal resistance provided the best results, closest to the measured values known in the Beier tests.

Table 4.3 Results of the ground thermal conductivity and grout thermal conductivity obtained from the new method using the Beier test 2. All experimentally measured data are included.

Equation used to calculate the equivalent pipe radius	Ground thermal conductivity [W/(mK)]	Grout thermal conductivity [W/(mK)]
$r_p = \sqrt{r_o s}$ (2.33)	2.318	1.179
$r_p = r_o\sqrt{2}$ (2.34)	2.111	3.129
$r_p = 2r_0$ (2.35)	2.058	2.193

Table 4.4 Results of the borehole thermal resistance obtained from the new method using the Beier test 2. All experimentally measured values are included. The first 33 hours of the calculated temperatures have not been included in the calculation of the borehole thermal resistance using Equation 2.27.

Equation used to calculate the equivalent pipe radius	**Borehole thermal resistance using Equation 2.27 [(mK)/W]**	**Borehole thermal resistance using Equation 2.25 [(mK)/W]**
$r_p = \sqrt{r_o s}$ (2.33)	0.141	0.122
$r_p = r_o\sqrt{2}$ (2.34)	0.131	0.091
$r_p = 2r_0$ (2.35)	0.128	0.087

The ground thermal conductivity obtained from the Beier test 2, including all experimentally measured data, are in the range of 2.06 - 2.32 W/(mK). Equation 2.33 provided the closest values to the measured values known in the Beier tests. The borehole thermal resistance obtained from Equation 2.27 are in the range of 0.13 - 0.14 (mK)/W and the values obtained using Equation 2.25 to calculate the borehole thermal resistance are in the range of 0.087 - 0.122 (mK)/W. Equation 2.33 used to calculate the equivalent pipe radius in combination with Equation 2.27 used to calculate the borehole thermal resistance provided the best results, closest to the measured values from the Beier tests.

Table 4.5 Results of the ground thermal conductivity and grout thermal conductivity obtained from the new method using the Beier test 2. Excluding the first 20 hours of the experimentally measured data.

Equation used to calculate the equivalent pipe radius	**Ground thermal conductivity [W/(mK)]**	**Grout thermal conductivity [W/(mK)]**
$r_p = \sqrt{r_o s}$ (2.33)	2.797	1.017
$r_p = r_o\sqrt{2}$ (2.34)	2.775	2.065
$r_p = 2r_0$ (2.35)	2.732	1.374

Table 4.6 Results of the borehole thermal resistance obtained from the new method using the Beier test 2. Excluding the first 20 hours of the experimentally measured data. The first 33 hours of the calculated temperatures have not been included in the calculation of the borehole thermal resistance using Equation 2.27.

Equation used to calculate the equivalent pipe radius	**Borehole thermal resistance using Equation 2.27 [(mK)/W]**	**Borehole thermal resistance using Equation 2.25 [(mK)/W]**
$r_p = \sqrt{r_o s}$ (2.33)	0.158	0.138
$r_p = r_o\sqrt{2}$ (2.34)	0.157	0.117
$r_p = 2r_0$ (2.35)	0.155	0.114

The ground thermal conductivity obtained from the Beier test 2, excluding the first 20 hours of experimentally measured data, are in the range of 2.732 - 2.797 W/(mK). Equation

2.33 provided the closest values to the known measured values from the Beier tests. The borehole thermal resistance obtained from Equation 2.27 are in the range of 0.155 - 0.158 (mK)/W and the values obtained using Equation 2.25 to calculate the borehole thermal resistance are in the range of 0.114 - 0.138 (mK)/W. Equation 2.33 used to calculate the equivalent pipe radius in combination with Equation 2.27 used to calculate the borehole thermal resistance provided the best results, closest to the measured values from the Beier tests.

Equation 2.33, from Section 2.6, used to calculate the equivalent pipe radius, provides the most accurate results of the ground properties when compared to the measured values from the reference cases. Thus this equation is used for the calculation of a grouted borehole to find the equivalent borehole radius. Equation 2.35 used to calculate the equivalent borehole radius for a groundwater-filled borehole was included in the comparison to evaluate if the results would be acceptable to use for the calculation of the equivalent pipe radius for a grouted borehole. Equation 2.35 provided the most inaccurate results in comparison to the other equations available and was not used for grouted boreholes. Equation 2.27 used for the calculation of the borehole thermal resistance gave the most accurate results and was thus used.

When the model was first programmed in MATLAB the power injected into the borehole, used in Equation 2.21, was neither assumed to be constant nor to be equal to one value. Instead all values of the power measured in the TRT were used for the calculations. Even though the model worked the simulations became very time consuming. To minimise the time needed to perform the simulations the power values had to be reduced. To do this the power values not differing more than ± 1.5 % in standard deviation and ± 10% in maximum variation were assumed to belong to the same heat injection rate in accordance with ASHRAE[1] recommendations. These values were used to calculate a mean value of the power input. This reduced the time for the simulation considerably for the model obtained.

The Beier test 1 and test 2 was also supposed to have been evaluated using the existing methods so that a comparison could have been made on how well the existing methods estimated the ground thermal properties, but the two cases were not able to be performed by many of the existing methods. This was due to the fact that the Beier test 1 had the experimentally measured values recorded with varying time intervals. For the Beier test 2 the injection rate and the time intervals were not kept constant. Mentioned in Chapter 2 most existing methods could not perform evaluations with these type of variations.

The equations have now been determined and the development of the code has been made. To make the model an easy to use method it has been programmed in MATLAB GUI, which is a graphical designed program. This program can further be made into an *.exe*-file, in this way the user does not need to have the software nor needs to have knowledge in programming. A flowchart for the MATLAB code's procedure can be seen in Figure 4.1. A software tutorial can be found in Appendix A.

The new TRT evaluation program, TEP, was further used to determine what ground thermal conductivity and borehole thermal resistance the different scenarios, explained in Section 3.1, provided. The results are presented in the following sections.

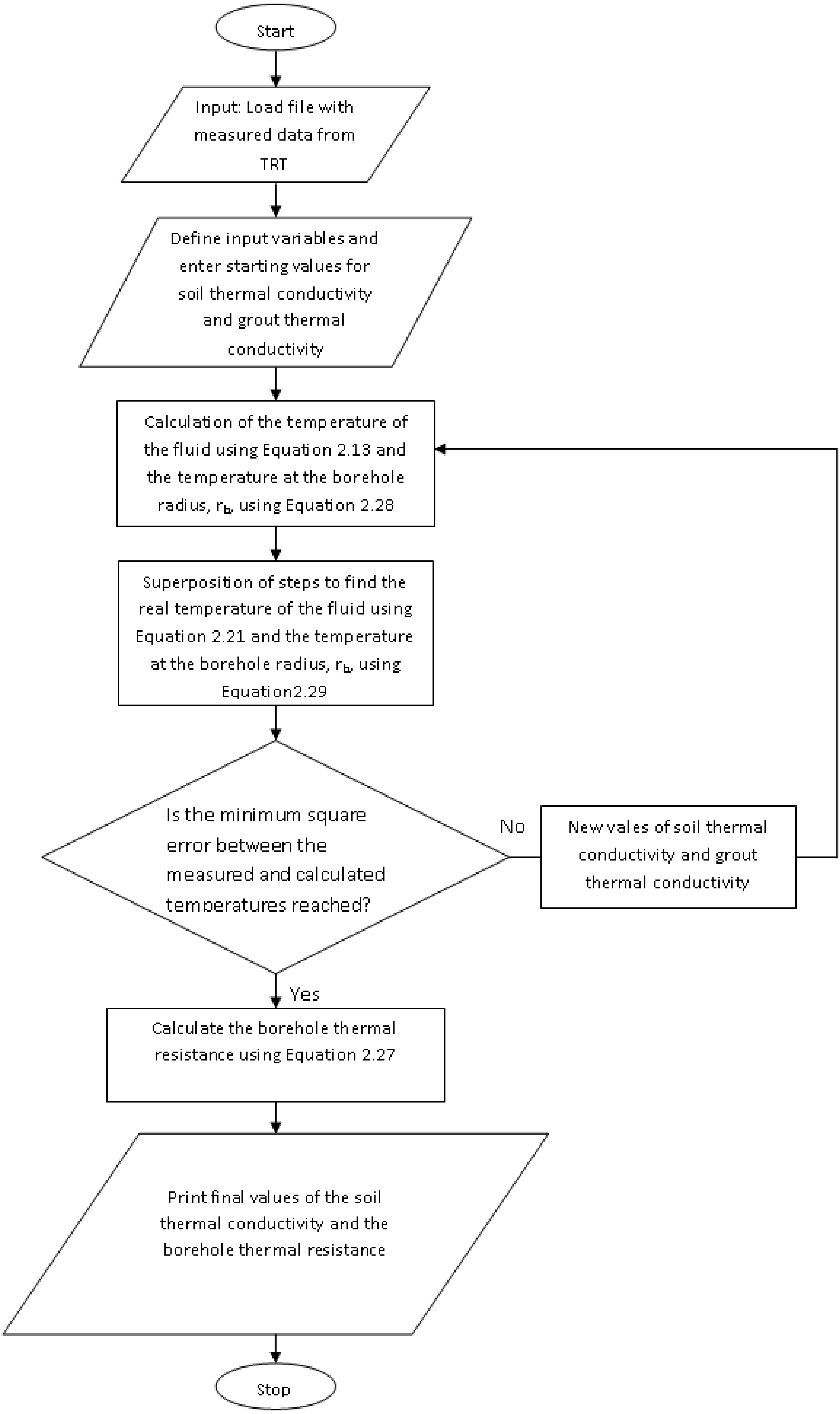

Figure 4.1 Flowchart of the new TRT evaluation program's procedure in MATLAB.

4.2 Estimated ground thermal properties from the methods using single heat injection rate

The methods described in Chapter 2 were used to estimate the ground thermal properties from the TRT conducted with constant injection rates. For these tests the first 15 hours of the experimentally measured data were not included for the LSM model as mentioned in Section 3.1.

The results from the estimation of the ground thermal properties using a single heat injection rate of 67 W/m are presented in Table 4.7.

Table 4.7 Values of the ground thermal conductivity and borehole thermal resistance for the single injection rate of 67 W/m.

Mehtod	**Ground thermal conductivity [W/(mK)]**	**Borehole thermal resistance [(mK)/W]**
LSM	3.13	0.055
GPM	2.99	0.063
FD Numerical Method	2.91	0.065
TEP	3.02	0.053

In this comparison the values obtained for the ground thermal conductivity are in the range of 2.91 - 3.13 W/(mK). The value from the new TRT evaluation program, TEP, is 3.02 W/(mK). The borehole thermal resistance is in the range of 0.055 - 0.065 (mK)/W for the existing methods. The borehole thermal resistance obtained from the TEP is 0.053 (mK)/W.

The results from the estimation of the ground thermal properties using a single heat injection rate of 140 W/m are presented in Table 4.8.

Table 4.8 Values of the ground thermal conductivity and borehole thermal resistance for the single injection rate of 140 W/m.

Mehtod	**Ground thermal conductivity [W/(mK)]**	**Borehole thermal resistance [(mK)/W]**
LSM	3.41	0.060
GPM	3.24	0.058
FD Numerical Method	3.29	0.059
TEP	3.36	0.054

In this comparison the values obtained for the ground thermal conductivity are in the range of 3.24 - 3.41 W/(mK) where the value from the TEP is 3.36 W/(mK). The borehole thermal resistance is in the range of 0.058 - 0.060 (mK)/W and the value obtained from the TEP is 0.054 (mK)/W.

For these tests conducted with a single injection rate, the ground thermal properties obtained from the new method are similar to the ones obtained from the existing methods. The curve fit optimisation from the experimentally measured temperature of the fluid in comparison to the calculated temperature of the fluid obtained from all the methods is presented in Figure 4.2 and Figure 4.3.

The ground thermal conductivity and borehole thermal resistance estimated from the new method were similar to the values estimated from the existing methods. The ground thermal conductivities estimated for the single injection rate of 67 W/m are lower than the ones estimated for the single injection rate of 140 W/m. The borehole thermal resistance values obtained with the FD numerical method and with the GPM software are lower for the higher injection rate in comparison to the lower injection rate. The borehole thermal resistance value obtained from the LSM model was higher for the injection rate of 140 W/m. The values from the TEP were similar.

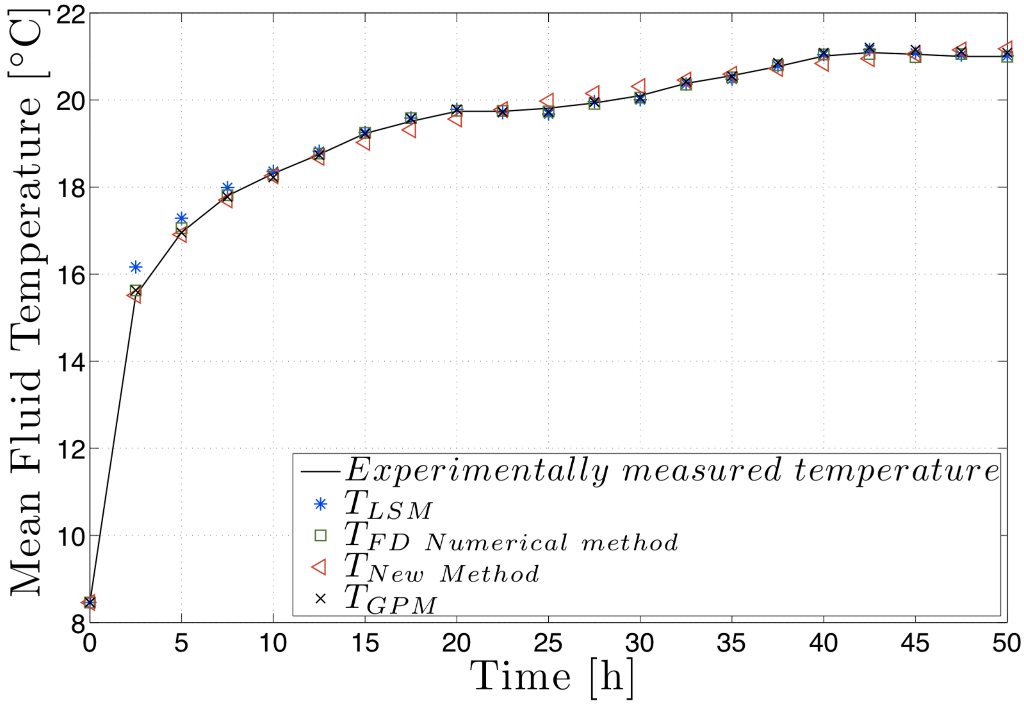

Figure 4.2 Single injection rate of 67 W/m.

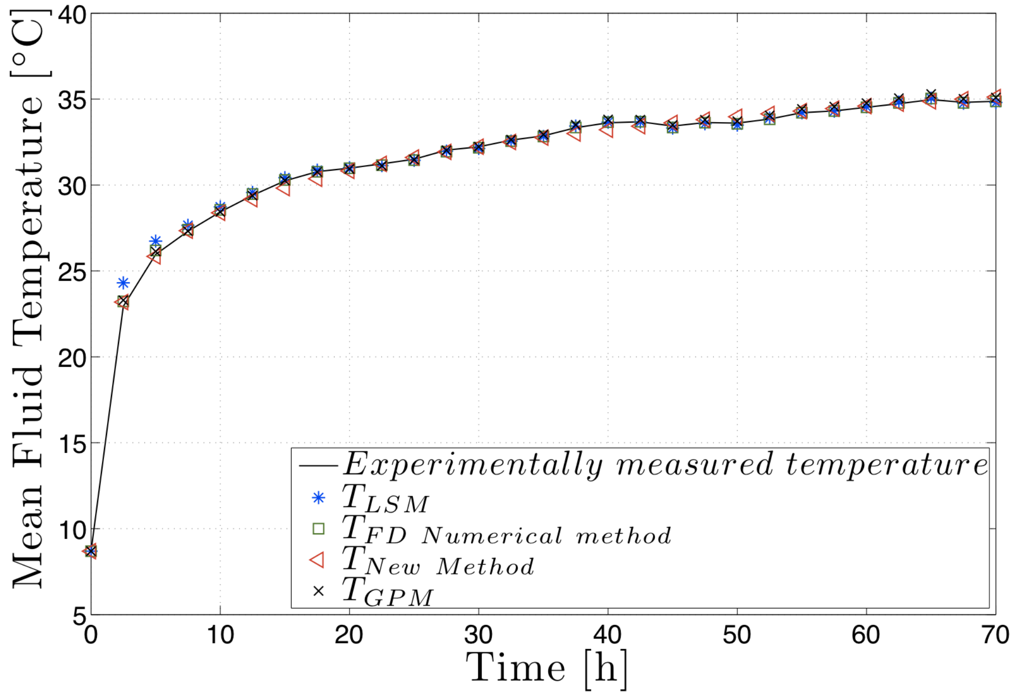

Figure 4.3 Single injection rate of 140 W/m.

4.3 Estimated ground thermal properties from the methods using increasing heat injection rate

This section describes the comparison of the methods for evaluation of the ground thermal properties using the increasing injection rate scenario described in Section 3.1. For this test first the values for the first injection rate were used which had an injection rate of 67 W/m and then the values from the second injection rate were used which had an injection rate of 140 W/m. The results can be seen in Tables 4.9 and 4.10. There is a limitation for the GPM model. For the GPM model it is not possible to choose specific injection rates to optimise. The second injection rate has to be neglected, since an optimisation performed for both injection rates would give inaccurate result. This is due to that these tests were performed on a groundwater-filled borehole and as mentioned previously in Section 3.1 the ground thermal conductivity and borehole thermal resistance will change depending on the heat injection rate.

Table 4.9 Values of the ground thermal conductivity and borehole thermal resistance for the increasing heat injection rate: Optimisation for the first injection rate of 67 W/m.

Method	Ground thermal conductivity [W/(mK)]	Borehole thermal resistance [(mK)/W]
LSM	3.03	0.060
GPM	3.01	0.062
FD Numerical Method	2.91	0.066
TEP	3.10	0.060

Table 4.10 Values of the ground thermal conductivity and borehole thermal resistance for the increasing heat injection rate: Optimisation for the second injection rate of 140 W/m.

Method	Ground thermal conductivity [W/(mK)]	Borehole thermal resistance[(mK)/W]
LSM	3.68	0.060
GPM	-	-
FD Numerical Method	3.36	0.068
TEP	3.48	0.055

In this comparison the values obtained for the ground thermal conductivity for the first injection rate were in the range of 2.91 - 3.03 W/(mK). The value from the TEP is 3.10 W/(mK). The borehole thermal resistance is in the range of 0.060 - 0.066 (mK)/W for the existing methods. The borehole thermal resistance obtained from the TEP is 0.060 (mK)/W.

The values obtained for the ground thermal conductivity for the second injection rate were in the range of 3.36 - 3.68 W/(mK) and the value from the TEP is 3.48 W/(mK). The borehole thermal resistance obtained from the existing methods is 0.060 - 0.068 (mK)/W. The borehole thermal resistance obtained from the TEP is 0.055(mK)/W.

The values from the new method are in good agreement to the values from the existing methods.

The curve fit optimisation from the experimentally measured temperature of the fluid in comparison to the calculated temperature of the fluid obtained from all methods is presented in Figure 4.4.

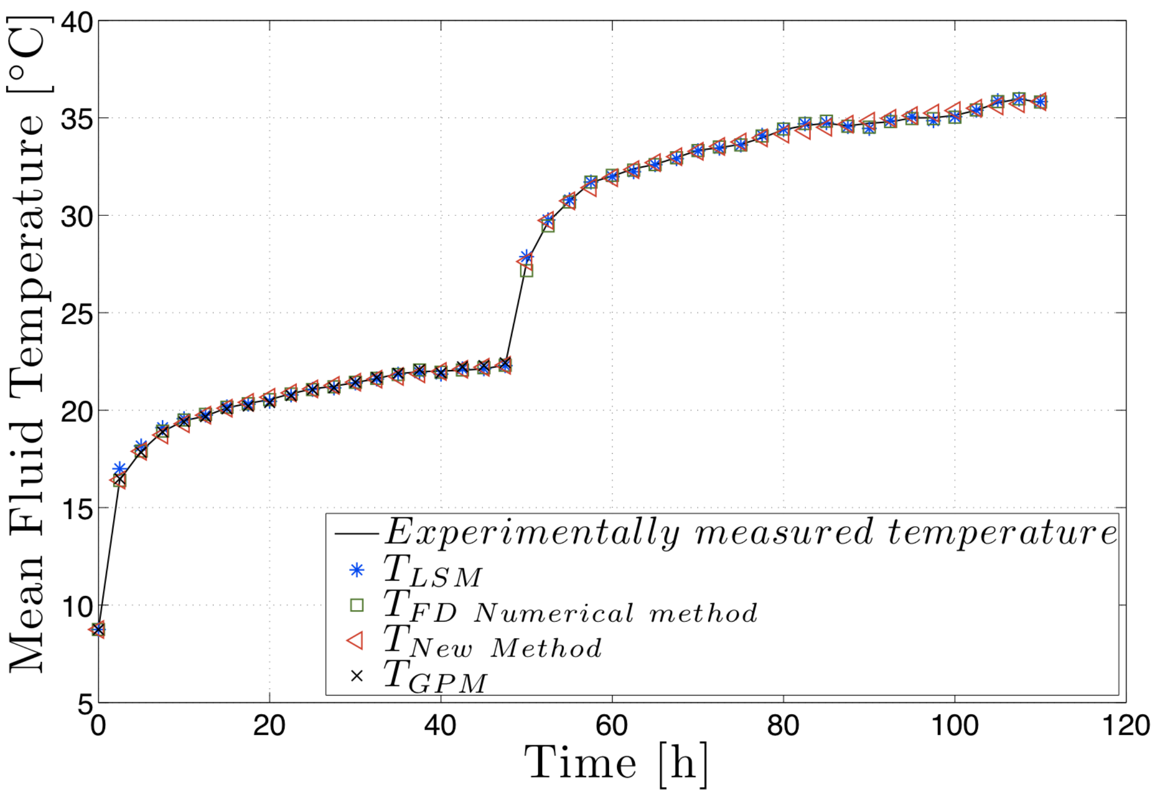

Figure 4.4 Increasing injection rate.

The values of the ground thermal conductivity and the borehole thermal resistance obtained from the single injection rate of 67 W/m, described in Section 4.2, have been compared to the values obtained from the MIR test for the optimisation of the first injection rate of 67 W/m. Respectively the single injection rate of 140 W/m described in Section 4.2 have been compared with the values from the MIR test for the optimisation of the second injection rate of 140 W/m.

The results from the MIR test with injection rate of 67 W/m show that the ground thermal conductivity decreased while the borehole thermal resistance increased using the LSM method. The FD numerical method had approximately constant values. The ground thermal conductivity estimated from the TEP and the GPM model increased for the MIR test, while the borehole thermal resistance decreased using the GPM model and increased using the TEP.

For the MIR test with injection rate of 140 W/m all the values of the ground thermal conductivity estimated have increased in comparison to the single injection rate. The borehole thermal resistance obtained from the FD numerical method and the TEP have increased for the MIR test. The increase for the value obtained from the TEP is small. The value estimated using LSM was unchanged.

4.4 Estimated ground thermal properties from the methods using decreasing heat injection rate

This section describes the comparison of the methods for evaluation of the ground thermal properties using the decreasing injection rate scenario described in Section 3.1. For this test first the values for the first injection rate were used that was 140 W/m and then the values from the second injection rate were used which was 67 W/m. Similar to the evaluation performed for the increasing injection rate, the second injection rate measured in this test has to be neglected when performing the GPM optimisation. The results of the optimisation of the first injection rate can be seen in Table 4.11 and results from the optimisation of the second injection rate can be seen in Table 4.12.

Table 4.11 Values of the ground thermal conductivity and borehole thermal resistance for the decreasing injection rate: Optimisation for the first injection rates of 140 W/m.

Method	**Ground thermal conductivity [W/(mK)]**	**Borehole thermal resistance [(mK)/W]**
LSM	3.46	0.052
GPM	3.22	0.055
FD Numerical Method	3.40	0.058
TEP	3.16	0.044

Table 4.12 Values of the ground thermal conductivity and borehole thermal resistance for the decreasing injection rate: Optimisation for second injection rates of 67 W/m.

Method	**Ground thermal conductivity [W/(mK)]**	**Borehole thermal resistance [(mK)/W]**
LSM	2.81	0.035
GPM	-	-
FD Numerical Method	3.43	0.075
TEP	3.15	0.053

In this comparison the values obtained for the ground thermal conductivity for the first injection rate were in the range of 3.22 - 3.46 W/(mK). The value from theTEP is 3.16 W/(mK). The borehole thermal resistance is in the range of 0.052-0.058 (mK)/W for the existing methods. The borehole thermal resistance obtained from the TEP is 0.044 (mK)/W.

The values obtained for the ground thermal conductivity for the second injection rate were in the range of 2.81 - 3.43 W/(mK). The value from theTEP is in the range with a value of 3.15 W/(mK). The borehole thermal resistance obtained from the existing methods are in the range of 0.035 - 0.075 (mK)/W. The borehole thermal resistance obtained from the TEP is 0.053 (mK)/W.

The values estimated for the first injection rate from the new method are lower than the values estimated by the existing methods. The values estimated for the second injection rate of the new method are in the range of the values estimated by the existing values.

The curve fit optimisation from the experimentally measured temperature of the fluid in comparison to the calculated temperature of the fluid obtained from all methods is presented in Figure 4.5.

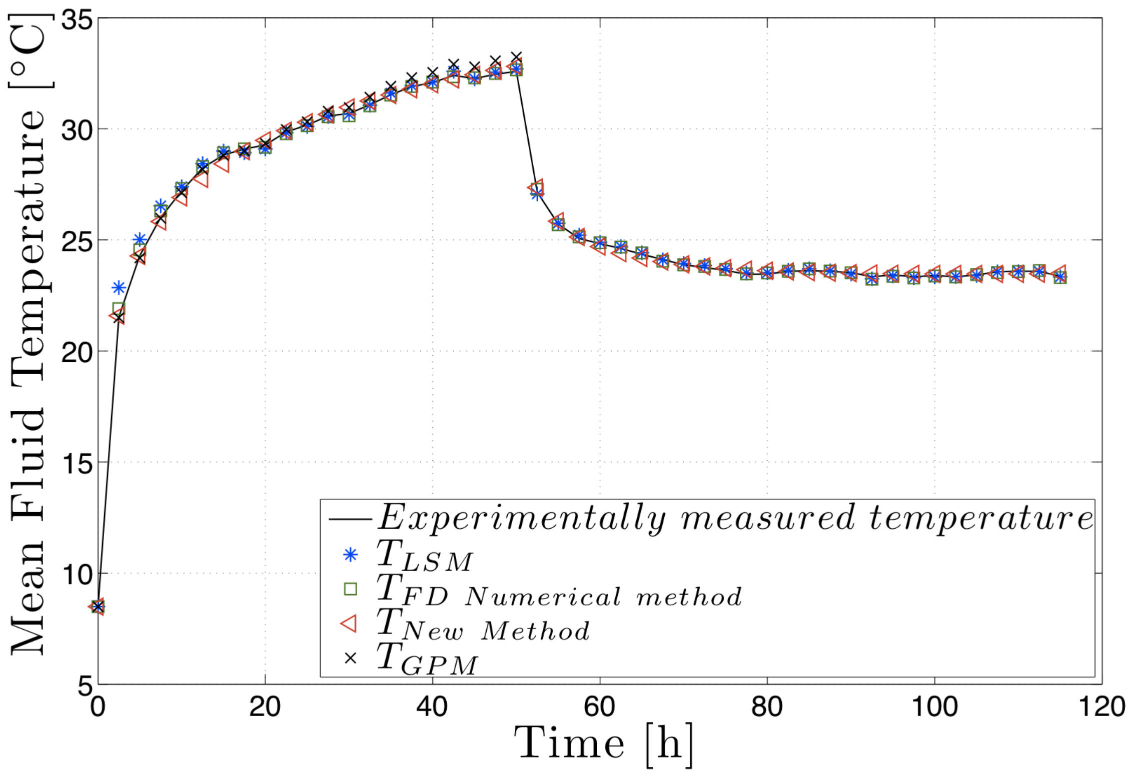

Figure 4.5 Decreasing injection rate.

The values of the ground thermal conductivity and the borehole thermal resistance obtained from the test described in Section 4.2, using a single injection rate of 140 W/m have been compared to the values obtained from the MIR test where the optimisation was performed for the first injection rate of 140 W/m. Respectively the single injection rate of 67 W/m described in Section 4.2 have been compared with the values from the MIR test for the optimisation of the second injection rate of 67 W/m.

The results from the MIR test for the injection rate of 140 W/m show that the ground thermal conductivity estimated from the LSM and the FD numerical method increased compared to the values from the single injection rate. The GPM and the TEP gave reduced values for the MIR. The borehole thermal resistance decreased for all methods in the MIR test in comparison to the single injection rate tests.

For the injection rate of 67 W/m the values of the ground thermal conductivity estimated from the TEP and the FD numerical method have increased for the MIR tests. The LSM gave a lower value of ground thermal conductivity for the MIR test. The borehole thermal resistance obtained from the FD numerical method had increased for the MIR test while the value obtained from the LSM had decreased. The value estimated using the TEP was unchanged.

4.5 Results from the modeling of the ground source heat pump system in the EED

This section presents the results from the modeling of the GSHP system in the EED[7] software. The borehole configuration chosen for each method is presented below. The number of boreholes as well as the total length needed for the boreholes are also presented. The comparison has been performed for the synthetic heat loads presented in Section 3.2. There were two load demands simulated, one where the heat load was balanced over one year, referred to as the balanced heat load, and one where the cooling load was dominating over one year, referred to as the cooling-dominated heat load. The first section presents the results for when the ground thermal properties were estimated using a single injection rate. The following section presents the results from when the property estimation was performed using MIR tests with increasing injection rates and the last section presents the results of the GSHP system modeled using the ground thermal properties estimated using MIR tests with decreasing injection rates. The temperature restrictions of -1°C and 35 °C on the fluid entering the heat pump, which are the minimum and maximum allowable temperature after 25 years to the heat pump, have not been exceeded for any of the cases.

4.5.1 GSHP system modeled from ground thermal properties evaluated using single injection rate TRTs

This section presents the results from the GSHP system modeled in the system design software EED[7]. The ground thermal properties used in the software are estimated using two different single injection rate TRTs. The results from the first single injection rate of 67 W/m are presented in Table 4.13 and Table 4.14. The results from the second single injection rate of 140 W/m are presented in Table 4.15 and Table 4.16.

Table 4.13 Results of the EED simulation based on TRT using single injection rate of 67 W/m, for the balanced heat load.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x3 rectangular	9	2111
GPM	3x3 rectangular	9	2265
FD Numerical Method	3x3 rectangular	9	2315
TEP	3x3 rectangular	9	2112

Table 4.14 Results of the EED simulation based on TRT using single injection rate of 67 W/m, for the cooling-dominated heat load.

Method	**Borehole configuration**	**Number of Boreholes**	**Total length of the boreholes [m]**
LSM	6x2 U-conf.	8	2350
GPM	6x2 U-conf.	8	2511
FD Numerical Method	6x2 U-conf.	8	2571
TEP	6x2 U-conf.	8	2355

The total length of the boreholes estimated from the existing methods by the software were varying between 2111 - 2315 meters, for the injection rate of 67 W/m and the balanced heat load. This variation between the borehole lengths are in the range of 8 - 10 %. The values obtained for the cooling-dominated heat load were varying between 2349 - 2571 meters which is a difference between the borehole lengths of approximately 9 %. The total borehole length estimated from the ground properties obtained from the TEP is 2111 meters for the balanced heat load and 2355 meters for the cooling-dominated heat load.

Table 4.15 Results of the EED simulation based on TRT using single injection rate of 140 W/m, for the balanced heat load.

Method	**Borehole configuration**	**Number of Boreholes**	**Total length of the boreholes [m]**
LSM	3x3 rectangle	9	2134
GPM	3x3 rectangle	9	2162
FD Numerical Method	3x3 rectangle	9	2159
TEP	3x3 rectangle	9	2069

Table 4.16 Results of the EED simulation based on TRT using single injection rate of 140 W/m, for the cooling-dominated heat load.

Method	**Borehole configuration**	**Number of Boreholes**	**Total length of the boreholes [m]**
LSM	6x2 U-conf.	8	2325
GPM	6x2 U-conf.	8	2359
FD Numerical Method	6x2 U-conf.	8	2354
TEP	6x2 U-conf.	8	2264

In the comparison of the single injection rate of 140 W/m, the values obtained of the total length of the borehole are in the range of 2134-2162 meters for the balanced heat load. The variation between the borehole lengths are approximately 1 %. For the cooling-dominated heat load the values obtained for the total borehole length are in the range of 2325 - 2359 meters which is a difference between the borehole lengths of approximately 1-2 %. The total borehole length obtained from the TEP is 2069 meters for the balanced heat load and 2264 meters for the cooling-dominated heat load.

The values estimated by the new method are similar to the values estimated by the existing methods for both single injection rate TRTs. The values from the balanced heat load with an injection rate of 67 W/m are higher than the lengths obtained for the injection rate of 140 W/m. This is also the case for the simulations performed for the cooling-dominated heat load. The difference between the lengths of the balanced heat load and single injection rate of 67 W/m in comparison to the balanced heat load and single injection rate of 140 W/m are approximately 2 % for the new method and 1-7 % for the existing methods. The difference between the lengths of the cooling-dominated heat load and the injection rate of 67 W/m in comparison to the cooling-dominated heat load and the injection rate of 140 W/m are approximately 4 % for the new method and 1- 9 % for the existing methods. The difference in the total borehole length for the balanced heat load are not differing more than 10 % from each other. This is also the case for the cooling-dominated heat load. Javed *et al.*[17] have showed in a study that uncertainties of about 10 % can be expected for the required borehole length due to the variations in the ground thermal properties estimated from the various methods.

4.5.2 GSHP system modeled from ground thermal properties evaluated from multiple injection rate TRTs in increasing order

This section presents the results from the GSHP system modeled in the system design software EED[7]. The ground thermal properties used in the software are estimated using TRTs with increasing injection rates. The TRT was performed with two different injection rates. The optimisations was first performed for the first injection rate of 67 W/m and was then performed for the second injection rate of 140 W/m. The results from the first injection rate are presented in Table 4.17 and Table 4.18. The results from the second injection rate are presented in Table 4.19 and Table 4.20.

Table 4.17 Results of the EED simulation based on TRTs using increasing injection rate, for the balanced heat load and the optimisation of the first injection rate of 67 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x3 U-conf.	7	2112
GPM	3x3 U-conf.	7	2147
FD Numerical Method	3x3 U-conf.	7	2242
TEP	3x3 U-conf.	7	2090

Table 4.18 Results of the EED simulation based on TRTs using increasing injection rate, for the cooling-dominated heat load and the optimisation of the first injection rate of 67 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x4 open rectangle	10	2586
GPM	3x4 open rectangle	10	2621
FD Numerical Method	3x4 open rectangle	10	2719
TEP	3x4 open rectangle	10	2558

For the increasing injection rate TRT when optimising the first injection rate of 67 W/m with the existing methods, the values obtained for the total length of the borehole are in the range of 2112 - 2242 meters for the balanced heat load and for the cooling-dominated heat load the values obtained for the total length of the borehole are in the range of 2586 - 2719 meters. The variation between the borehole lengths for the balanced heat load are approximately 6 % and for the cooling-dominated heat load the difference is 5 %. The total borehole length given from the ground properties obtained from the TEP was 2090 meters for the balanced heat load and 2558 meters for the cooling-dominated heat load.

Table 4.19 Results of the EED simulation based on TRTs using increasing injection rate, for the balanced heat load and the optimisation of the second injection rate of 140 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x3 U-conf.	7	1970
GPM	-	-	-
FD Numerical Method	3x3 U-conf.	7	2145
TEP	3x3 U-conf.	7	1931

Table 4.20 Results of the EED simulation based on TRTs using increasing injection rate, for the cooling-dominated heat load and the optimisation of the second injection rate of 140 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x4 open rectangle	10	2327
GPM	-	-	-
FD Numerical Method	3x4 open rectangle	10	2560
TEP	3x4 open rectangle	10	2331

In the comparison of the simulation based on the increasing injection rate when optimising the second injection rate of 140 W/m with the existing methods, the values obtained for the total length of the borehole are in the range of 1970 - 2145 meters for the balanced heat load and for the cooling-dominated heat load the values obtained for the total borehole length are in the range of 2327 - 2560 meters. The variation between the borehole lengths for the balanced heat load are approximately 8 - 9 % and for the cooling-dominated heat load the difference is 9-10 %. The total borehole length given from the ground properties obtained from the TEP was 1931 meters for the balanced heat load and 2331 meters for the cooling-dominated heat load.

The values estimated by the new method, in comparison to the existing methods, vary more for the increasing injection rates compared to the values obtained from the single injection rates. The lengths estimated from the new method are though comparable to the lengths obtained from the existing methods. The lengths from the balanced heat load with an injection rate of 67 W/m are higher than the lengths obtained for the injection rate of 140 W/m. This is also the case for the simulations performed for the cooling-dominated heat load. The difference between the lengths of the balanced heat load and the injection rate of 67 W/m in comparison to the balanced heat load and the injection rate of 140 W/m are approximately 8 % for the new method and 4-7 % for the existing methods. The difference between the lengths of the cooling-dominated heat load and the injection rate of 67 W/m in comparison to the cooling-dominated heat load and the injection rate of 140 W/m are approximately 10 % for the new method and 6 - 11 % for the existing methods. The difference in the total borehole length for the balanced heat load are not differing more than 10 % from each other. The difference in the total borehole length for the cooling-dominated heat load are around 10 %. The differences are in the expected range of about 10 % for the required borehole length due to the variations in the ground thermal properties estimated from the various methods[17].

4.5.3 GSHP system, modeled from ground thermal properties evaluated from multiple injection rate TRTs in decreasing order

This section presents the results from the GSHP system modeled in the system design software EED[7]. The ground thermal properties used in the software are estimated using TRTs with decreasing injection rates. Two decreasing injection rates were used. First the first injection rate of 140 W/m was evaluated and then the second injection rate of 67 W/m was evaluated. The results from the first injection rate are presented in Table 4.21 and Table 4.22. The results from the second injection rate are presented in Table 4.23 and Table 4.24.

Table 4.21 Results of the EED simulation based on TRTs using decreasing injection rate, for the balanced heat load and the optimisation of the first injection rate of 140 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	3x3 open rectangle	8	1953
GPM	3x3 open rectangle	8	2055
FD Numerical Method	3x3 open rectangle	8	2041
TEP	3x3 open rectangle	8	1929

Table 4.22 Results of the EED simulation based on TRTs using decreasing injection rate, for the cooling-dominated heat load and the optimisation of the first injection rate of 140 W/m.

Method	Borehole configuration	Number of Boreholes	Total length of the boreholes [m]
LSM	1x8 line	8	2256
GPM	1x8 line	8	2369
FD Numerical Method	1x8 line	8	2400
TEP	1x8 line	8	2252

In the comparison of the simulations based on decreasing injection rate when optimising the first injection rate of 140 W/m with the existing methods, the values obtained for the total length of the borehole are in the range of 1953 - 2055 meters for the balanced heat load and for the cooling-dominated heat load the values obtained for the total borehole length are in the range of 2369 - 2400 meters. The variation between the borehole lengths for the balanced heat load are approximately 1 % and for the cooling-dominated heat load the variation is 5 %. The total borehole length given from the ground properties obtained from the TEP was 1929 meters for the balanced heat load and 2252 meters for the cooling-dominated heat load.

Table 4.23 Results of the EED simulation based on TRTs using decreasing injection rate, for the balanced heat load and the optimisation of the second injection rate of 67 W/m.

Method	**Borehole configuration**	**Number of Boreholes**	**Total length of the boreholes [m]**
LSM	3x3 open rectangle	8	1938
GPM	-	-	-
FD Numerical Method	3x3 open rectangle	8	2248
TEP	3x3 open rectangle	8	2051

Table 4.24 Results of the EED simulation based on TRTs using decreasing injection rate, for the cooling-dominated heat load and the optimisation of the second injection rate of 67 W/m.

Method	**Borehole configuration**	**Number of Boreholes**	**Total length of the boreholes [m]**
LSM	1x8 line	8	2290
GPM	-	-	-
FD Numerical Method	1x8 line	8	2550
TEP	1x8 line	8	2371

For the simulation based on decreasing injection rate when optimising the second injection rate of 67 W/m with the existing methods, the values obtained from the total length of the boreholes are in the range of 1938 - 2248 meters for the balanced heat load and for the cooling-dominated heat load the values obtained for the total borehole length are in the range of 2290 - 2550 meters. The variation between the borehole lengths for the balanced heat load are approximately 1- 2 % and for the cooling-dominated heat load the difference is 1 %. The total borehole length given from the ground properties obtained from the TEP was 2051 meters for the balanced heat load and 2371 meters for the cooling-dominated heat load.

The lengths estimated from the new method for the first injection rate are comparable to the lengths obtained from the existing methods. This is not the case for the values obtained from the second injection rate. The lengths from the balanced heat load with an injection rate of 67 W/m are higher than the lengths obtained for the injection rate of 140 W/m. This is also the case for the simulations performed for the cooling-dominated heat load. The difference between the lengths of the balanced heat load and the injection rate of 67 W/m in comparison to the balanced heat load and the injection rate of 140 W/m are approximately 6 % for the new method and 7 - 10 % for the existing methods. The difference between the lengths of the cooling-dominated heat load and the injection rate of 67 W/m in comparison to the cooling-dominated heat load and the injection rate of 140 W/m are approximately 5 % for the new method and 1 - 6 % for the existing methods. The difference in the total borehole length for the balanced heat load are in the order of 10 %. The difference in the total borehole length for the cooling-dominated heat load are not higher that 6 %. The differences are in the expected range for the required borehole length according to a study by Javed *et al.*[17]

5 Conclusions

This chapter presents the conclusions derived from the results presented in Chapter 4. The comparison performed for the existing methods and the new TRT evaluation program, TEP, described in Chapter 3 included experimentally measured data from TRTs performed with both single injection rates and different scenarios of multiple injection rates.

Section 4.1 shows the comparison between the different equations used to calculate the equivalent pipe radius and the borehole thermal resistance presented in Section 2.6. A reference case was used to evaluate the equations. All ground thermal properties were known in the reference case. There were two reference cases, one where the power was kept constant, but the time step was varying and one where the power was turned off and then restarted. In that way the obtained ground thermal properties estimated from the TEP could be compared to the measured ground thermal properties given by the reference case. The results showed that Equation 2.33, used for the calculation of the equivalent pipe radius, in combination with Equation 2.27, used for the calculation of the borehole thermal resistance, gave the most accurate results. Thus these equations were used for the mathematical model of the TEP. Equation 2.27 used for the calculation of the borehole thermal resistance gave more accurate results since the equation is independent of the grout thermal conductivity unlike Equation 2.25 that uses the estimated grout thermal conductivity. Since the estimated value of the grout thermal conductivity is more sensitive compared to the ground thermal conductivity, using this value can occasionally provide inaccuracies in the results. The grout thermal conductivity is not a value as sought after as the ground thermal conductivity and borehole thermal resistance values when it comes to the design of the GSHP system.

After the new method was programed in MATLAB GUI it was used to estimate the ground thermal properties of the various scenarios of single injection rates as well as the scenarios with multiple injection rates described in Section 3.1. The same scenarios of injection rates were also used to estimate the ground thermal properties from the existing methods.

The comparison of the ground thermal properties estimated using the scenario of single injection rate showed that all methods including the new method gave similar results. The results of the ground thermal conductivity values were higher for the single injection rate of 140 W/m than the values obtained for the single injection rate of 67 W/m. The borehole thermal resistance decreased for the FD numerical method and the GPM when the tests were conducted with the higher injection rate of 140 w/m. The borehole thermal resistance increased when estimated by the LSM model for the higher injection rate of 140 W/m compared to the injection rate of 67 W/m. The TEP estimated the value to be approximately constant. When taking the results from the TEP in combination with the observations made by Gustafsson and Westerlund[11], this borehole suggests that it is surrounded by fractured bedrock. This is due to the fact that the ground thermal conductivity increases with increasing injection rates and the borehole thermal resistance stays approximately constant. If the values of the ground thermal properties estimated from the existing methods are used to make a similar comparison using the observations by Gustafsson and Westerlund[11] it is more difficult to suggest that the borehole is surrounded by fractured bedrock. However, the change in borehole thermal resistance is small when comparing the values from the different injection rates and can be considered as being nearly constant.

The scenario for the increasing injection rate test consisted of two injection rates, where the first injection rate was 67 W/m and the second injection rate was 140 W/m. The methods that first optimised the first injection rate should give similar results as the values they estimated with the single injection rate of 67 W/m. Similarly, for the optimisation performed by the methods on the second injection rate, the results should be similar to the single injection rate of 140 W/m. The results showed that for the MIR test using 67 W/m the values of ground thermal properties were differing from the values obtained by the single injection rate of 67 W/m. However, this difference between the values is small. The same applies to the values from the MIR test using 140 W/m and the single injection rate test of 140 W/m. When comparing the values of the ground thermal conductivity and borehole thermal resistance, provided by the new method to the values obtained from the existing methods they were in accordance to each other in the two MIR tests. However, the GPM software could not perform the optimisation for the second injection rate.

The comparison of the curve fit optimisation from the experimentally measured temperature of the fluid to the calculated temperature of the fluid are represented by Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5 for the different scenarios of injection rates. The figures show that the methods have calculated a temperature of the fluid that is close to the experimentally measured temperature of the fluid. For the scenarios of the single injection rates none of the methods had problems with the optimisation. For the increasing and decreasing injection rates the existing methods seem to have performed a good optimisation of the temperature of the fluid. The optimisation has been performed with values of the ground thermal conductivity and borehole thermal resistance that are not consistent with the values obtained from the single injection rate tests. This is clear when the scenario of the decreasing injection rate is analysed, where the optimisation seems to have been performed consistent with the single injection rate tests when looking at Figure 4.5. However, the combination of the values obtained from the ground thermal conductivity and borehole thermal resistance are not consistent with the values obtained from the single injection rate tests. Thus there are different combinations of the ground thermal conductivity and borehole thermal resistance that can give an accurate calculation of the fluid temperature, but the existing methods have problems finding the combinations that provide values that are consistent with the values obtained from the single injection rate tests.

If the values of the ground thermal properties estimated from the different methods for the MIR tests are used to make a comparison using the observations by Gustafsson and Westerlund[11], the results suggest that the borehole is surrounded by fractured bedrock. The LSM model suggest that this is the case since the ground thermal conductivity increases for increasing injection rate and the borehole thermal resistance stays constant. For the FD numerical method and the TEP the ground thermal conductivity increases for the higher injection rate. The change in borehole thermal resistance is small when comparing the values from the different injection rates and can be considered as being nearly constant.

The scenario for the decreasing injection rate TRTs consisted of two injection rates as well, where the first injection rate was 140 W/m and the second injection rate was 67 W/m. The methods first optimised the first injection rate and then the second injection rate. Similar to the increasing injection rate tests the methods that first optimised the first injection rate should give similar results as the values they estimated with the single injection rate of 140 W/m. For the optimisation performed by the methods on the second injection rate the results should be similar to the single injection rate of 67 W/m. The results showed that for the MIR test using 140 W/m the values of ground thermal properties were differing from the values obtained by the single injection rate of 140 W/m. The variation of these values do not differ more than the variations obtained from the increasing injection rate. The same does not apply for the values from the MIR test using 67 W/m and the single injection rate test of 67 W/m. The variation for the optimisation of the second injection rate is greater than the one obtained from the increasing injection rate. The greatest difference can be observed for the values of the borehole thermal resistance that differ more from the values obtained from the single injection rate of 67 W/m. However, the new method estimated values close to the values obtained from the single injection rate tests and had smaller variations. When comparing the values of the ground thermal properties, provided by the new method to the values obtained from the existing methods the values were not in accordance to each other.

If the values of the ground thermal properties estimated from the different methods for the MIR tests are used to make a comparison using the observations by Gustafsson and Westerlund[11] it is difficult to make any suggestions on the type of bedrock. Although the ground thermal conductivity increases for the higher injection rate, the borehole thermal resistance estimations using the existing methods have large variations. Using the new analytical method though to do this kind of comparison it is easier since the borehole thermal resistance has been more consistently estimated and the value stays approximately constant during the test suggesting a borehole surrounded by fractured bedrock.

The new method managed to handle an optimistion when the injection rate was decreasing or turned off and then continued. This was not possible for the other methods since they could not perform the optimisation for the reference cases used due to that they had both varying time steps and varying injection rates.

The variation between the values of ground thermal conductivity and borehole thermal resistance will affect the size of a GSHP system. Depending on the type of borehole, if it is grouted or groundwater-filled the heat transfer will depend on different factors. Since the boreholes used for the TRTs in this Master's Thesis are groundwater-filled, the type of bedrock and the size of the injection rate will affect the heat transfer and in its turn it will affect the size of the GSHP system. Expected is that the higher values of ground thermal conductivity and lower values of borehole thermal resistance creates good heat transfer and thus a smaller size of GSHP system is needed for these properties. This was shown in the EED simulations. The bigger injection rates gave lower values of borehole length.

The borehole lengths obtained from the TEP were similar to the values obtained from theLSM method in the single injection rate comparison. The results show that the values obtained from the new method can be compared to the existing methods already used today and that the borehole length variations between the methods do not vary more than 10 % from each other. Javed *et al.*[17] observed that uncertainties of this magnitude can be expected in this type of comparisons.

The analysis in this Master's Thesis have showed that the new method can be compared to the existing methods already used today. The new method show good evaluation for multiple injection rates compared to the existing methods since they can have problems with the evaluation of groundwater-filled boreholes.

The new method and some findings of this Master's Thesis are also reported in a scientific paper[16] which has been accepted for publication in ASHRAE Transactions[1].

6 Recommendations

Recommendations from this thesis are:

- The equations on how the equivalent pipe radius is calculated has been an important evaluation in this Master's Thesis. The evaluation have showed that this parameter affects the results greatly. A good estimation of this parameter can improve the results further for different types of boreholes. More accurate set of equations for the equivalent pipe radius should be investigated through computational fluid dynamics techniques to estimate how to model the heat transfer area of the U-tube. With an accurate estimation of the heat transfer area the equivalent pipe radius can in its turn be calculated.
- To optimise the simulation time of the new method, further investigations should be made on the set of equations currently used and determine if there are ways to simplify the calculations.
- Investigations should be conducted on the optimisation technique used to determine the minimised square errors between the calculated and the measured temperature of the fluid, if there is a technique providing shorter simulation times and if the results could be improved further.
- Javed and Claesson[15] have also presented a numerical solution for the evaluation of experimental data obtained from TRTs. It should be investigated if this method reduces the optimisation time and what results of ground thermal conductivity and borehole thermal resistance were to be obtained if this model was to be used instead.
- Develop the MATLAB program to include estimations of other unknown thermal properties if the grout thermal conductivity is known beforehand.
- Develop the MATLAB program to make it more user-friendly by providing drop-down menus and having data input forms.

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A TEP tutorial

This section provides an introduction to the new TRT evaluation model programmed in MATLAB GUI. It will include illustrations to show what the user will see on the computer screen and explanations on how the user should work with the program. The options available in the input menu and the information that is provided in the output window will also be explained in this section.

A.1 Main Menu

The main menu is the window that can be seen when the program is first opened. Figure A.1 shows how the main menu will look like when it is first opened. On the window the user can see which input data are needed to be defined in the program.

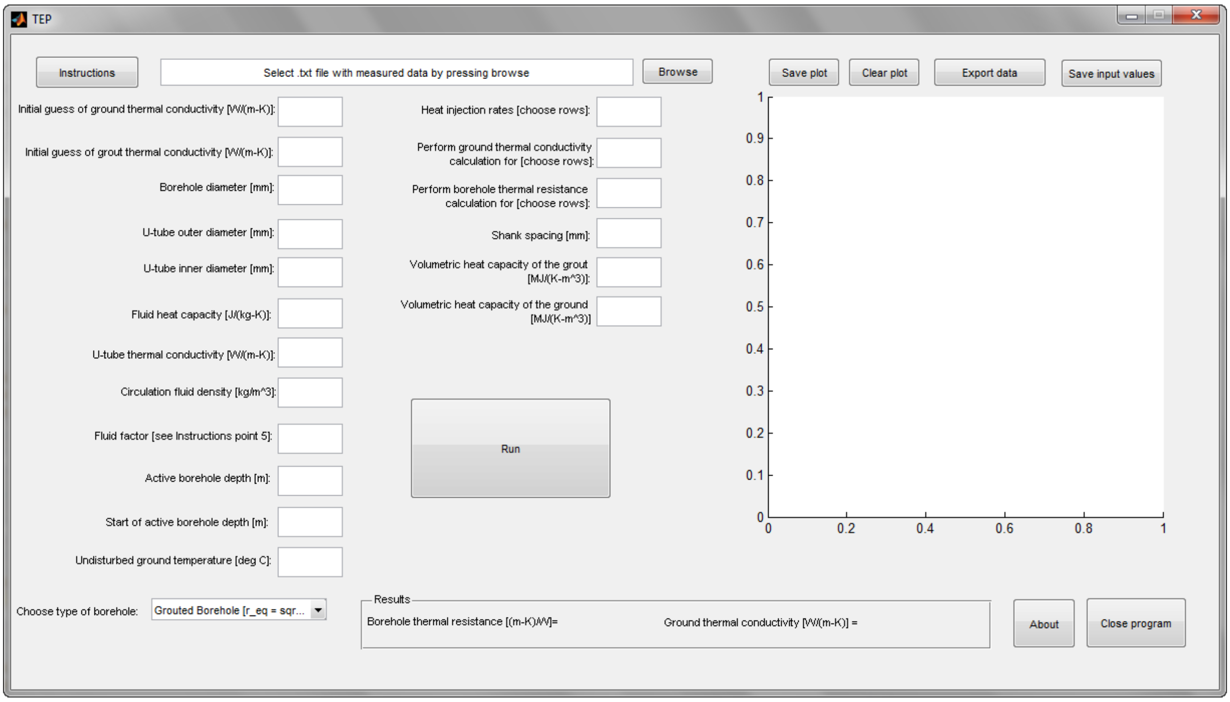


Figure A.1 Main menu.

The user needs to have prepared an input file consisting of some of the experimentally measured data from the TRTs. This file will be loaded into the program. How to construct the input file is discussed in Section A.1.1.

In the main menu the user needs to define the values for which the optimisation should be performed. This should be defined both for the calculation of the ground thermal conductivity and the borehole thermal resistance. This is further discussed in Sections A.1.2 and A.1.3. Section A.1.4 describes how the values in the input window named *"Heat injection rates [choose rows]"* should be defined. In Section A.1.5 it is discussed how to choose type of borehole. The user has the possibility to choose if the borehole to be evaluated is a grouted borehole or a groundwater-filled borehole. The values defined by the user in the main menu and in the input file should be separated using dot, ". ", to display fraction numbers.

The button named *"Instructions"* consists of instructions on how the input file needs to be constructed, how the input values should be defined as well as instructions on how the optimisation values are chosen. Finally the user only needs to push the button *"run"* to run the program. The program can be terminated by pushing the button *" close program"*.

A.1.1 Input file

The name and location of the input file can be manually typed in the appropriate file window or can be selected by using the *"Browse"* button. A dialog box is opened from where the file prepared by the user can be chosen by clicking to the folder where the file is saved in and then double clicking on the corresponding file to load it into the program. The file should preferably be saved in *.txt* format. The file name is chosen by the user but should not include blank space. The file must consist of 4 columns.

- Column 1: Experimentally measured power input in watt [W]. The first value has to be zero. The value at the following row is the first injection rate. In the following rows the next heat injections are inserted. The mean value of all experimentally measured power input values not differing more than $\pm$ 1.5% in standard deviation and $\pm$ 10% in maximum variation belong to the same injection rate.

- Column 2: Time, in seconds [s], when the experimentally measured data were recorded at in the test. The first value has to be zero.

- Column 3: Time, in seconds [s], when the power input changed in the test. The first value is the time when the power input started. The following values will be the times when the next injection rate started *etc.* If Figure A.2 is taken as an example, the power input first changes at 300 seconds when it is first turned on. The user then types 300 in row 2 in the third column. The power input then changes again at 167399 seconds. The user should type this value in row 3 in the third column. The first value has to be zero.

- Column 4: Experimentally measured mean temperature of the fluid in degree Celsius [deg C]. The first value has to be the undisturbed temperature of the ground.

All columns need to have same amount of rows. The number of rows are determined by the number of values used in the forth column. The rows that are empty (should only be in the first and third column) have to be filled with zeros. An example of how the input file should be constructed can be viewed in Figure A.3.

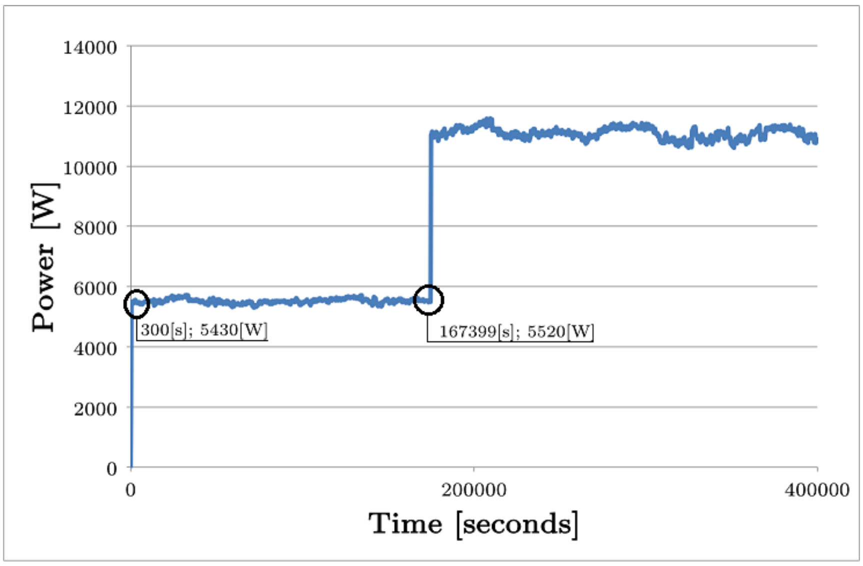
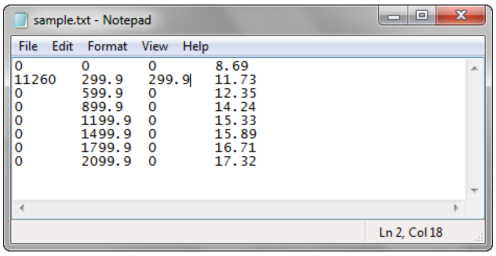


Figure A.2 Example of how the values in column 3 should be chosen.



0	0	0	8.69
11260	299.9	299.9	11.73
0	599.9	0	12.35
0	899.9	0	14.24
0	1199.9	0	15.33
0	1499.9	0	15.89
0	1799.9	0	16.71
0	2099.9	0	17.32

Figure A.3 Example of how the input file should be constructed.

A.1.2 How to perform the ground thermal conductivity calculation

To perform the evaluation of the ground thermal conductivity, the user defines for which values the optimisation will be performed for in the input window named *"Perform ground thermal conductivity calculation for [choose rows]"*. First type the number of row corresponding to the time value the optimisation should start at followed by " : " and then type the number of row which corresponds to the time the optimisation should finish at, *e.g.* 1:500 the optimisation is performed for times corresponding to rows 1-500. If the user wants to perform the optimisation until the final row the user needs to take the value of the final row and subtract 2. *E.g.* if the total number of rows is 502 then to perform the optimisation for all values type, 1:500. Hence the user takes 502 - 2 = 500.

A.1.3 How to perform the borehole thermal resistance calculation

To perform the evaluation of the borehole thermal resistance the user need to choose the values that will be included in the optimisation. These values need to be chosen for steady-state conditions. This will generally require that the borehole resistance is sought 10-15 hours after starting the tests or until an injection rate is changed. The user defines for which values the optimisation will be performed in the input window named *"Perform borehole thermal resistance calculation for [choose rows]"*. First type the number of row corresponding to the time the optimization should start at followed by " : " and then type the number of row corresponding to the time the optimisation should finish at, *e.g.* 240:500 the optimisation is performed for times corresponding to rows 240-500. If the user wants to perform the optimisation until the final row the user needs to take the value of the final row and subtract 2. *E.g.* if the total number of rows is 502 then to perform the optimisation until the final value type, 240:500. Hence the user takes 502 - 2 = 500.

A.1.4 Heat injection rates

In the input window named *"Heat injection rates [choose row]"* the number of rows in the third column of the input file that have times for when the power input changed should be defined. If the power input is only a single injection rate the row where the time for when the power started is defined. If more values are used then first type 2 (since the first value will always start at row number 2) followed by " : " and then type at what row the last value is *e.g.* 2:4, the times are inserted at rows 2-4.

A.1.5 Choose borehole type

The type of borehole that is being evaluated is chosen from a popup menu on the input window. The popup menu have three options, each with a unique equation for the calculation of the equivalent pipe radius. The equations can be seen next to the corresponding name of the borehole type. The two first options are recommended to use for grouted boreholes.

If the shank spacing is known, choose the first option. If the shank spacing is not available choose the second option and type *"1"* in the input window asking for the shank spacing. The third option should only be chosen if groundwater-filled boreholes are to be evaluated. For the third option type *"1"* in the input window asking for the shank spacing. For the third option users are referred to the work of Gustafsson and Westerlund[12]. However, the second option works in most cases and is recommended to use if the user is unfamiliar with the theory used to model the TEP.

A.2 Output Window

After the program has performed the simulation, the values of the ground thermal conductivity and borehole thermal resistance can be seen in the program window. An example of how the output window would look like is shown in Figure A.4.

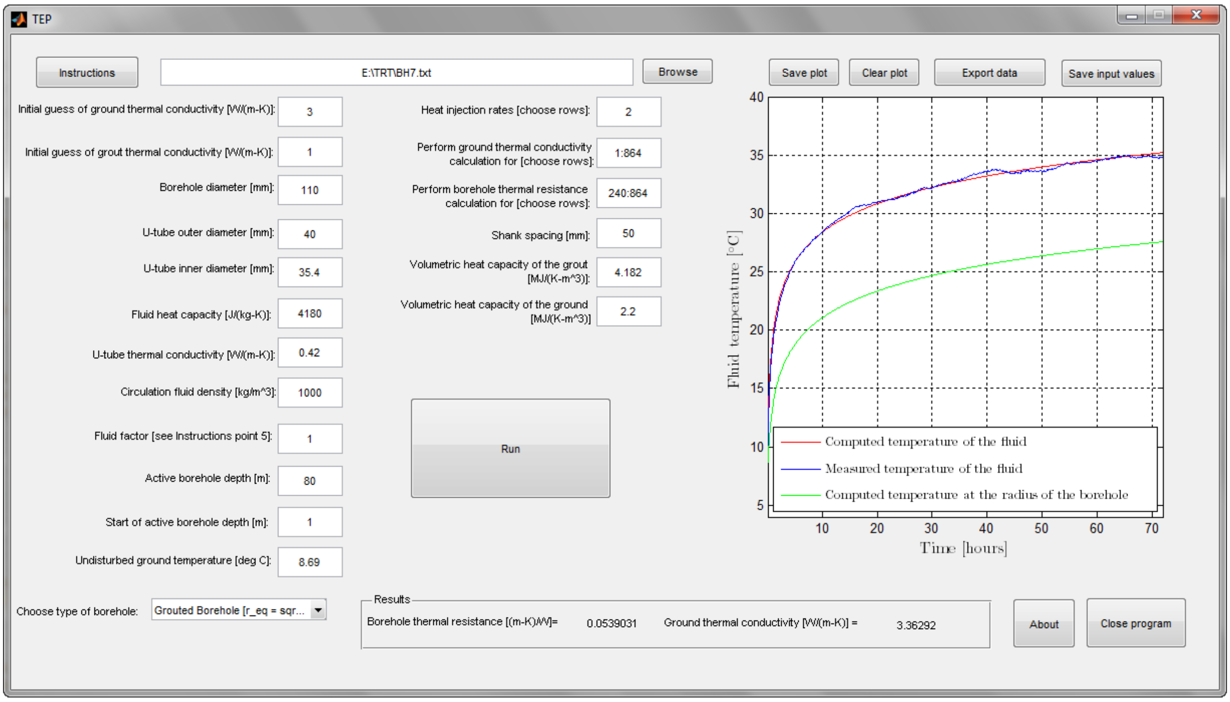


Figure A.4 The program window after the evaluation has been run.

The user has the option to export the results. The exported file will be in .csv (comma separated values) format. The values that will be exported by pushing the button, *"Export data"* is:

- The calculated data of the temperature of the fluid.
- The experimentally measured temperature of the fluid.
- The calculated temperature at borehole radius, r_b.
- The result of the borehole thermal resistance.
- The result of the ground thermal conductivity.
- The result of the grout thermal conductivity.

By pushing the button named *"Save input values"* the user has the option to export the values inserted in the main menu. The exported file will be in .csv (comma separated values) format. The user can also save the plot by pushing the button, *"Save plot"*.