Master Final Dissertation

Investigation of Soil for Shallow Geothermal

Field tests and laboratory measurements for the determination of thermal properties for the design of combined abstraction of heat and storage of solar energy

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Abstract

Soil thermal properties determination for shallow geothermal systems is vital since they constrain the design and optimisation of the system for either heat extraction or storing aims. Hence, the testing of the ground becomes an important aspect. This subsoil understanding can be achieved by literature estimations, laboratory tests, in-situ tests and numerical simulations.

VIA University College owns in its facilities three 100 m depth different BHE (Single U, Double U and Coaxial) and the equipment to execute thermal conductivity measurements in the laboratory and in-situ TRT. So, in this dissertation a three way approach to the obtaining of the ground thermal conductivity has been executed: i) a priori estimation from literature; ii) laboratory test using the Thermal Needle Probe Procedure and iii) in-situ TRT. The results have been compared. In addition, from the TRT the borehole resistance can be calculated and an evaluation of the three BHE has been made.

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Nomenclature

μ	*Dynamic Viscosity of the Carrier Fluid [Pa·s]*
v	*Speed of the Carrier Fluid Inside the Pipes [m/s]*
σ	*Stefan-Boltzmann constant [$5{,}67 \cdot 10^{-8}$ W m^{-2} K^{-4}]*
ρ	*Density [kg m^{-3}]*
λ	*Thermal Conductivity [W m^{-1} K^{-1}]*
α	*Thermal Diffusivity [m^{2} s^{-1}]*
z	*Depth Coordinate [m]*
t_s	*Break Time for Steady State Situation [s or h]*
T_{fl}	*Temperatures of the Fluid [ºC or K]*
T_f	*Average or mean BHE Temperature [ºC]*
T_{diff}	*Input Temperature minus Output Temperature [ºC]*
T_{body}	*Temperature of the Body [ºC or K]*
T_b	*Borehole Wall Temperature [ºC]*
T_o	*Undisturbed Ground Temperature*
T_o	*Initial Undisturbed Ground Temperature [ºC]*
t	*Time [s]*
T	*Temperature [ºC or K]*
S_{VC}	*Volumetric Heat Capacity [MJ m^{-3}K^{-1}]*
S_C	*Specific Heat Capacity [J K^{-1}]*
R_g	*Thermal Resistance of the Surrounding Ground [ºC]*
R_f	*Thermal Resistance of the Carrier Fluid Inside the Pipes [K m W^{-1}]*
Re	*Reynolds number*
R_b	*Borehole Thermal Resistance [K m W^{-1}]*
r_b	*Borehole Radius [m]*
q	*Heat Transfer Rate from Body to Fluid of surface area [W m^{-1}]*
Q	*Heat Flow [kW]*
Ø	*Inner Diameter of the Pipe [m]*
k	*Slope of the Function along the Horizontal Axis as Logarithm of Time t.*
h	*Local Coefficient of Heat Transfer [W m^{-2} K^{-1}]*
E_b	*Energy Radiated [J]*

A	*Cross-Sectional Area [m²]*
ΔT	*Temperature Increment [K]*
T_{out}	*Outlet Temperature of the Fluid [ºC]*
T_{in}	*Inlet Temperature of the Fluid [ºC]*
R_{bhw}	*Thermal Resistance of the Grouting Material [K m W^{-1}]*
R_{bhf}	*Thermal Resistance of the Pipe Wall [K m W^{-1}]*

Acronyms

ASHRAE	*American Society of Heating and Ventilating Engineers*
BHE	*Borehole Heat Exchanger*
BTES	*Borehole Thermal Energy Storage*
CHFM	*Constant Heating-Flux Method*
CHP	*Combined Heat and Power*
COP	*Coefficient of Performance*
DHW	*Domestic Hot Water*
DMI	*Danish Meteorological Institute*
DSC	*Differential Scanning Calorimetry*
GHG	*Green House Gas*
GSHP	*Ground Source Heat Pump*
HH	*High heating*
LSH	*Line Source Heat*
MH	*Medium Heating*
PE	*Polyethylene*
PTES	*Pit Thermal Energy Storage*
ROT	*Rate of Penetration*
SCW	*Standing Column Well Systems*
SPF	*Seasonal Performance Factor*
TC	*Thermal Conductivity*
TRT	*Thermal Response Test*
UTES	*Underground Thermal Energy Storage*

Dissertation Report Outline

This Final Dissertation is presented as the fulfilment of the requirements for the degree of Master in Science in European Construction Engineering. It accounts with 20 ECTS credits. The research was carried out at the Division of Civil Engineering, at VIA University College in Horsens, Denmark. This final dissertation summarizes three different approaches for the obtaining of soil thermal conductivity and the determination of the borehole resistance from the Thermal Response Test TRT.

The final dissertation consists of a state of the art in order to understand the basic concepts that arise to the idea of heat extraction and storage in ground, as well as the following parts:

a) Preliminary Study: overview of the current status in Denmark and at VIA University College.
b) Experimental Section: three approaches to the thermal conductivity determination is given: a priori estimation from the literature, thermal conductivity measurements using the Thermal Needle Probe method and Thermal Response Test, which additionally provides the borehole resistance.
c) Result Interpretation and Conclusions
d) A broad part with different appendix that support the results and conclusions of this final dissertation. This part also includes the two manuals for good practises for the execution of the laboratory measurements of thermal conductivity with the Non Steady Probe Method and the execution of the TRT.
   These two manuals are independent documents, with independent numbering, references and editing. This is why they are placed at the end.

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1. Introduction

1.1. Background

Nowadays, VIA University College needs to proof the reliability of their equipment for the determination of soil thermal properties with Ground Source Heating objectives in VIA Energy Park, in Horsens Campus (Denmark). One of the main objectives of the projects at VIA is the study of the feasibility of the storage of solar energy in the ground. Besides, there is a lack of reliable values regarding thermal properties of Danish Geology since common literature values are based on British and German lithology.

This is why a need to establish good practices for the execution of the tests for determination of soil thermal properties is conceived. The importance of these results comes from the improvements that a GSH system will receive when the thermal properties of the soil around the heat exchangers are known. That is to say, the systems will be optimized regarding performance and economic aspects. Hence, testing the ground is a vital activity.

In this case, the dissertation will be focused on Borehole Heat Exchangers BHE with both, heat extraction and storing aims. But the issue of the solar thermal energy is not treated.

The facilities in VIA give the chance to check the performance of the 3 main types of boreholes in 100 m depth ones: Single U, Coaxial and Double U.

So, in order to obtain the designing parameters for Ground Sour Heat Pump GSHP systems and Borehole Thermal Energy Storage BTES, some tests need to be done. It is highlighted then the importance of finding the thermal properties for the optimisation of the mentioned systems.

Moreover, the Thermal Energy Storage TES concept particularly is coming with arising importance when it comes to balance energy costs and productions. Here, BHE and BTES seem to constitute potential alternatives to other TES systems.

1.2. Aims and Objectives

There are many different tools and tests to determine soil thermal properties. However, at VIA University College there are available the following ones:

- Different literature sources.
- Thermal Conductivity Measurements with Non-Steady-State Probe procedure by Hukseflux in order to measure different soil samples from the cores extracted when drilling the boreholes.
- Thermal Response Test TRT equipment assembled at VIA University College.

So, the conclusions have been reached from three different approaches. The objective of this research is, therefore, the study and evaluation of the available equipment, finding limitations and improving the procedures, as well as overcoming any kind of problem appearing in the process. Thus, it will serve to be aware of the limitations, constraints and advantages of each method.

In addition, by means of these tests, a secondary objective will be the obtaining of an evaluation of the design of the boreholes' configuration or heat exchangers that exist nowadays at VIA University College for both energy storage and extraction aims.

When all the results are available, a comparison will be drawn and some conclusions and recommendations will be given regarding the three different Borehole Heat Exchangers.

The execution of these tests, in addition, leaves the door open to further investigations related to numerical simulations in order to determine heat capacities with a higher accuracy.

Finally, as a global aim, this dissertation would like to contribute to pave the way for a wider use of BHE by providing knowledge, tools and best practice procedures addressed to the development of the underground thermal storage, making this issue more accessible.

1.3. Research Methodology

The author has been working individually during the dissertation period, although an adaptation period of some days was received working with the previous team in charge of the TRT and very useful information was received from their research.

Nevertheless, regarding the laboratory measurements, the beginning has been from zero.

The research will consist of three main approaches as it has been shown in the previous section. And literature data as well as real data has been treated. Hereafter the methodology followed is further described:

a) A priori estimation of the soil thermal conductivity with literature values.

b) Execution of good practices manual to provide accurate thermal conductivity measurements in soil samples by the Non-Steady-State Probe procedure by Hukseflux.

b.1) Laboratory measurements of thermal conductivity studying different soil samples and gathering information of the deviations. Some of the analysed samples were gathered in the execution of the boreholes. These samples are kept and saved in accordance to the depth they were extracted. These results will be compared to the results of the Thermal Response Test.

b.2) The Laboratory tests for thermal conductivity have been carried out in the Energy lab of VIA University College. For that, the student has been provided of the required equipment for its determination by the Thermal Needle Probe procedure following the protocol established by the Hukseflux Thermal Sensors system.

c) Field measurement by means of a TRT equipment so as to determine a good practices manual and the obtaining of the effective thermal properties of the soil (thermal conductivity and borehole resistance).

c.1) The TRT will be executed in 3 boreholes of 100 m depth with heat extraction and seasonal heat storage aims. The first TRT was performed in March in the Energy Park of VIA University College and before this dissertation had started, just two TRT were performed: one in the Single U heat exchanger and another one in the Coaxial. So, the disposability to carry out the final dissertation was optimum since the rest of the tests could be carried out. This is why the moment to start the investigation in this place seemed to be the best. In total, three TRT have been studied, one per borehole and the numbering starts from 3 on since two previous tests have been executed.

c.2) The Thermal Response Tests will be carried out on site and in a real case and it will be a quantitative research. The facilities consist of:

c.3) For the execution of the tests, the required tools for the temperature measurements and for the TRT execution are provided. The TRT equipment has been made in VIA University College.

c.4) These tests will be addressed to the development of the study of the comparison of the three main types of borehole pipe configurations. Each of the boreholes has a different configuration as it has been said before.

d) Comparison of results and obtaining of conclusions and recommendations.

So, it could be said that the research consists of three main methodology protocols:

- Theoretical research.
- Practical Investigation.
- Evaluation and interpretation of the results from the tests.

1.4. Scope and Limitations

Regarding the scope of the final dissertation there could be remarked the following project facts:

- Academic objective: the work of this project has been developed as a MSc Final Dissertation in April 2013 in order to proof the reliability of the equipment at VIA University College in Horsens (Denmark) and to test the boreholes located in there.
- State of the Art: in order to introduce the student into the field of the GSHP systems, a wide study of the topic has been executed regarding the theoretical background of the thermogeology and the performed tests.
- End users: the main beneficiary of this research will be the VIA University College since it will receive an improvement of the procedures for the tests execution, as well as the results of the main thermal properties corresponding to the three studied BHE and the surrounding soil.

On the other hand, this final dissertation has suffered from several limitations which could be divided in three groups:

Academic Limitations

- Four months were provided for the execution of all the research, from April to August. The lack of time has constrained the scope.
- The author has worked alone in the execution of tests and evaluation of results. However, some information regarding the use of the TRT equipment has been received from the previous working team, although that information was not documented.
- The number of words were limited as well, so the need to synthesize the content shows a summary of all the managed information.
- Linguistic barriers when leading with data in Danish.
- In order to allow the understanding of the final dissertation in different countries, the International Unit System (SI) has been used.
- When has come to deal with costs, the Euro € has been used as currency.

Professional Limitations

- The author is not an expert in GSHP systems, neither in BHE. The author is a civil engineer that is right now being introduced in this field. Hence, the professional background of the researcher could have affected the accuracy of the results and analysis.
- During the execution of the TRTs the assistance of Víctor Marcos Mesón, a MSc student non expert in the topic, has been received in order to set up the equipment.

Technical Limitations

- The dissertation is focused on Denmark since all the tests have been performed in this country.
- The tests and their results have been directly linked to the limitations that the facilities have imposed.
- The first month was not possible to use the Hukseflux equipment for the thermal conductivity measurements because it was being repaired and calibrated.
- TRT equipment needed to be repaired so until July was not possible to do tests.
- There has not existed the chance to study in detail the previous two tests, so they have not been taken into account.

2. State of the Art

2.1. Introduction to Thermogeology and GSHP

The geothermal energy is defined as high enthalpy energy, e.g. high temperature energy that is not accessible in every geological situations (Banks 2008). Based on their potential for use or on the characteristics of the fluids they produce, there are different geothermal systems.

However, this final dissertation deals with low enthalpy technology, which is not exactly geothermal energy, but some authors call it "thermogeology" due to its similarities to the hydrology (Banks 2008). This paper will be focused just on this type, without going deeper in more explanations about other classes.

Thermogeology is linked to the ground source heat. And ground source heat is directly linked to shallow geothermal energy. Although it is complicated to establish, this shallow depths are considered until 200 m and the low enthalpy has its boundaries around the 30 ºC (Banks 2008).

2.1.1. Ground Source Heat

Following the definitions of the GSHP Association, Ground Source Heat GSH is the heat stored in the ground, in fact, the ground works as a huge energy store (Ground Source Heat Pump Association 2011).

GSH can be used as a source of heat in winter and as a source of cold in summer, so it is used both in space heating and cooling (Ground Source Heat Pump Association 2011). GSH could be perceived as it is shown by Geotrainet (2011a) in order to:

a) Increase or decrease of the temperature of geothermal heat to a usable level using heat pumps (Ground Source Heat Pumps GSHP).
b) Increase or decrease of the temperature in the ground by storing heat when there is a surplus or extracting heat when it is necessary (Underground Thermal Energy Storage, UTES).

Besides, a great strength of the GHSP technologies is that most rocks have rather constant thermal properties and this behaviour does not hardly depend on the lithology (Banks 2008).

2.1.2. Geothermal Gradient and Potential Geothermal Fields

Before continuing with technology basis, it should be understood how the heat flux arrives to such a shallow depth and why it is possible to take advantage of such a continuous energy source.

The earth's structure is composed by (Banks 2008):

a) A solid inner core of metallic iron-nickel with a radius of 1370 km
b) A molten outer core iron-nickel with a thickness of 2100 km

c) A mantle of Fe and Mg rich composition with a thickness of 2933 km
d) A very thin crust

Along the earth, there are some potential Geothermal Fields where heat could be extracted more easily. The first three reasons (a to c) are linked to the composition and internal structure of the earth and the tectonics settings, which provoke a big dynamic activity regarding temperature (Banks 2008):

a) Extensional plate margins
b) Convergent plate margins
c) Mantled plumes localizations
d) Variations in the thermal conductivity of rocks
e) Internal heat production (radiation) of some bodies and rocks
f) Transport of heat by groundwater flow
g) The earth and its climate are dynamic system

Deeper explanations can be found in the proposed literature: Geotrainet (2011a) and Banks (2008).

2.1.3. Heat Movement

When it comes to understanding GSH technology, two main concepts or thermogeological properties must be clarified:

Thermal conductivity (λ): it consists of the ability of the material to transfer heat by conduction (Banks 2008), e.g., it provides an indication of the energy rate transferred in the diffusion process. Its unit in SI are [W m^{-1} K^{-1}] (Incropera et al. 2013). The thermal conductivity of a geological material depends on the porosity, water content and mineral composition (Vangkilde-Pedersen, Ditlefsen & Højberg 2012).

Specific heat capacity (S_C): it is the ability to store heat. A more useful magnitude is used called *Volumetric Heat Capacity* (S_{VC}). It means the energy stored in the body for each cubic meter and each Kelvin of temperature. Its units in SI are [MJ m^{-3} K^{-1}] (Banks 2008).

Thermal diffusivity (α): it is the ratio between the thermal conductivity and the volumetric heat capacity. Its units in SI are [m^2 s^{-1}] (Banks 2008).

(2.1.3.1)

$$\alpha = \frac{\lambda}{S_{VC}} = \frac{\lambda}{\rho \cdot S_C}$$

Where ρ = density in [kg m^{-3}].

Regarding soils, most of them are based on silicate materials and they are likely to store heat and their thermal conductivity is modest since they transport heat relatively slowly. This is positive because the saved heat is not dissipated immediately and it is not retained so as to allow the extraction of heat by means of heat exchangers (Banks 2008).

But how does heat move through the subsoil and how it is possible to take advantage of it? Heat is transferred by three mechanisms: conduction, convection and radiation (Incropera et al. 2013).

Conduction

It describes the transport of energy in a body provoked by a temperature gradient. The physical reason is the molecular activity of the material (Incropera et al. 2013). It is governed by Fourier's Law:

(2.1.3.2)

$$Q = \lambda \cdot A \cdot \frac{dT}{dz}$$

Where Q is the heat flow [W], A is the cross-sectional area [m^2], T is the temperature [ºC or K], z =is the depth coordinate [m] and λ the thermal conductivity [W m^{-1} K^{-1}] of the type of soil forming the ground (Banks 2008).

Thermal conductivity is temperature dependent, although as thermogeology deals with almost constant temperatures, this fact can be neglected (Banks 2008).

Convection

It happens when heat transfers between a surface and a moving fluid which are at different temperatures (Incropera et al. 2013). When this heat transport by convection is forced, it is called advection. This is what happens when hot water is pumped from one place to another (Banks 2008):

(2.1.3.3)

$$q^* = h \cdot (T_{body} - T_{fl})$$

Where, q^* = heat transfer from body to fluid [W m^{-2}] of surface area, h = local coefficient of heat transfer [W m^{-2} K^{-1}], T_{body} and T_{fl} = the temperatures of the body and the fluid, respectively.

Groundwater movement has much to say here. Due to the advection, the presence of groundwater can determine the use of a BHE. In fact, if there is groundwater movement along the aestifer (see definition in next point), the storage capacity will decrease since the thermal energy losses will increase. However, for dissipative type applications (the ones for heat extraction), the groundwater flow presence allows the heat recharge (Hellström 1998). So, groundwater movement is a very important parameter to bear in mind and many studies have been developed for modelling since it requires an intense evaluation: Eskilson (1987), Jansson (1998), Kirsch (2006).

Radiation

The bodies emit energy in form of electromagnetic waves just because of their surface temperature (Incropera et al. 2013). The colder the body, the less energy it radiates (Banks 2008). In 1879, Stefan and Boltzmann stated up that the energy radiated is:

(2.1.3.4)

$$E_b = \sigma \cdot T^4$$

Where E_b = Energy radiated, σ = Stefan-Boltzmann constant of $5{,}67 \cdot 10^{-8}$ W m^{-2} K^{-4} and T = the temperature in Kelvin.

2.1.4. The Heat Energy Budget of the Subsurface Reservoir

The aforementioned mechanisms lead to a heat energy budget in the aestifer, or the heat reservoir, due to the changes in the annual average air and soil temperature, the geothermal temperature gradient and the geochemical energy (Banks 2008).

An aestifer is considered by David Banks (2008) as a “body or stratum of rock or sediment that has adequate thermal properties to permit the economic abstraction of ground source heat”.

In this volume of soil there will be entering a constant heat from the geothermal heat flux (Q_{gf}), there might be groundwater coming into (Q_{gwin}) and going out (Q_{gwout}), and there might be as well gains or losses of heat from the surface (Q_{surf}). This way, a balanced situation is expected (Banks 2008):

(2.1.4.1)

$$Q_{gwout} + Q_{surf} = Q_{gwin} + Q_{gf}$$

The important parameter to bear in mind is the heat stored in the ground, whose equation is (Banks 2008):

(2.1.4.2)

$$Energy\ Stored = (V_{aest} \cdot \Delta T \cdot S_{VC})$$

However, if heat is being extracted for heating aims or heat is being injected for cooling, this equilibrium will be broken as the energy stored will be run out. Anyway, it could be expected a new equilibrium due to an induced heat flux from the surface and a decrease in the temperature of the out-going groundwater flow. Nevertheless, this extraction must be sustainable for the lifetime it is designed for.

In summer the surface is heated by the intense solar radiation and the elevated air temperatures. This heating effect just reaches the first meters of the subsurface. Deeper, the temperature remains constant, similar to the annual average subsurface temperature for long term (Banks 2008).

2.1.5. Ground Source Heat Pump GSHP

A heat pump is a device that transfers heat by a refrigerant fluid that is circulating around a compression-expansion circuit. As a rule, these circuits consist of PE pipes buried in the ground, circulation pumps, manifolds, heat pumps and the pipes of the domestic installation. The heat pump itself is composed, basically, of heat exchangers, compressor and the refrigerant liquid (Geotrainet 2011a). It is not the aim of this dissertation to study in greater depth heat pumps, so further reading is recommended for a better understanding in the references mentioned: Banks (2008), Chiasson (2001) and Geotrainet (2011a), where explanations in chapter 10 are very clarifying.

GSHP are heat pump systems that use the earth, ground water, or surface water temperature as a heat source and/or sink. They use the earth as part of a heat exchanger to supply heating and cooling needs. The good efficiency of the ground as a source of heat is justified because of the relative constant temperature of the ground. Hence, a heat pump requires a low and constant (around 10 ºC) temperature heat source (Eskilson 1987). This leads to a good COP of the water to water heat pump (Chiasson 2001). In general, a heat pump working connected to a shallow geothermal energy resource produces from 3 to 4 times the amount of energy consumed in form of electricity. Thus, the typical values for COP are from 3 to 4 (Banks 2008).

So, it is not an electricity independent technology. However, many reasons support the use of heat pumps which are more efficient than direct electric heating systems since they offer an increased heat output per input electric unit (Harris 2011).

The utilization of heat pumps give to the energy system a flexibility when choosing the moments to use the electricity and because of this, the most economical moments to produce heat can be selected (Harris 2011). Besides, savings up to 60% are achievable with the use of this technology according to VDI (2010) standard.

Typologies of Systems

Nowadays, all the materials required for the implementation of a GSHP system are available from manufacturers and different methods have been developed to calculate ground parameters. Besides, design rules, guidelines and standards are being spread for the execution of reliable installations (Geotrainet 2011a).

There are several GHSP configurations and each of them has several characteristics and design rules. Besides, depending on the author, the names could differ. To know more about each of these systems, the reader can address to the classifications made by David Banks (2008) or Andrew Chiasson (2001). Here they are shortly defined:

a) *Open-loop Systems or Ground-Water Heat Pump Systems*
Water is pumped from a conventional well for water supply directly to a heat pump. In fact, it is the direct abstraction of water from a source by heat convection with groundwater flow (Banks 2008).

b) *Closed-loop Systems or Ground-Coupled heat Pump Systems*
There are Direct Circulation Systems (DX) and Indirect Circulation Systems. Both could be systems buried in the subsurface in shallow trenches or in vertical boreholes. Here, the ground heat is not directly extracted by the water, but used to heat the liquid circulating in the system. Thus, the conduction becomes the most important heat transport mechanism. The first ones are the ones where the subsurface ground loop works as the evaporator of the heat pump (Banks 2008) so they circulate the refrigerant liquid directly into the ground, while the second ones avoid that fact by circulating a fluid through a closed loop and exchanges the gained heat in the heat pump.
Inside of this group can be found:

- Horizontal Closed-loops

There are closed-loop systems installed in 1,2 to 2 m depth trenches. There are the cheapest ones to install but they require of greater space (Banks 2008).

- Pond and Lake loops

These ones place the pipe coils in deep ponds or lakes in a depth where there are not big temperature fluctuations expected. E.g., the heat exchangers can also be used to abstract heat from natural water accumulations (Banks 2008).

- Borehole Heat Exchangers BHE or Vertical Closed-loop Arrays

This is a way to safe space replacing the horizontal loops. A deeper explanation is provided later since these heat exchangers are the core of this study (Chapter 2.2.3. System Configuration of a BHE).

- Piles as Boreholes or Energy Piles

This consists of using the reinforced concrete piles of the foundations of the buildings as Vertical Closed-loop systems (Banks (2008), Smith (2011), Park, Lee, Yoon, et al. (2013)).

- Angled or Inclined Boreholes

Eskilson (1987) made some analytical models regarding this issue and nowadays more studies have been developed by Cui, Yang & Fang (2006) and Rees & He (2013). The selection of the configurations and the location of the boreholes affect directly the thermal influence between them and the heat extraction rate. The point of making inclined boreholes (20º angle with the vertical) outwards oriented is that this way the required surface is reduced since the thermal interference between the boreholes is less than being vertical (Eskilson 1987) so that the distance between them can be reduced. The bigger the distance, the smaller the thermal influence. This way the required borehole length to extract or inject the same amount of energy can be reduced (Marcotte & Pasquier 2009a). According to the study executed by Marcotte & Pasquier (2009b) the use of slightly inclined boreholes could reduce the total length of a vertical one by a 20%. These ones might be treated as BHE since they are able to host the same pipe configurations as the ordinary BHE.

c) *Hybrid GSHP Systems*

There are used when the system is not balanced and the application rejects more heat than the heat quantity that is extracted or vice versa. This is the reason why supplementary rejecters or secondary heat sources are integrated like shallow ponds or pavement heating systems for the first option (Chiasson 2001) or thermal solar collectors for the later ones (Cauret & Kummert 2011). These last ones are known as solar assisted GSHP. Acquiring equilibrium is vital for the long-term sustainability of the system (Banks 2008).

d) *Standing Column Well Systems SCW*

These systems are between the closed and the open loops. Basically they consists of the optimization and combination of both. The borehole, which is uncased, permits the circulating fluid to be in contact with the ground and allows groundwater infiltration as well as over the length of the borehole (Chiasson 2001).

e) *Jacob Doublet Well*

It could be understood within the previous type. However, it consists of dividing the water well in two chambers (upper and lower). Groundwater might be extracted from the upper chamber while the same water is rejected after circulating through the heat pump to the lower chamber. This is very useful in coastal aquifers where fresh water can be abstracted from the upper chamber whereas the lower chamber receives the reinjection in the saline groundwater which is denser than the fresh one (Banks 2008).

As it has been said previously, this final dissertation will deal with closed-loop systems, concretely with Vertical Closed-loop arrays or Borehole Heat Exchangers BHE. From now on, the report will be focused on these geo-exchangers.

2.2. Borehole Heat Exchangers BHE

2.2.1. Definition and BHE Types

A BHE can be treated as a tubular heat exchange, concretely as a Double-Pipe Heat Exchanger (Incropera et al. 2013). The heat exchangers allow effective temperature transfer from one fluid to another. And basically, this is what a BHE does. A BHE carries a circulating liquid inside the subsoil through the pipes and permits the heat exchange from the underground into the fluid for heating systems or the heat rejection from the fluid to the underground in cooling systems (Geotrainet 2011a).

When it comes to designing a BHE, there are two main parameters worth bearing in mind (Incropera et al. 2013):

a) According to the rating: firstly, the heat transfer/extraction rate q [W/m] and secondly, the fluid outlet temperature for the established flow rates and pressure values. The temperature difference between the circulating fluid and the borehole wall is proportional to the heat transfer rate (Geotrainet 2011a). For the delimitation of the heat transfer, the principles of the heat movement mechanisms must be taken into account (conduction, convection and radiation).
b) Determination of the dimensions of the BHE.

The BHE are composed of pipes through which circulates the fluid up and down the borehole. These pipes are long and slim due to the length that they are buried in (between 30 to 200 m) (Geotrainet 2011a). There can be different materials, but the more usual one is the polyethylene PE with diameters from 25 to 54 mm. In addition, the diameters of the boreholes are around 150 mm and the pipes are surrounded by a grouting material that for the best performance of the BHE should have a high thermal conductivity so as to reduce the borehole thermal resistance. This concept will be explained later (chapter 2.2.2. Thermal Resistance Concept).

The grouting materials are usually quartz-based since the thermal conductivity of this mineral is elevated, around 7,7 W m^{-1} K^{-1} (Banks 2008) and they could be bentonite or concrete. In some cases, water is used as a grouting material despite of its low thermal conductivity due to the enhancement of the heat transfer between the ground and the heat exchanger provoked by the natural convection happening thanks to the groundwater flow. So, groundwater can directly affect the designing process of the heat exchanger (Monzó 2011).

When it comes to different borehole configurations to circulate the water up and down there are three main options to place the pipes (Geotrainet 2011a):

a) *Coaxial type BHE or concentric, also known as pipe in pipe*
   Inside this group, coaxial BHE without liner, BHE with tube-in-tube, BHE with soft liner, multichamber BHE, multiple BHE and coaxial with spiral coil (Park, Lee, Park, et al. 2013) flow channel can be found.

b) *U-pipe type BHE with two or more simple pipes connected at the bottom of the borehole*

This group contains Single-U pipes, Single-U pipes with spacers, Multitube U-pipes, and Three-pipe arrangements.

c) A single pipe is enough if it is only for heat pipes. The vapour goes up while the condensed fluid goes down into the bottom along the walls.

Along the "Training Manual for design of shallow geothermal systems" written by Geotrainet (2011a) further information about each configuration can be found regarding descriptions, figures, advantages and disadvantages, designing guidelines, advice, comparisons, etc. and in case deeper explanations are required, Acuña & Palm (2013) and Oberdorfer, Maier & Holzbecher (2011) have developed really good comparison studies.

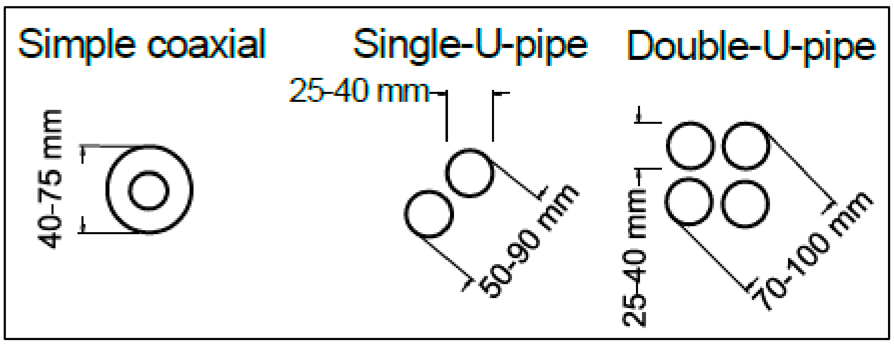

Figure 2.2-1: Training Manual for design of shallow geothermal systems. (Geotrainet 2011a).

Some new advanced designs have several advantages over the other heat exchangers since they have a higher relative surface of heat exchange up to the order of 1,25 times the surface of a U pipe heat exchanger. So, the principal pro is the good thermal contact that makes easier the heat transfer between external flow channel and the borehole wall. Besides, they show lower thermal diversion between inlet and downward channels, lower pressure descent, etc. (Oberdorfer, Maier & Holzbecher 2011).

Regarding principal drilling systems, useful information for drillers can be obtained from the *"Geotrainet Training Manual for Drillers Shallow Geothermal Systems"* by Geotrainet (2011b). The most important drilling systems are as follows:

a) *Percussion*

b) *Rotation*
This one could be with direct circulation, reverse circulation, or double rotary head and double piping (Odex type or Simmetrix type).

c) *Roto-Percusion*
It can be top-hammer or down the hole hammer both direct and reverse circulation.

d) New drilling systems are being developed as *vibration* systems for inclined boreholes with a short length (20-30 m). With this system the steel tubes that set up the borehole wall are pushed into the ground with a small vibration by means of a relatively small driller (Sunwell 2012). *Sonic drilling, Horizontal Directional Drilling* and *Coil Tubing* are other new methods.

2.2.2. **Thermal Resistance Concept**

The heat transport in a BHE can be separated in two mechanisms or two different thermal resistances (Banks 2008; Geotrainet 2011a):

a) The heat conduction through the undisturbed subsoil that surrounds the borehole. This is denominated the *Thermal Resistance of the Surrounding Ground* R_g. Here the main parameters involved are the thermal conductivity of the soil material and the existence of groundwater flow which affects the temperature by means of advection. The thermal conductivity of the ground is, then, the capacity of the rock to transmit the heat from the surrounding to the BHE and vice versa.
(2.2.2.1)

$$T_b - T_0 = q \cdot R_g$$

Where T_b and T_o are the temperature at the borehole wall and the temperature of the undisturbed ground respectively.

b) The *Borehole Thermal Resistance* R_b [K m W^{-1}]. This parameter summarises the effectiveness of the BHE and its calculation is the objective of the TRT and the numeric simulation softwares. It takes into account all the heat transfer phenomena from the borehole wall to the circulating liquid inside the pipes (Geotrainet 2011a). It defines the proportional relationship between the specific heat extraction rate of the borehole and the temperature difference between the borehole wall and the heat carrier fluid. The *specific heat extraction rate q* [W/m] increases while the R_b decreases as the Hellström-Efficiency parameter demonstrates for an established range of parameters (Geotrainet 2011a). So the objective of the designers should to achieve low R_b values.

The local process in a borehole can be described as it is stated in paper 2 of the thesis by Eskilson (1987):
(2.2.2.2)

$$T_b - T_f = q \cdot R_b$$

Where T_b and T_f are the temperature at the borehole wall and the temperature of the heat carrier fluid respectively.

At the same time, this R_b can be decomposed in three resistances: the resistance of the carrier fluid inside the pipes R_f, the thermal resistance of the pipe wall R_{bhf} and the thermal resistance of the grouting material R_{bhw}. So, R_b can be given as an addition of those three constituent parts shown in the figure below (Monzó 2011):
(2.2.2.3)

$$R_b = R_f + R_{bhf} + R_{bhw}$$

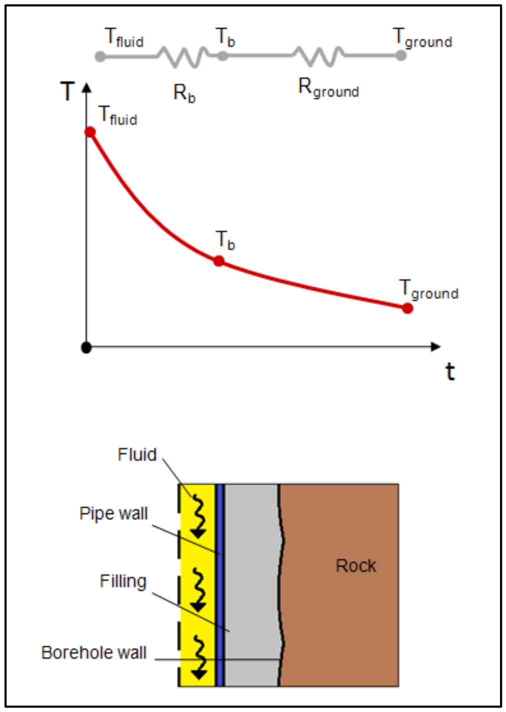

Figure 2.2-2: Thermal resistance fundamental in borehole heat exchanger (Monzó 2011) .

Definitely, thermal resistance of the pipe material and the convective heat transfer inside the pipe have to be kept low (Hellström 1998).

So, when it comes to designing guidelines, as the underground conditions around the borehole (type of soil, the ROT, groundwater level and the groundwater movement) cannot be changed or altered, the designer can just play modifying the next parameters (Geotrainet 2011a):

a) Fluid flow rate
b) Circulating fluid
c) Pipe material and diameter
d) Number of pipes
e) Pipe position or shank distance (spacers)
f) Pipe geometry
g) Filling material or grouting (different thermal conductivity)

h) Diameter of the borehole
i) Depth of the borehole

This Thermal Resistance concept is well explained in the article "*Thermal performance of Borehole Heat Exchangers*" by Hellström (1998) in case more information is required.

2.2.3. System Configuration of a BHE

Now that almost all the important parts of the system are described, it is time to see how the ensemble of components works as a whole. The system is composed of manifolds, grouting material, pipes and heat pumps. And as it is shown in Figure 2.2-3 schematically, they are linked in this way:

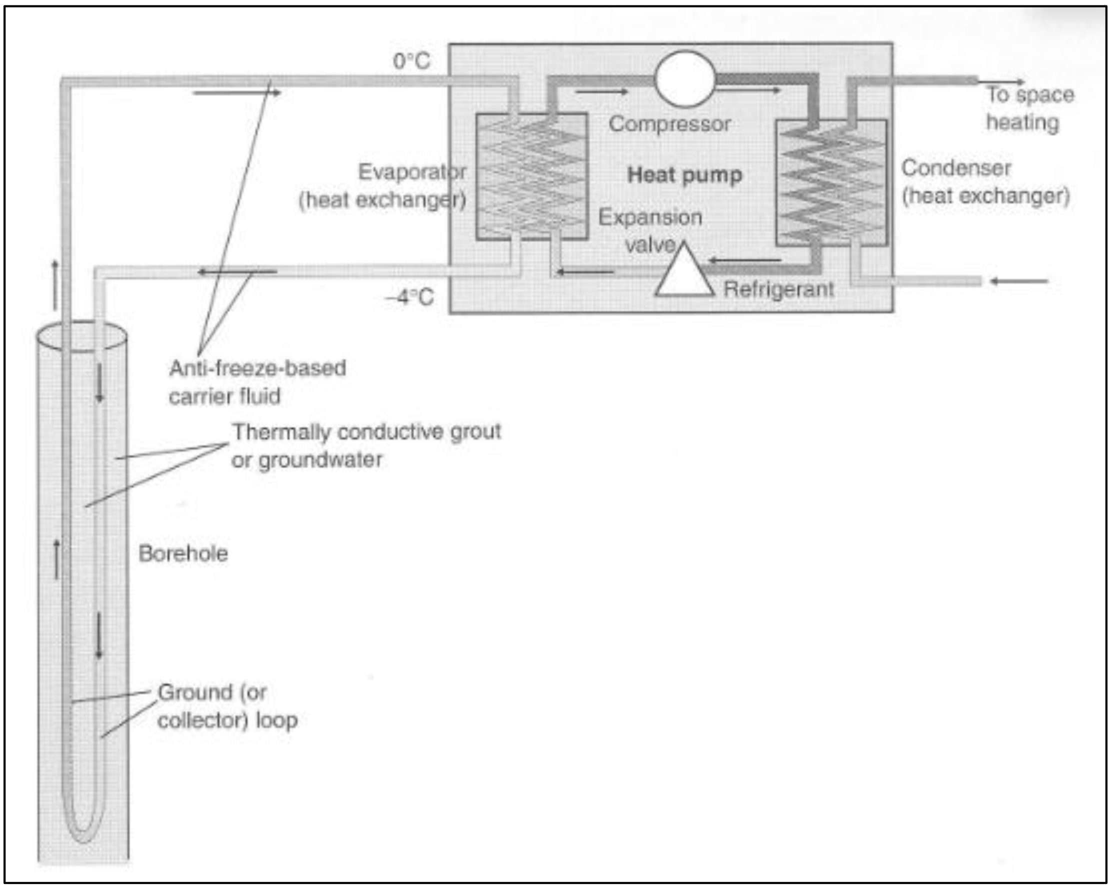

Figure 2.2-3: A schematic diagram of an indirect circulation closed-loop scheme, installed in a borehole (Banks, 2008).

As it has been said before, the carrier fluid circulates inside the closed-loop (PE pipes). The circuit goes by the underground through the BHE. The system shown in the figure represents a single-U pipe configuration where the refrigerant fluid goes downwards in one branch and upwards through the other. In a heating system, the heat pump extracts the heat that the fluid gathers during interaction with the subsoil along the circuit. Then, this liquid exits the heat pump condenser and starts again the circuit once and again. In a cooling system the opposite situation happens, where the heat pump works in a reversed way and this time the heat is rejected into the ground when the carrier fluid goes downwards (Banks 2008).

The carrier fluid is normally a water-based antifreeze solution. And the fluid flow rate and pipe diameter have as main constrains (Banks 2008):

a) The need to obtain a turbulent flow conditions to make easier the heat transfer from the ground to the fluid.
b) The carrier liquid can transmit the required quantity of heat.

Apart from this, because of the lower capacity at charging and discharging of the BHE usually a buffer store (water tank or accumulator) is integrated into the system for diurnal storage and this way ensure the supply of the demand and the equilibrium of the system.

When it comes to calculating this type of systems, there are three main calculation procedures: theoretical models, analytical models and numerical models. However, there are rules of thumb that facilitate the designing of the GSHP systems. Many useful information about this issue and step by step advice can be found along the papers and articles written by Banks (2008), Geotrainet (2011), Eskilson (1987), German Standard VDI (2010) and EBA Engineering Consultants Ltd. (2007). Regarding BHE design software, Nagano, Katsura & Takeda (2006) make a good overview of the available tools.

Summarising, it could be said that the main limitations and parameters to take into account when designing are:

a) Specific heat extraction rate
b) Maximum building heat load
c) Average full-load hours of heat pump
d) Heat distribution system
e) Heat supply temperature
f) Expected average SPF
g) Underground geology
h) Mean ground and surface temperatures

2.2.4. **Underground Thermal Energy Storage UTES**

Nowadays, energy storage is an important issue in the energy field dealt by many researchers, and ground, makes it possible. According to Hadorn (2004), there are two main reasons to support energy storage:

- The time: the seasonal storage supports the future development of solar energy.
- The space: the production of heat is not at the location of consumption in big installations.

Heat can be stored in many different ways apart from soil, and deeper explanations can be found in several references: Hadorn (2004), Carson and Moses (1963) or Pavlov and Olsen (2011).

When it comes to combine heat pumps with renewable energy resources, it must be said that the heating demand is not constant throughout the year, neither the electricity generation. These factors turn energy storage a vital issue. However, this issue is not just about controlling daily fluctuations, but also long term variations, like seasonal storage (Harris 2011).

In order to achieve a balanced system throughout the year, either for heating or cooling, underground energy storage is an option. In many schemes that have been already mentioned, a heating demand in winter and a cooling demand in summer will happen. This means that heat will be rejected into the ground in summer and re-extracted during the winter (Banks 2008).

For diurnal storage and small solar installations, water tanks seem to be one of the most feasible options, while for seasonal storage there is a wider range of possibilities. Of course, water tanks are still viable, but soil appears as an important competitor since big water tanks are unaffordable and soil has more than acceptable thermal properties at low cost (Hadorn 2004). Here is where the modularity of the Borehole UTES or BTES gains strength (Pavlov & Olesen 2011).

When it comes to UTES, four main solutions are provided: water tanks, water-gravel pits, Aquifer Thermal Energy Storages (ATES) and Borehole Thermal Energy Storage (BTES) (Pavlov & Olesen 2011). The reading of *"Seasonal Ground Solar Thermal Energy Storage – Review of Systems and Applications"* by Pavlov and Olesen (2011) and the fact sheet 7.2 *"Solar district heating guidelines"* by Thomas Schmidt (2012) is recommended in order to learn more about these systems.

Besides, according to VDI (2001), different uses can be obtained from UTES. Some of them they do not even use heat pumps, others use low-temperature heat systems. Solar energy storage is proposed as well together with the storage of heat produced in a CHP plants or the storage of waste heat.

It is not objective of this research going deeper in energy storage typologies either for diurnal storage or seasonal storage, but yes in BTES since are the core of the investigation. That is why the next explanation about BTES is given. In case the reader is interested in the topic of energy storage, both short term and long term storage, the reading of the texts by Dincer & Rosen (2002), Harris (2011), Pavlov & Olesen (2011), Hadorn (2004); Schmidt, Mangold & Müller-Steinhagen (2003) are suggested and recommendations linked to different UTES systems are provided in VDI (2001).

Borehole Thermal Energy Storage BTES

As the study has been focused on the analysis of boreholes, the most important ideas about BTES will be provided from now on, since BTES systems consist of several BHE (Gehlin 2002):

According to Banks (2008), the total thermal stored load H [W] in a cylindrical array of boreholes is calculated by:

(2.2.4.1)

$$H = S_{VC} \cdot \pi \cdot r_{array}^2 \cdot D \cdot \Delta T$$

Where S_{VC} = volumetric capacity of the aestifer material; r_{array} = borehole effective radius; D = borehole depth and ΔT = average change in the ground temperature of the ground enclosed by the borehole thermal array.

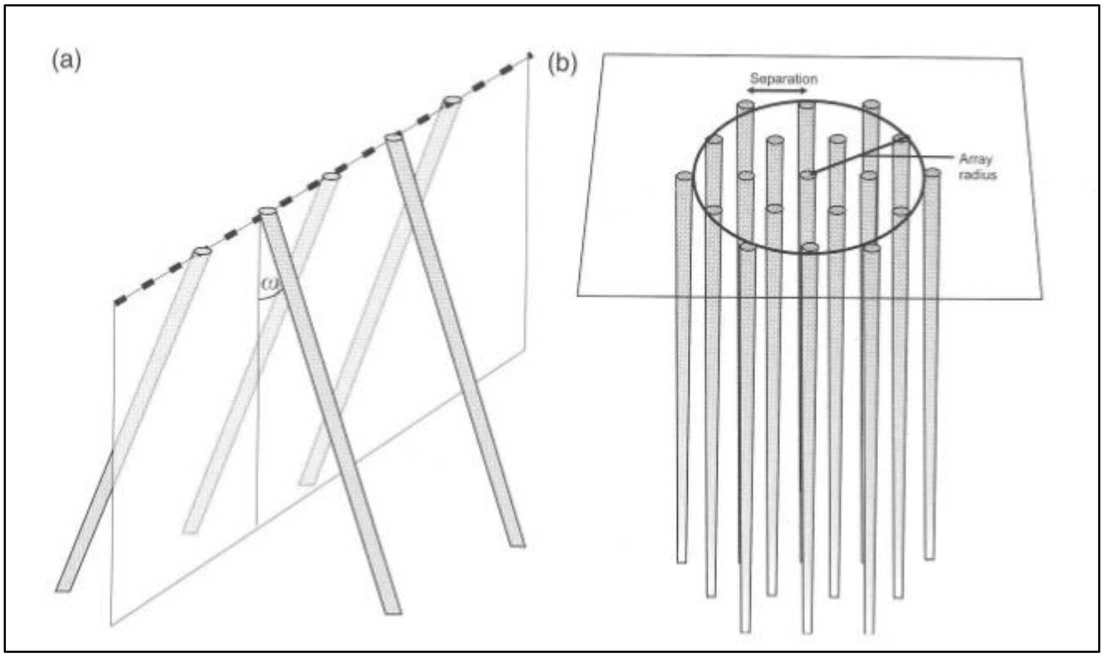

Figure 2.2-4: a) Alternate inclined boreholes in opposing directioctions optimized for continuous heat extraction and rejection; b) Closed borehole array designed for BTES (Banks 2008).

The main objective of these systems is the solar thermal energy storage collected in summer for space heating in winter and if possible for DHW supply. These systems started their development in the early seventies due to the oil crisis in that period. Besides, this technologies contribute to the GHG emission reduction and the energy efficiency (Pavlov & Olesen 2011).

So as to obtain an optimum installation for TES, the array should form a compact geometrical pattern relative to each other as it is shown in Figure 2.2-4. It will work better with large volume and small surface are, e.g., most favourable possible ratio of volume to surface are (VDI 2001).

But, what is the problem with the optimization of the storage systems? The sun is an intermittent source of heat, most of all in high latitude countries where the seasonal variation of solar radiation is significant throughout the year. Besides, in cold climates where heating demand is much higher than the cooling one, the energy storing becomes vital. This is why energy storing systems' efficient performance is so important. So, high latitude and cold climate countries become potential consumers of this kind of systems (Pavlov & Olesen 2011).

Denmark fits perfectly with this description. Indeed, large-scale solar systems have already been built in this country. However, the lack of cost-effectiveness is still the weakness of these systems (Pavlov & Olesen 2011). In the article recommended by Pavlov and Olesen (2011) a state-of-the-art of many large-scale installations for BTES is done. Buffer tanks, supporting heaters and low temperature heating systems are some option to combine the different solar collectors and borehole arrays systems. However, individual domestic systems are not mentioned.

Just to make an idea about the possibilities this technology offers, one of the biggest BTES scheme is explained: it is located in New Jersey, where 400 boreholes of 135 m depth access 1,2 million m^3 of ground with a cooling demand up to 5000 kW (Banks 2008). The same author describes more cases in his book *"An Introduction to Thermogeology"*.

As it could be deduced from equation (2.2.4.1), the amount of heat that can be stored is maximum as ΔT is bigger. It is true that in northern countries due to the need to abstract in winter almost all the heat stored during summer, the temperatures of the carrier fluid go around 40ºC and they are not considered energetically efficient. However, if the waste heat available in the ground is at a high temperature (65ºC), it will allow a very efficient heat extraction during winter (Banks 2008).

But… how can the energy stored in the ground be at a higher temperature apart from the use of solar thermal panels that collect summer heat? So as to ensure that the energy storage is a sustainable activity that has not required from explicit heat production and represents a real money saving, the used heat is recommended to be waste heat from (Banks 2008; VDI 2001):

- Industrial processes or combined heat-and-power installations.
- Loops installed under black surfaces.
- Renewable resources.

According to VDI (2001) the stored thermal energy can be recovered at least along three months later after the energy injecting process ended.

2.2.5. Environmental and Economic Aspects of BHE

A question arises when it comes to the environmental analysis of BHE and of GSHP Systems in general: do they constitute a renewable energy? GSHP do not work by themselves. They require an electricity supply. So, they have to be seen as a complementation for other renewable sources. In fact, GSHP allow the use of electricity in a more effective way. And this electric power should be generated as far as possible by a low-carbon or "green" technology (Banks 2008).

Following with the same author, a deep overview about the environmental impacts, regulations and subsidies related to GSHP Systems can be found in chapter 13 of the book *"An Introduction to Thermogeology. Ground Source Heating and Cooling"* where a LCA point of view of BHE can be noticed since it is treated the decommissioning of BHE. More aspects about environmental issues could be found in chapter 19 of the Geotrainet (2011a).

However, it has to be mentioned that the regulations are more restrictive for open systems than for closed systems because in the later ones there is not a direct use of the groundwater for the system performance.

Important aspects worthy bear in mind when it comes to BHE lifetime can be found in chapter 5 of Geotrainet (2011a). When designing, it must be considered that the BHE have to be able to work with at least three different new generations of heat pumps since it is considered that along the lifespan the devices might have to be changed.

Regarding economic aspects, as Banks (2008) states, the capital cost of a domestic installation of about 6 kW including the drilling of the borehole, the pipework and manifolds it might reach the 9000 €. Geotrainet (2011a) in its manual proposes for vertical close-loop systems a price higher than 1200 €/kW.

Comparison studies have been performed in order to obtain the differences in the costs of different systems (Banks 2008). I has been shown that although the running costs of a GSHP are much lower than the ones corresponding to a conventional gas boiler, the savings for a domestic small installation are not as attractive as it could be thought, since the payback period seems to be too long (over 12 years or even decades) comparing to traditional systems (Geotrainet 2011a).

However, it must be taken into account the economy of scale. The larger the heat pump, the cheaper the installation becomes. So GSHP systems seem to be very attractive to large buildings and requirements (20-30 kW) (Banks 2008).

Just for clarifying purposes and in order to be aware of numbers, the next figure shows a table with typical designing values for BTES for heat storage applications:

Borehole diameter	100 - 150 mm	Flow rate in U-pipes	0.5 - 1.0 m/s
Borehole depth	30 - 100 m	Average capacity per m borehole length	20 - 30 W/m
Distance between boreholes	2 - 4 m	Min. / max. inlet temperature	-5 / > +90℃
Thermal ground conductivity	2 - 4 W/(m·K)	Typical cost of BTES storage per m borehole length	50 - 80 €/m

Figure 2.2-5: Typical values of BTES system for heat storage application (Thomas Schmidt 2012).

2.2.6. **Borehole Testing**

One of the main problems when it comes to the optimization in the design phase of BHE, BTES and GSHP Systems in general comes when ground parameters are required. This is why there are different tests to calculate the properties of the soils. Either in situ or laboratory tests are used as tools to obtain them so as to reduce the errors arising from the rules of thumb and literature values (Witte, Gelder & Spitler 2002).

Literature values have to be used as approximate but not as fixed. These values are not reliable anymore since it is known that soil properties change due to many factors from one place to another (Witte, Gelder & Spitler 2002). This uncertainties are very important to bear them in mind when it comes to results analysis. Anyway, there are very useful tables with values for well-known materials in order to have a first approximation (VDI 2010).

It has been already said that the main ground properties are the thermal conductivity and the volumetric heat capacity, and, besides, it has been highlighted the importance of the calculation of the borehole resistance. In this chapter an overview of the systems to measure the mentioned parameters will be given.

Several models to determine the thermal properties from available data are known. These models, either the analytical line source and cylindrical source models or different numerical models, there are all based on the Fourier's low of heat conduction (Witte, Gelder & Spitler 2002).

Regarding laboratory methods, generally entail expensive equipment and will not provide a wide overview of the underground conditions at the site (Gehlin 2002).

In the next list, the principal measuring techniques are mentioned for each one of the properties. It is not aim of this final dissertation going deeper in explanations.

a) *Thermal conductivity*
   There are several tests to calculate the thermal conductivity of a material in the laboratory:
   - Non-Steady-State Probe methods where the Thermal Needle Probe and the Dual Probe or Two Needle techniques can be found.
   - Steady-State Methods like the Heat Flow Methods, the Divided bar or the Tempe cell where the sample is tightly packed.
   - The Hot and Cold plates which can be used to calculate the heat capacity as well.

   Regarding modelling, there are two dimensional finite models and for in situ tests, there are available Soil Thermal Needle Probes and Thermal Response Tests. With the TRT the borehole resistance can be calculated as well.

b) *Volumetric heat capacity*
   Its calculation is not simple. There are different laboratory tests but the ones developed so far are more addressed to homogeneous materials:
   - Hot Plate Apparatus or Parallel Hot and Cold Plates.
   - Differential Scanning Calorimetry DSC in the dynamic and isothermal steps variations.
   - T-history method (Günther, Hiebler & Mehling 2006).
   - Different devices and processes have been produced in several universities in order to obtain thermal properties of soil samples, such as heat capacity and diffusivity due to the cost of some of the standardised methods. These

procedures use to follow the Ingersoll model equation, which represents a heat flow from a point source along an infinite, homogeneous and isotropic medium. The studies reveal good accuracies (Alonso-Sánchez et al. 2012).

c) *Diffusivity*
The calculation of the diffusivity it could be very useful since it is the ratio between the thermal conductivity and the volumetric heat capacity. So as the calculation of diffusivity and thermal conductivity can be more feasible than the one of the heat capacity, the latter one can be calculated as the ratio of the first ones.

There are several techniques apart of the mentioned ones, some of them proposed by Dr. Nestoros (2013) in his article "Thermal and Electronic Wave Methodology in Non-Destructive Evaluation of Composite Materials":

- Techniques with optical excitation source.
- Techniques with thermal excitation source.
- Photo-thermal techniques.

d) *Borehole Resistance*
The most widely known system to obtain it is the execution of TRT. However, it can be obtained by numerical simulation.

Some of the above-mentioned methods are not applicable in soils because they are either too expensive or too difficult to carry out. Two tests have been developed in this final dissertation, which will be the ones described right after: the Non-Steady-State Probe Method for thermal conductivity determination and the TRT for the effective thermal conductivity and the borehole resistance calculation.

2.2.7. Non-Steady-State Probe Method

By means of this method, using a Thermal Needle Probe, the thermal conductivity of soil samples with a minimum size can be measured in the laboratory in quite an easy and fast way. In fact, Thermal Probe method can be used effectively to determine the thermal conductivity of all types of soils and two phase materials used in engineering (Kumar, Raja & Karhikeyan 2010).

More information about this type of test and its theoretical background can be found in Chapter 4.2 and in Appendix 8.10 can be found a manual for good practices for the execution of this test and a deeper explanation of the equipment. For further knowledge the reading of the next literature is recommended: Kumar, Raja & Karhikeyan (2010) and Witte, Gelder & Spitler (2002).

2.2.8. **Thermal Response Test TRT**

TRT make sense when it comes to the design of installations bigger than 30kW since they provide a good estimation of the soil thermal conductivity and the borehole resistance, in order to optimize the heating and cooling or the BTES systems. On the other hand, for single family houses and installations up to 30kW, it is considered enough the use of tables, simple software or nomograms (VDI 2001).

So, TRT extended to the conductivity test are recommended at the initial stage of designing big BHE installations (Gonet et al. 2012) so as to predict the thermal power reliability and optimize the BHE installation by minimizing the depth of the boreholes and the associated drilling costs as well as improving the performance of the system (Wagner & Clauser 2005).

The first practical applications of TRT appeared in the 90s after a couple of decades of theoretical research (Sanner et al. 2005).

The outputs of a TRT are the thermal conductivity of the soil λ and the borehole resistance R_b. However, since the thermal conductivity determined is a value for the total heat transport in the underground around the borehole, including effects like convective heat transport and other kind of disturbances, it is more correct to call it “effective” thermal conductivity (Sanner et al. 2005).

The TRT logs the temperature variation along time of a closed loop BHE provoked by a continuous fluid circulation. This fluid can be continuously heated or cooled, depending on which type of TRT is being performed. The most conventional TRT type is the one that heats the carrier fluid by means of a constant heater and a circulating pump makes it run through the pipes (Wagner & Clauser 2005). This one is called by some authors as the TRT with Constant Heating-Flux Method CHFM (Wang et al. 2010).

The change in the temperature of the circulating fluid is directly linked to the soil thermal conductivity around the borehole. Performing the test in a correct way, the TRT can estimate the thermal conductivity with an expected error of $\pm$ 10% (Wagner & Clauser 2005).

Operation of the Test

Mean fluid temperature T_f is defined as an average temperature of the inlet and outlet temperatures of the BHE, while the estimated injected heat q is used to calculate the mean borehole wall temperature T_b. If a constant heat injection q (W/m) is provoked, T_f and T_b will vary over time but after a short initial period the temperature difference will reach a persistent value. This situation is named “Steady-Flux” state, where the next equation is fulfilled (Gehlin 2002):

(2.2.7.1)

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

The general layout of a TRT device is the one shown in the picture:

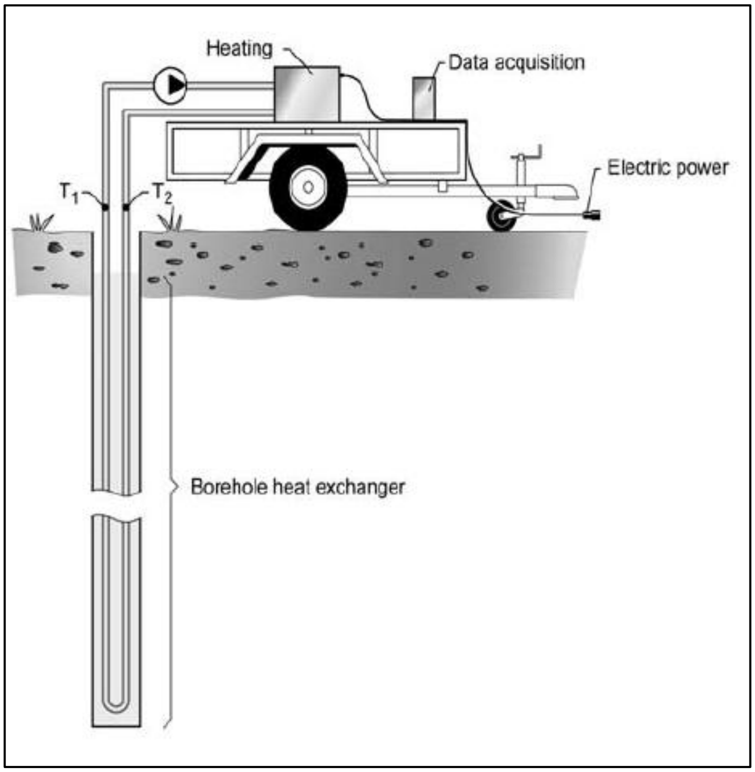

Figure 2.2-6: Test setup for a TRT (Gehlin 2002).

These tests are characterized by long testing times. Although due to commercial reasons there is a willing to reduce it to 12 hours (Sanner et al. 2005), the reasons to come with these long testing times (at least 48 h) are as follows (Gehlin 2002):

- Ensuring statistical correction of data.
- Ensuring the time interval where the simplifications in the formulation are usable.
- Ensuring a stable heat flow in the pipes.
- Ensuring that the temperature development is controlled by the surrounding soil and not by the borehole filling.

Apart from the conventional TRT, more developed TRT types have been used in several studies. Some devices are able to perform both, heating a cooling TRT. The ones that allow the cooling use directly a heat pump together with a sink in order to extract the heat from the carrier fluid and this way, cool the ground (Gustafsson & Westerlund 2011; Witte 2001). Nevertheless, some authors warn about this cooling option based on the operational difficulty of this type of TRT (Witte, Gelder & Spitler 2002).

Acuña & Palm (2013) and Shim et al. (2007) make some evaluation of Distributed TRT which can measure the temperature along the borehole while executing the test with fiber optic techniques allowing the plot of vertical temperature profiles.

Another improvement in TRT is the development of the Constant Heating-Temperature Method CHTM ensuring by means of a water tank a stable input fluid temperature to the BHE and allowing this way both heat-extraction and heat-injection TRT. This reduces the time required to obtain a steady heat-transfer state.

Hu et al. (2012) propose a TRT with unstable Heat Rate and TRT with heating and cooling options (Gustafsson & Gehlin ; Witte 2001) also used to study the groundwater flow influence in groundwater filled BHE.

An interesting proposal made by Gehlin (2002) is the opportunity to execute a TRT while performing the drilling of the borehole. This would give the chance to obtain the ground thermal conductivity of the soil around each borehole.

Test Evaluation

As Beier, Smith & Spitler (2011) have stated, there are two main areas of research in order to establish models to assess the data obtained from the TRT and be able to predict the performance of BHE as much accurate as possible. These two trends are the analytical models and the numerical models which need to be compared to real data in order to check their reliability.

Inside of the analytical models can be found two main approaches: the most widely used one, the Line Source Model, and the Cylinder Source Model, which is more complicated to apply (Monzó 2011).

However, in each of these approaches, the data can be treated in different ways, where the accuracy level is different, although they all are correct. Different authors have developed diverse evaluation methods as the parameter estimation method (Bauer, Heidemann & Diersch 2011; Hwang, Ooka & Nam 2010) which can be used for groundwater advection consideration (Wagner et al. 2013), the step-wise evaluation method (Bozzoli et al. 2011), the composite-medium line-source theory (Li & Lai 2012a) based on the Cylindrical Source Model, the Horner Plot Model (Fujii, Akibayashi & Ohshima 2002), etc.

Nevertheless, all the models, either analytical or numerical ones, have in common a series of assumptions as it is stated in the thesis by Monzó (2011):

- Models just take into account heat transfer by conduction, neglecting convective phenomena.
- Symmetry is considered to describe the thermal process in the radial direction along the axis of the borehole.
- Heat conduction is neglected through the direction of the borehole axis.

Besides, some studies give an approximate solution to specific problems or give an acceptable approximation to thermal diffusivity and heat capacity values of the soil. For instance, when backfill material is missing, Zheng et al. (2013) propose a methodology which seems to give accurate results.

Limitations of TRT

The accuracy of the different types of TRT is constrained by different factors as it is shown in the articles written by Wagner & Clauser (2005) and Sanner et al. (2005) and this factors directly affect the grade of uncertainty:

- The variations of the voltage in the grid affect the resistance heater, so fluctuations are provoked in the power injected into the subsoil.
- The effects of the surroundings of the borehole are linked to the low thermal conductivity of the grouting material.
- Vertical heat flow variation due to the fluctuations in the ambient temperature gradient which is largest close to the surface can happen. Climatic influences directly affect the results in the connection between the test rig and the BHE, even the rainwater. Considerable insulation is required to protect the connection pipes.
  Ambient air temperature variations affect the results and some studies have been done in order to subtract that effect (Bandos et al. 2011).
- The heat convection provoked by the groundwater flow limits the determination of the real thermal conductivity. This is why a TRT is not useful for a good design of a BHE plant if there is a high groundwater flow movement.
  This convective phenomena needs to be considered in order to obtain more trustworthy results, and in the text written by Sanner et al. (2005) a method to check for excessive groundwater flow and influence from external factors is proposed.
- It is known that the thermal conductivity of soils decreases with temperature increments. However, this effect can be neglected for the temperature ranges used for GSH applications. Bear in mind, anyhow, that for high temperature energy storage is a point worth taking into account.
- Assumption of volumetric heat capacity values from general literature or from previous research in the tested land (Alonso-Sánchez et al. 2012). This is one of the main uncertainty sources.
- An overestimation of the borehole thermal resistance results from the consideration of the average temperature for the analysis. According to the study executed by Marcotte & Pasquier (2008) this leads to a considerable economic impact.
- Studies have been executed in order to assess the error analysis and be aware of the problems and aspects of parameter estimation: Witte (2013) and Li & Lai (2012b). This last reference uses a Monte Carlo simulation in order to analyse the reliability of two uncertainty minimization algorithms.

BHE Optimization

It has been checked that even using different equipment, the tests performed in the same underground conditions, have very similar results. As well as using either a cooling rig or a heating one (Witte, Gelder & Spitler 2002).

As it has been explained before, the R_b is a parameter modifiable by engineering. So the efforts are focused on optimizing this factor by working on grouting materials, pipe configurations, diameters, etc.

In order to make TRT executions easier, remote controlling and self-working equipment are being developed, so as to avoid the controlling of the test while running (Witte, Gelder & Spitler 2002).

Many work can be done in the field of TRT, using them for small systems for residential houses or producing more sophisticated tests in order to obtain additional information without depending on numerical models (Sanner et al. 2005).

Using an in situ test is smart since it gives information about the thermal conductivity and volumetric heat capacity of a considerable volume of the soil around the borehole under truthful conditions and considering the real BHE configuration.

Besides, provides more information about drilling conditions and optimize project feasibility (energy and economic point of view).

So as to perform a good TRT, several guidelines have been published likewise Sanner et al. (2003) and ASHRAE (2007).

Moore information about this type of test and its theoretical background can be found in chapter 4.3 and in Appendix 8.8 and 8.11 which contains the good practices manual about the test equipment.

Numerical Simulation

The above-mentioned handicaps can be overcome partly by numerical simulations which are more complicated to use and require more computing time (Sanner et al. 2005).

Some authors confirm that there is the possibility to simulate a TRT by numerical modelling in order to get an acceptable estimation of thermal conductivity and heat capacity. These modelling are based on parameter estimation and they could consist of replacing the pipes of the BHE by a constant heat source with only diffusive heat transport. It seems that by means of numerical simulations can be overcome mostly all the restrictions of LHS. However, the model parameters for those synthetic TRT need to be chosen in respect of a real TRT (Wagner & Clauser 2005). In fact, a TRT needs to be performed in order to use a reference value for thermal conductivity in the parameter estimation.

So, numerical models can improve the accuracy and give further information, but cannot reduce the test time considerably (Sanner et al. 2005).

A case where numerical simulation is crucial as has been established by Gehlin (2002), is when the groundwater influence has to be taken into account in open-loop BHE, in the situation where there is a high fracture flow. In these conditions, a thermosiphon phenomena happens and it has a high influence in the BHE performance since it directly alters the results. Molina-Giraldo et al. (2011) have developed a numerical simulation for groundwater advection.

There are numerical simulations trying to describe as accurate as possible a wide range of probable situations: Raymond & Lamarche (2013) have developed a model for layered surfaces, Li & Lai (2013) have worked on models to describe short-time responses of BHE and, in addition, Marcotte & Pasquier (2008) have executed 3D models based on "p-linear" average which fits accurately the average temperature computed by numerical models.

More information about numerical models can be found in the studies developed by Gehlin (2002), Witte, Gelder & Spitler (2002), Eskilson (1987), Bennet, Claesson & Hellström (1987), Wang et al. (2010), etc.

2.2.9. **Future of BHE and BTES**

The world of the renewable energies is getting more important since they might have the potential to become the substitutes to the fossil fuels and the nuclear energy. The geothermal energy and concretely the shallow geothermal or thermogeology have much to say in this world since the latter one is directly linked to the solar energy:

a) BTES have a great potential related to solar thermal energy (Cauret & Kummert 2011).
b) Energy storage makes more affordable the solar energy use and the deployment of renewable energies. In fact, the constant temperature obtained from the ground is being studied as refrigeration for the PV solar panels in order to improve their performance and so as to inject the heat transferred in the refrigeration in the ground. The possibilities and opportunities this technologies provide are multiple.

Besides, many efforts are being addressed to achieving electricity from low temperature geothermal applications. The tools used for this development are the Organic Rankine Cycle and the ammonia-water-based Kalina Cycle. This systems use fluids with low vaporisation temperatures as secondary fluids that receive the heat by means of a heat exchanger. Once this secondary fluid is volatilised, the stream performs mechanical work in a electricity generating turbine (Banks 2008).

3. Preliminary Study

3.1. Current Status in Denmark

This final dissertation is focused on Denmark since all the data used is gathered in Horsens. This is why a deeper study of the current situation in this Scandinavian country regarding GSHP is considered before going on with the study.

In this preliminary study, an overview in the current Danish framework will be done regarding current status, legislation, social acceptance and physic environment.

3.1.1. BHE Installation Current Status

Denmark aims to become an independent society from fossil fuels. The government is trying to boost the use of Renewable Energies and the reduction in CO_2 emissions in order to achieve a 30% of RE of the total energy in 2020 (Elf 2010).

So as to achieve those objectives, shallow geothermal shows a big potential together with other renewable energies, concretely in areas without district heating (Mahler et al. 2013). However, the deployment of thermogeology is limited in Denmark compared to countries like Sweden or Germany.

Nowadays, according to Ditlefsen et al. (2013) the total number of GSHP in Denmark is around 27 000, with an approximate increase of 5 000 per year, an average COP of around 3 and a total heat production up to 2-3 PJ/year (Mahler et al. 2013). Most of these installations are horizontal closed loops, whereas less than 5 % are BHE, while just a set of ten are open BHE using groundwater. On the other hand, the development seems positive since in 2011 and 2012 more than one hundred of new BHE have been installed per year.

It must be highlighted the installation in Brædstrup. It consist of a district heating plant powered by a combination between solar systems and CHP. The plant owns 48 boreholes of 45 m depth with seasonal storage aims which are insulated using local seashells. This BTES installation takes up 19 000 m^3 which is equivalent to 5 000 m^3 of water heat accumulation capacity (Bach 2012). This means that it has a storage capacity of 275 MWh approximately. The storage system is connected to a heat pump with an expected COP of 3, requiring an electric input of 500 kW in order to deliver 1,5 MW (SDH Solar District Heating 2012).

When it comes to thermal conductivity measurements, universities and companies are involved in different projects for the obtaining of these properties' values, either for soils or other materials.

On the other hand, regarding TRT execution in Denmark, there is not enough public information.

3.1.2. Legislation and Social Acceptance

So as to achieve the mentioned goals, several plans have been made. And regarding shallow geothermal, some specific legislation has been established by the Danish environmental protection act and Municipalities (Haehnlein, Bayer & Blum 2010; Mahler et al. 2013):

- Order on Heat Abstraction and Groundwater Cooling Plants (BEK-1206, 24/11/2006)
- Order on Groundwater Heating (BEK-1203, 20/11/2006)

National and legally compulsory regulations only exist in few countries so far. The existing regulations generally show constraints for minimum distances and temperature limits for groundwater uses. In the case of Denmark, heat extraction and alteration of groundwater due to closed systems are not considered an environmental problem. Nevertheless, a 300 m minimum distance between a GSHP system and a drinking water supply well must be respected but nothing is specified about distances to buildings and other structures (Vangkilde-Pedersen, Ditlefsen & Højberg 2012).

When it comes to social acceptance, in Denmark the most spread energy storage systems are the PTES. And as the study developed by Harris (2011) and called "Thermal Energy Storage in Sweden and Denmark. Potentials for Technology Transfer", it confirms that there is a lack of information about BTES and ATES in Denmark. The reasons supporting the non-development of these technologies in Denmark as much as in Sweden are shown in the mentioned study. Some of those arguments are as follows:

- In BTES, so many variables have to be taken into account to suit local conditions (number of heat exchangers, configurations, depth, heat storage capacity of the ground, grouting, groundwater movement, etc.).
- It is an unfamiliar technology for people and being underground systems, it seems quite difficult for them to understand.
- The taxes and the "Obligation to connect" to District Heating or Gas Heating in some areas of Denmark has not allowed the development of these systems.
- The government has not boost the use of electricity for heating aims, despite the high efficiency of heat pumps.
- The requirement of a permission from the Danish Energy Agency to exploit a geothermal resource.

However, in the future, due to the increasing of electricity generation by renewable resources such as the wind, thermal energy storage and heat pump applications show a great potential since direct electricity storage is quite problematic. Denmark and, in general, the countries that form the Nord Pool (Norway, Finland, Estonia and Northern Germany), where an electricity market has been established exploiting their renewable resources, seem to be potential users of these thermal energy storage technologies. In fact, the use of heat pumps allows the generation of heat from electricity, and heat is far easier to store (Harris 2011).

Anyhow, a support from authorities and stakeholders is expected in order to allow the deployment of shallow geothermal systems, both for extraction and store aims. Related to this topic, some recommendations are given in the last part of the aforementioned article by Harris (2011).

3.1.3. Hydrogeological frame

In order to evaluate the chance of energy extraction or injection from a specific place, information about lithology and hydrogeology is vital. The biggest part of Denmark is formed by a sedimentary basin dominated by shallow marine to deep marine clastic and biogenic sediments, covered by Quaternary deposits of variable thickness (Mahler et al. 2013). The variation in the geological features of the Quaternary deposits is high so a local study is required for an energy extraction project (Vangkilde-Pedersen, Ditlefsen & Højberg 2012). For more information about the Danish geological framework the open source GEUS Jupiter (2012) is available on the internet.

Some useful data for shallow geothermal installations in Denmark are the following ones (Vangkilde-Pedersen, Ditlefsen & Højberg 2012):

- Net Solar insolation: 400 kWh m^{-2} $year^{-1}$.
- Heat flux from earth core: from 0,20 to 0,35 kWh m^{-2} $year^{-1}$.
- Geothermal gradient: from 25 to 30 ºC km^{-1}.
- Seasonal variation of the ground temperature due to change in ambient temperature reaches 15 m depth (Gehlin 2002).

As it has already been said, when it comes to design a GSHP system, they depend on the thermal properties of the sediments surrounding the heat exchangers. However, a very few research has been carried out about Danish soils thermal properties so a big effort is required in this field (Mahler et al. 2013).

Regarding climate, the weather in Denmark is determined by the proximity of the country to the North Sea, the Baltic Sea and to mainland Europe. So, the weather changes are influenced by the season and the dominant wind direction. Besides, comparing to other geographic areas in the same latitude, Denmark has a relatively warm climate. This happens because of the warm North Atlantic Drift originated in the tropical seas off the U.S.A. east coast (Jørgensen & Cappelen 2009).

Checking the data provided by the DMI Danish Meteorological Institute (2012), it could be seen that Denmark has a temperate climate with average temperatures in January and February of 0,0 ºC and average temperatures in August of 15,7 ºC. In addition, there are large seasonal variations in daylight with short days in winter and long days in summer due to the northern location (DMI Danish Meteorological Institute 2012).

3.2. Facility Description

3.2.1. Location of Project Area

The project area is situated in Horsens Kommune, in the Danish region of Midtjylland. Here is where the VIA University College in Horsens is located.

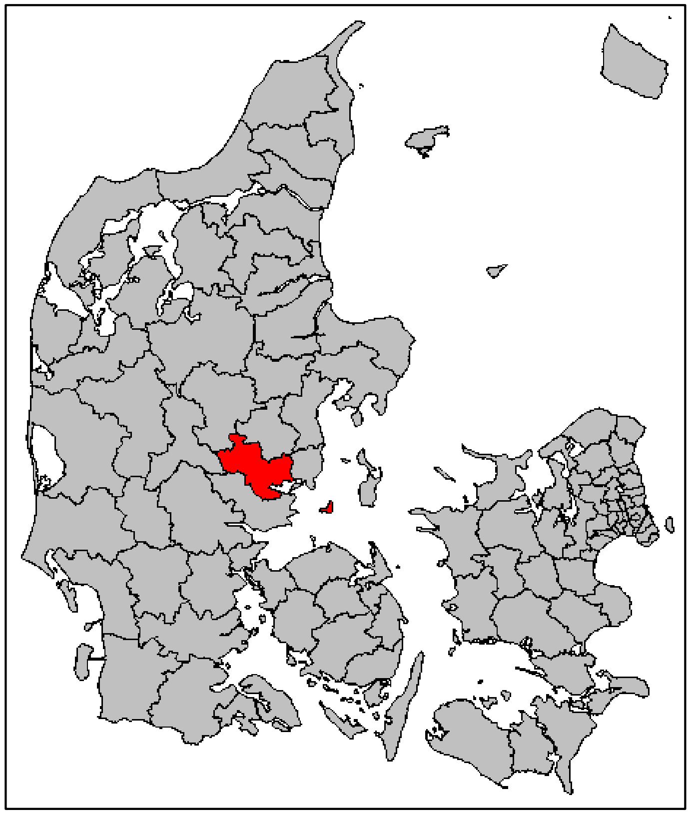

Figure 3.2-1: Location of Horsens in Denmark (Michiel 1972)

3.2.2. VIA Energy Park

The VIA University College hosts several laboratories and in addition, it has built an energy park for investigation aims: VIA Energy Park.

In the VIA Energy Park a research about renewable energies and energy-producing buildings is promoted. Here, many investigation projects are being developed, and this final dissertation forms part of this plan. For more information about this project, in the Appendix 8.2 a short explanatory document is provided.

On the other hand, the laboratories hosted in the Campus possess a wide range of testing equipment. This final dissertation has required the use of equipment from both the Energy Laboratory and the Geo Laboratory. Besides, these tests have been addressed for:

- The checking of the reliability of the owned equipment.
- The study the boreholes executed in the VIA Energy Park.

The project layout and the tests performed have been:

- A priori estimation of the soils thermal conductivities and volumetric heat capacities from the literature.
- Thermal conductivity measurements using the Thermal Needle Probe Procedure.
- Measurement of the undisturbed ground temperature.
- 3 Thermal Response Test execution and analysis.

Despite of the thermal conductivity measurements which have been executed in the VIA Energy Lab, the rest of the tests have been performed on site, i.e., there have been field tests. The description of the equipment used will be developed in the chapters dedicated to each of the tests. However, a description of the installations related to the BHE in VIA Energy Park is considered since they are the core of the investigation:

3.2.3. Description of the Boreholes

Regarding the geology of the campus area where the boreholes are placed, it can be said that it corresponds to the Oligocene and the thickness of the quaternary sediment is estimated between 50-80 m. In the Appendix 8.1 the maps to check the location and the thickness are provided.

When it comes to the facilities involving this final dissertation, the BHE installations must be described:

There are four geothermal boreholes of 100 m depth. The aim of this final dissertation is studying three of those four boreholes in order to obtain the properties of the soil hosting them and check the feasibility of this ground for heat extraction or energy storing goals. Of course, the pipes in the boreholes will be connected to a heat pump placed in the house built, where in future researches the performance of the systems will be checked. The heat pump is not installed yet.

The maps provided in Appendix 8.3 show the location of each borehole and their numeration in GEUS Jupiter (2012).

In order to check the profiles of each of the boreholes provided in GEUS Jupiter (2012) the reader can address to Appendix 8.3.

The three studied boreholes have been performed with the same drilling system and they have a separation distance of around 10 m between them. However, each of them has a different pipe configuration. The VIA 13 borehole has a Double U configuration system, while the VIA 14 has a Single U and the VIA 15 has a Coaxial pipe.

It must be said that following the Designers Manual proposed by Geotrainet (2011a), before executing a BHE, a Site Investigation must be performed in order to be aware of the feasibility of the project. This preparation consists of three main parts:

- Desk study
- Legal and regulatory issues study
- Site Investigation

The point is that the author of this final dissertation has started the research with the boreholes already executed. So if it is wanted to follow the procedure proposed, this means that the research starts in the Site Investigation part, where theoretically a pilot borehole should be executed in order to be able to perform two type of tests:

- Hydraulic testing. Required for open loop testing.
- Thermal Response Test. Required for closed loop testing.

This second point is the starting point of the investigation. In fact, the laboratory measurements of the thermal conductivity is a way to compare the results of the TRT, since the thermal conductivity of the ground is one of the results of the TRT.

However, due to the impossibility access to samples of each of the layers and each of the boreholes and due to the small distance between the boreholes (10 m approximately), the geology is assumed to be the same in the whole area. In Appendix 8.3 a scheme of the reproduced stratigraphic column is given.

At this point a sum table is provided in order to show the most important characteristics of each of the boreholes object of study:

<table>
<tr><th>BOREHOLE-NUMBER</th><td>107,1605</td><td>108,1606</td><td colspan="2">107,1607</td></tr>
<tr><th>BOREHOLE-NAME</th><td>VIA 13</td><td>VIA 14</td><td colspan="2">VIA 15</td></tr>
<tr><th>COTE-LEVEL</th><td>16,93</td><td>17,27</td><td colspan="2">17,17</td></tr>
<tr><th>DEPTH (m)</th><td>96</td><td>100</td><td colspan="2">102,5</td></tr>
<tr><th>DIAMETER (m)</th><td>0,16</td><td>0,16</td><td colspan="2">0,16</td></tr>
<tr><th>PIPE TYPE</th><td>DOUBLE U</td><td>SINGLE U</td><td colspan="2">COAXIAL</td></tr>
<tr><th>DRILLING METHOD</th><td>Rinse Drilling</td><td>Rinse Drilling</td><td colspan="2">Rinse Drilling</td></tr>
<tr><th>WATER LEVEL</th><td>15,35</td><td>15,35</td><td colspan="2">15,35</td></tr>
<tr><th>LITHOLOGY</th><td>Almost everything Sand, Glacial Layer.</td><td>Almost everything Sand, Glacial Layer.</td><td colspan="2">Almost everything Sand, Glacial Layer.</td></tr>
<tr><th>GROUTING MATERIAL</th><td>Dantonit</td><td>Dantonit</td><td colspan="2">Dantonit</td></tr>
<tr><th>PIPE MATERIAL</th><td>PE Polyethylene</td><td>PE Polyethylene</td><td colspan="2">PE Polyethylene</td></tr>
<tr><th rowspan="2">PIPE DIAMETER (m)</th><td rowspan="2">0,032</td><td rowspan="2">0,040</td><th>Outer pipe</th><th>Inner pipe</th></tr>
<tr><td>0,040</td><td>0,020</td></tr>
<tr><th>SHANK DISTANCE (cm)</th><td>11</td><td>11</td><td colspan="2">-</td></tr>
</table>

Table 3.2-1: Summary of existing borehole characteristics.

From now on, each of the performed tests will be developed in the Experimental Section.

4. Experimental Section

One of the aims of this MSc Final Dissertation is to check the reliability of the systems owned in VIA University College in order to determine the ground's thermal properties, concretely, the thermal conductivity and the borehole resistances.

The calculation of those two parameters are a great challenge when it comes to optimize the design of GSHP Systems. The BHE performance is very dependent on the ground thermal properties (Witte, Gelder & Spitler 2002) and in order to be able to predict those characteristics, different tools are available. In order to estimate the thermal properties of the ground there are available values from literature, laboratory experiment execution and in situ tests.

In this chapter three ways to calculate the thermal conductivity are developed and compared: a priori estimation of the soil thermal conductivity with values from the literature, thermal conductivity measurements using the Thermal Needle Probe Procedure in laboratory and 5 in situ TRTs.

In fact, a discussion of an extensive test including long time scale experimental data/in situ measurements will be executed, together with independent measurements of thermal conductivity, detailed geological descriptions and temperature measurements.

Hereunder, each methodology will be described independently, explaining the theoretical background, the used equipment, the way of procedure and the results. Later, in chapter 5, those results will be put together, analysed and compared.

4.1. A Priori Estimation of the Soil Thermal Conductivity

A priori estimation of the soils thermal conductivities and volumetric heat capacities from the literature is provided in this chapter. Indeed, this is a traditional estimation based on a complete geological description.

4.1.1. Background and Analysis Method

This method entails the least effort. However, the range of the values is so large since the local conditions have a great influence, that the accuracy of this method is highly altered (Witte, Gelder & Spitler 2002).

4.1.2. Experimental Setup

The geological description has been obtained from Geus Jupiter GEUS Jupiter (2012) and from the data available in the Geo Laboratory of VIA University College, since the boreholes are located in the domains of the cited university.

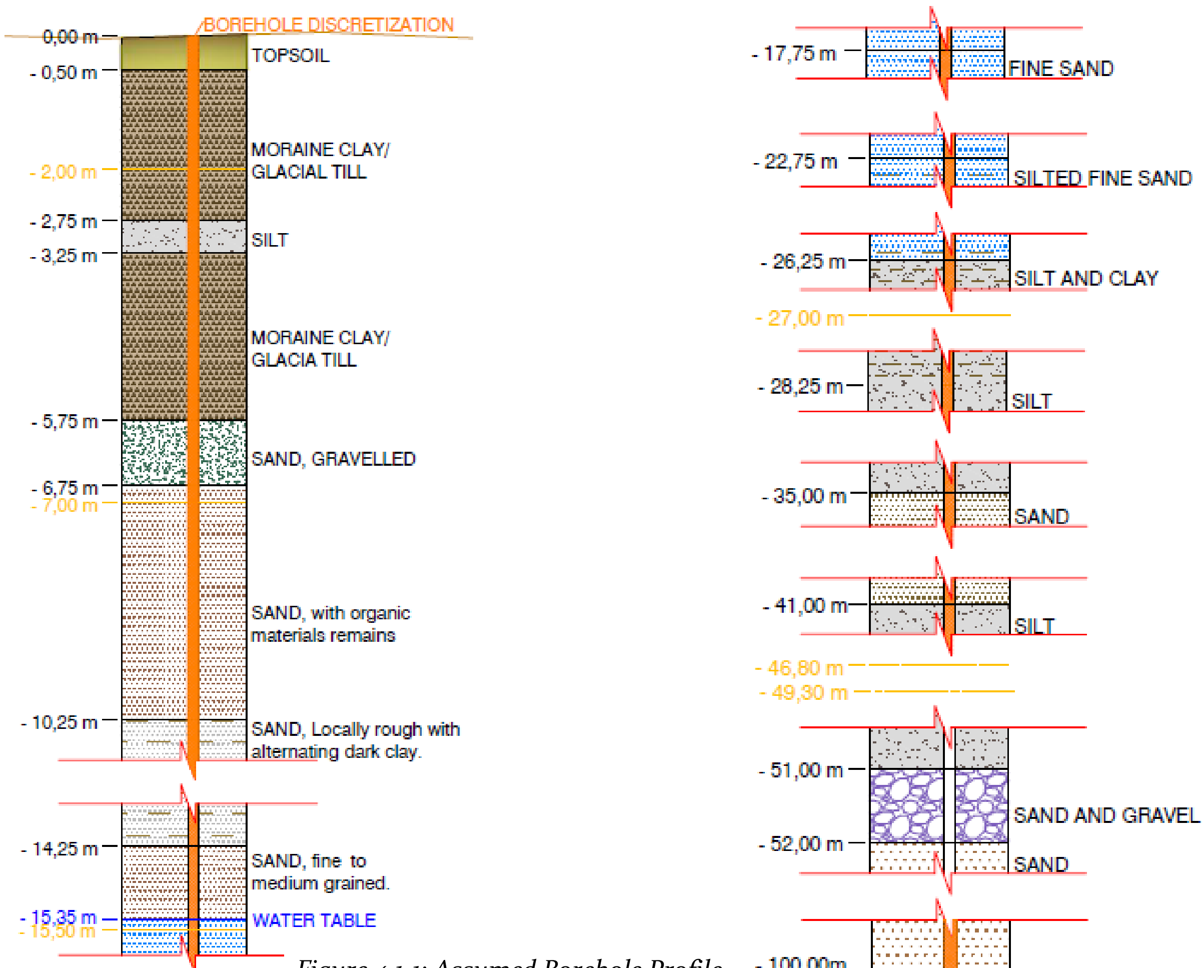

Figure 4.1-1: Assumed Borehole Profile for the three boreholes studied.

The profiles taken as reference in order to assemble the provided profile are shown in Appendix 8.3.

Due to the high alteration grade of the topsoil in the first half meter, and due to the lack of information, that part has been neglected for the calculations.

4.1.3. TC Calculations

The stratigraphic column has already been given. To see it together with the thermal conductivity and volumetric heat capacity values taken from the tables available in the texts by Banks (2008) and VDI (2010), address to Appendix 8.3 (point 8.3.2).

Once all the λ and S_{vc} values for each of the layers are known, the method followed by Banks (2008) to obtain an average value for non-uniform geology depending on the thickness of each of the layer is applied. This Thermogeological Anysotropy can be overcome calculating the horizontal thermal transmissivity of the depth of the borehole along the 100 m. The transmissivity of this 100 m thick borehole can be found by summing the product of the λ and the thickness for each layer:

(4.1.3.1)

$$T_{the} = \sum_{n=1}^{100} \lambda \cdot D$$

Being λ the thermal conductivity for the material in each layer, and D the thickness in meters for each layer.

The bulk horizontal thermal conductivity λ_{bh} is calculated dividing T_{the} by the total thickness of the borehole (100 m).

It can be concluded that it is the thickness-weighted arithmetic mean of all the layers. This is why the same procedure has been followed in order to obtain the Volumetric Heat Capacity.

4.1.4. Results and Interpretation

Below, a summary table is provided with the aforementioned calculations together with the results:

Depth (m)	Layer Thickness (m)	Material	Thermal Conductivity ʎ (Wm⁻¹K⁻¹)	Volumetric Heat Capacity S_{vc} (MJ m⁻³K⁻¹)	Horizontal Thermal Transmissivity per layer (W K⁻¹)	Layer Thickness (m) * Volumetric Heat Capacity Svc (MJ m⁻³K⁻¹)
0,00	-	-	-	-	-	-
0,50	0,50	Topsoil	-	-	-	-
2,75	2,25	Moraine Clay	1,6	2,4	3,60	5,40
3,25	0,50	Silt	1,7	2,3	0,85	1,15
5,75	2,50	Moraine Clay	1,6	2,4	4,00	6,00
6,75	1,00	Gravelled Sand	2,3	2,0	2,30	2,00
10,25	3,50	Sand, with organic material remains	2,3	2,1	8,05	7,35
14,25	4,00	Sand, locally rough	2,0	2,0	8,00	8,00
17,75	3,50	Sand, fine to medium grained	2,3	2,1	8,05	7,35
22,75	5,00	Fine Sand	2,3	2,1	11,50	10,50
26,25	3,50	Silted Fine Sand	2,5	2,1	8,75	7,35
28,25	2,00	Silt and Clay	1,6	2,4	3,20	4,80
35,00	6,75	Silt	1,7	2,3	11,48	15,53
41,00	6,00	Sand	2,3	2,1	13,80	12,60
51,00	10,00	Silt	1,7	2,3	17,00	23,00
52,00	1,00	Sand and Gravel	2,3	2,1	2,30	2,10
100,00	48,00	Sand	2,3	2,1	110,40	100,80
Total Horizontal Thermal Transmissivity T_{the} (WK⁻¹)					213,28	-
Bulk horizontal TC $ʎ_{bh}$ (Wm⁻¹K⁻¹)					**2,1435**	-
Total Volumetric Heat Capacity (MJ m⁻³K⁻¹)					-	**2,15**

Table 4.1-1: Summary of the stratigraphic column with the corresponding thermal conductivity and volumetric heat capacity values per each layer assumed from literature.

As in the tables used as data source some values are given as an interval, a mean value has been taken.

This way, the average λ of the ground surrounding the borehole is predicted as 2,14 W m^{-1} K^{-1} while the S_{vc} is 2,15 MJ m^{-3} K^{-1}.

It is not considered a good estimation, due to the lack of geological information about the layers constituting the last 50 m. The contemplation of sand as the main soil type in this section can lead into an overestimation of the result obtained since thermal conductivity of saturated sand is higher than the one of the silt and clay. This means that this result cannot be very trustworthy when it comes to the design of a GSHP system.

Nevertheless, it has been followed the information provided by the profiles in GEUS Jupiter (2012), and as there is established, the last 50 meters are considered sand.

4.1.5. Conclusions and Recommendations

This way of proceed is simple and fast, but as it has already been said, it does not take into account the local conditions.

It is a useful methodology to follow in order to know the range of values a project is going to deal with. But it is not a very reliable result. It must be used as a guide.

In order to be able to do a more acceptable approach by means of literature, a data base of Danish characteristic soil properties should be used. Even so, it would not be an accurate approach.

4.2. Thermal Conductivity Measurements

4.2.1. Background and Analysis Method

A more accurate alternative to the previous method is the measurements in the laboratory of the samples obtained from extraction of the borehole core. The methodology used in this chapter consists of the thermal conductivity measurements using the Thermal Needle Probe Procedure.

Nevertheless, in this method only individual samples are analysed and it is impossible studying the soil around the borehole as a whole. The values need to be translated as a representative values for the whole profile.

A manual for good practices for the use of the equipment available in the Energy Lab can be found in the corresponding Appendix 8.10. As well as a more detailed explanation about the probes and the needles used.

Once many measurements are gathered, the same way of procedure as in the first methodology will be used calculating the transmissivity for the 100 m depth borehole by summing the product of the thermal conductivities and the thickness for each layer.

The Thermal Needle Probe Method is based on the Line Source Heat LSH theory. This theory has two main approaches: the analytical solution and the ideal model (Kumar, Raja & Karhikeyan 2010). The first one takes into consideration the geometry of the probe, the different thermal properties of the probe and the medium and the contact resistance between them. On the other hand, the ideal model does not consider the thermal properties of the probe, neither the contact resistance (Hukseflux Thermal Sensors 2013b; Kumar, Raja & Karhikeyan 2010).

Beginning from the consideration of a LSH in an infinite homogeneous medium initially maintained at a uniform temperature, the corresponding equation is Equation (4.2.1.1). Starting from time $t \rightarrow 0$, the heat is dissipated by this source at a rate q per unit source length. A rise in temperature T at a distance of r from the LSH is described as a function of time as:

(4.2.1.1)

$$T\ (r, t) = \frac{-q}{4\pi\lambda} E\ i\ \left(\frac{-\ r^2}{4\alpha t}\right)$$

Where *Ei* indicates an exponential integral and which being approximated by series expansion and neglecting terms of high order, the next expression could be reached:

(4.2.1.2)

$$T = \frac{q}{4\pi\lambda}\left[\ln t + \ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right]$$

Being γ Euler's constant (0,5772) and α the thermal diffusivity of the medium.

So, for both models, the next equation is valid in a non-steady state:

(4.2.1.3)

$$\Delta T = \left(\frac{q}{4\pi\lambda}\right)(\ln t + B)$$

What happens is that for the long time solution for both models, both of them lead to the same result for the thermal conductivity λ. The only difference is that for the analytical model the value of the constant B is higher due to the contact resistance. However, the time is not long enough to produce a steady-state situation.

It could be deduced that B cancels from the previous equation since the effects of the probe and the thermal properties and the contact resistance are no longer visible sometime after the heating has started. In fact, for fixed values of λ and α , temperature T increases logarithmically with time. Plotting the temperature increase versus the logarithm, time gives a straight line along a section whose slope is inversely proportional to the λ:

(4.2.1.4)

$$slope = \frac{q}{4\pi\lambda}$$

So, this method is based on LHS and is the basis of the methodology chosen for the evaluation of the TRT as well. At any point in the medium, the temperature rise T_1 at time t_1 is linked to the temperature rise in T_2 at time t_2:

(4.2.1.5)

$$\lambda = \left(\frac{q}{4\pi\Delta T}\right) \cdot ln\left(\frac{t_2}{t_1}\right)$$

4.2.2. Experimental Setup

From the soil profile, six samples were taken and analysed by the author by means of the equipment from Hukseflux Thermal Sensors (2013a). The measurements have been carried out 5 or 6 times and the overall inaccuracy at 20ºC was determined to be less than ± (3% + 0,02) W m^{-1} K^{-1}. The results are presented in Table 4.2-2.

The setup is shown in Figure 4.2-1 and it consists of the next main parts:

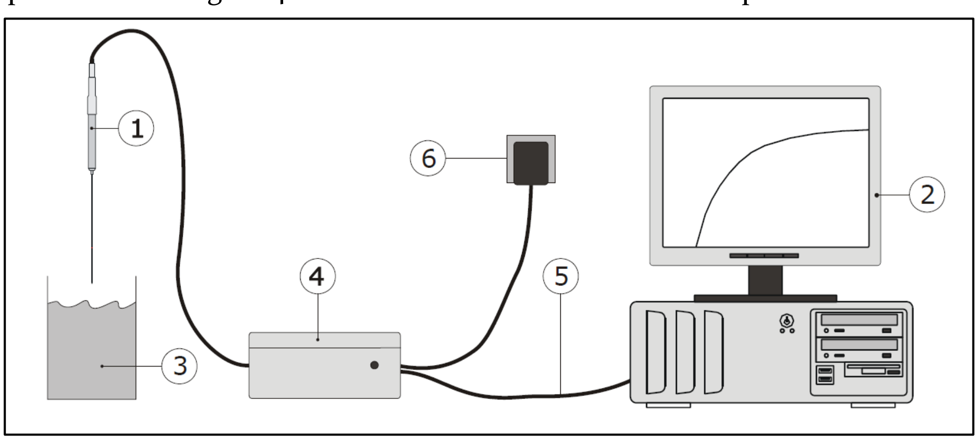

Figure 4.2-1: Setup scheme for Hukseflux system TPSYS02 (Hukseflux Thermal Sensors 2013b)

(1) Thermal probe or needle: TP02 (long needle)
(2) Computer
(3) Soil Test Sample Container
(4) CR 1000 Measurement and Control Unit (MCU)
(5) PC cables / USB port
(6) Adaptor cable connected to the electrical contact (DC Power Supply)
(-) The samples are saved in a climatic chamber Termaks Cooling Incubator KB8400 in order to execute the measurements at 20ºC

This equipment is in conformity with the following standards:

- ASTM ASTM D 5334 – 08
- ASTM D 5930 – 97
- IEEE Std 442-1981

Sample Preparation

The samples are saved in cylindrical plastic made recipients with plastic lids for top and bottom, 20 cm height and with a diameter of 8 cm. The needle or thermal probe with the thermal sensors is inserted directly into the middle of the sample or in a guiding tube previously placed if the sample is too hard.

In order to temper the samples, they are placed inside of a climatic chamber that maintains the ambient temperature in 20ºC in order to have a higher accuracy in the measurement according to the instructions of the manufacturer (Hukseflux Thermal Sensors 2013b).

Power Supply and Temperature Measuring Unit

The heating source is a 12V DC output voltage power source. The input voltage goes from 100 to 240 V AC. The supplied power can be adapted to the requirements. Two thermocouple junctions, a hot one at 1/3 of the needle length and a cold one at the tip, are placed in the needle. The temperature difference is measured between this two points as a result of the voltage output provoked in the heating wire which runs across 2/3 of the needle length.

In order to record the continuous changes in temperature along time the PC software LoggerNet is used as a data logger. Later, the measured results are imported into a specific excel file so as to analyse them and check the reliability of the measurement.

More information about the system could be find in the manuals of the product (Hukseflux Thermal Sensors 2013b).

Probe Specifications and Working of Thermal Probe

The probe/needle has been calibrated just before the execution of this research so it is assumed the correct performance of the system. In addition, the Hukseflux needles are supposed to be resistant to water and they are able to handle measurement repetitions.

The thermal probe used is the TP02, a 150 mm length and 1 mm thick stainless needle with an accuracy at 20ºC of ± (3% + 0,02) W m^{-1} K^{-1}.

Looking at equation (4.2.1.5) it can be deduced that the plotting of the temperature versus time give a straight line with the mentioned slope in equation (4.2.1.4) where q can be known and λ can be calculated. Actually, the graph will not show a straight line in all the length. But if the errors linked to short and long term testing times are neglected, the slope of the straight section of the plot can be used to determine λ (Kumar, Raja & Karhikeyan 2010).

Software Interfacing and Measurement Procedure

So as to connect the needle with the LoggerNet software in the computer, the CR 1000 Measurement Control Unit is used which can be connected to the computer by a USB port. At the same time this box is connected to the grid and to the thermocouples. The given outputs are: the temperature in ºC, the heating period in seconds, the voltage and the thermal conductivity in W m^{-1} K^{-1} together with the standard deviation.

The steps followed for each of the measurements are: i) Tempering of samples in the climatic chamber for 24 hours; ii) Turning on the equipment; iii) Inserting the needle in the sample; iv) Setting the required parameters; v) Executing the measurements one after another (100 s or 150 s heating periods); vi) Noting the results and the remarks and saving them; vii) Turning off the system and cleaning it; viii) Importing the results into the specific excel file; ix) Analysing the results and the plots, selecting the linear part in each graph. x) Checking the accuracy of the measurements.

4.2.3. **TC Calculations**

The output from LoggerNet is directly a value for λ. However, a checking of the value in the excel file is required in order to check that the obtained result corresponds to the straight part of the plot as it is shown in Figure 4.2-2. The first value has to be taken as an approximation. The accurate λ value is the one from the visual inspection of the data measured in the excel file.

The studied graphs in the excel file show the data gathered during the measurement as $4\pi\Delta T/Q$ versus logarithmic time. This way, λ is inversely proportional to the slope of the straight section of the graph. The visual analysis of the logarithmic time is required in order to ensure the results.

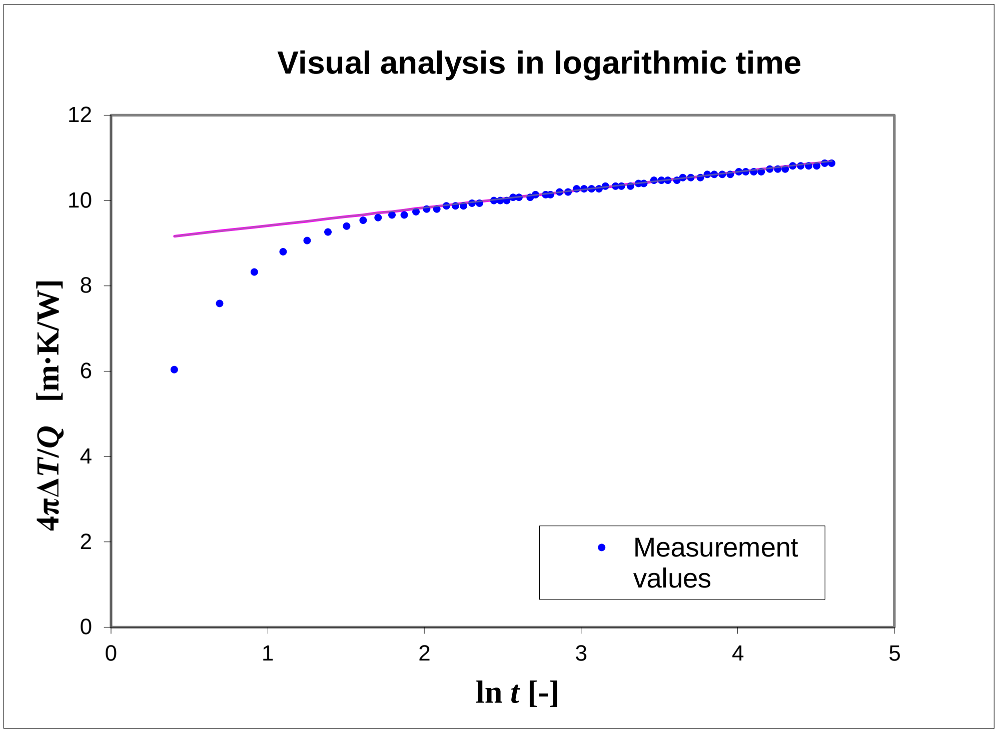

Figure 4.2-2: A typical plotting for 4πΔT/Q vs time.

In order to have more information about the procedure to execute the measurements, address to the Appendix 8.10 where the manual for good practices is provided.

Assumptions

It has been assumed that the equipment works properly since it has been calibrated just before the research was started. And regarding the uncertainty of the measurements, as they have been performed at 20 ºC, are supposed to be accurate enough to rely on them.

Although the ASTM D 5334 – 08 standard recommends the use of a calibration factor, it has been decided to follow the procedure established by the manufacturer, were its use is not considered.

As the samples have been modified, altered, they are not analysed in the initial conditions since some of them were very old. That is why have been studied in saturated way.

For the calculation of the total thermal conductivity the combination with the literature values has been considered, also for volumetric heat capacity values because of the author's impossibility to have access to samples in each layer. Just 6 samples from different depths have been studied. So the result is not as accurate as it should be and the need to rely on literature values has been compulsory.

Reliability Tests

Some test have been performed so as to measure well known materials in order to check the reliability and the good performance of the system. For that, the glycol has been used. Glycol has a known thermal conductivity of 0,29 W m^{-1} K^{-1} at 20ºC. The allowed deviation with the literature value with this equipment is twice the accuracy according to the manufacturer, e.g., ± (6% + 0,04) W m^{-1} K^{-1}.

All the values are between the allowed interval which it has been calculated with the allowed deviation recommended by the manufacturer (Table 4.2-1).

Test No.	Exp_ Id	λ Measurement (W/m*K)	λ Measurement after analysis in Excel (W/m*K)	Standard Deviation Measurement after analysis in Excel (W/m*K)	Average λ value (W/m*K)	Standard Deviation of Average Value (W/m*K)	Error (%) = (measured λ - known λ)/known λ	Allowed Deviation (+/-) (6%+0,04) (W/m*K)	Allowed interval (min λ, max λ)	
1	84	0,25	0,2597	0,0006			-10,45			
2	89	0,25	0,2600	0,0007			-13,79			
3	94	0,25	0,2575	0,0006			-13,79			
4	108	0,25	0,2607	0,0008			-13,79			
5	153	0,25	0,2607	0,0007	0,2602	0,0012	-13,79	0,057	0,23	0,35
6	160	0,25	0,2598	0,0007			-13,79			
7	172	0,26	0,2608	0,0005			-10,34			
8	187	0,26	0,2609	0,0004			-10,34			
9	204	0,26	0,2618	0,0004			-10,34			

Table 4.2-1: Reliability test with Glycol, taking as known value λ = 0,29 W m-1 K-1.

Making the error analysis (Appendix 8.6) of these 9 measurements, the thermal conductivity values of the glycol in the laboratory at 20ºC could be given as:

$$\lambda = 0{,}2602 \text{ W m}^{-1} \text{ K}^{-1}$$

Which is expected in the interval. Besides, although the errors according the known value seem to be high, it must be due to the alteration of the substance because of the long time spent in the chamber or due to the difference in the glycol type.

4.2.4. Results and Interpretation

Thermal Conductivity Measurement of the Samples

The Thermal Conductivity of 6 different soil samples from different depths were measured 5 or 6 times each at 20ºC. The results are presented in Table 4.2-2. The studied depths were the shown ones since they were the ones available in the deposit of VIA University College.

The measurement conditions were the same in all of the samples: saturated and compacted. There was not the possibility to execute the measurements in real conditions since some of the samples were too old.

The samples from depth 7 m was too hard so a guiding tube was used in order to execute the measurements. Therefore, the heating period was increased 50%, e.g., from 100 s to 150 s.

The description of the samples is shortly given in the Table 4.2-2 and more information about them is provided in Appendix 8.4.

DEPTH (m)	SAMPLE	TEXTURE	SOIL CONDITION	Mean Value for λ of 5/6 Measurements (W/m*K)	Standard Deviation of Mean Values
2	VIA 10	Moraine Clay	Saturated + Compacted	1,5426	0,1761
7	VIA 10	Sand with flint and other hard rocks	Saturated + Compacted GT (300s)	2,3640	0,3068
15,5	VIA 9	Sand, fine to medium grained	Saturated + Compacted	2,3450	0,1327
27	VIA 10	Silt and Clay	Saturated + Compacted	1,7415	0,1495
46,8	VIA NR 41	Silt and Clay	Saturated + Compacted	1,3149	0,0606
49,3	VIA NR 44	Silt and Clay	Saturated + Compacted	1,1019	0,0464

*GT: Guiding tube used. 300 s is the length of the measurement.

Table 4.2-2: Mean values for thermal conductivity measurements for the six samples at different depths.

As it could be seen in Table 4.2-2 the conductivity values ranging between 1,1019W m^{-1} K^{-1} and 2,3640 W m^{-1} K^{-1}. Minimum for a formation of silt and clay and maximum for a sand formation. The error in the measurement is expected to be less than $\pm$ (3% + 0,02) W m^{-1} K^{-1} following the instruction of the manufacturer. The implications regarding errors and information about measurements are in Appendix 8.10.

Besides, it can be checked that the thermal conductivity values are lower for clays than for sands. This is in accordance to the literature.

Once the Thermal Conductivity values are available for the given depths, the transmissivity can be calculated.

As it has been said before, it has been considered the need of combining the measurements with the literature values for the layers where there was not a sample available. Having just 6 samples has not been considered enough in order to translate a total value for the whole depth of the borehole.

This is why another table, as in the first methodology, is provided (Table 4.2-3), but instead of being all the values of the thermal conductivity from the literature, six of them have been measured in the laboratory. However, the problem comes when calculating the volumetric heat capacity. In the facilities of VIA University College there is not equipment for the measurement of the volumetric heat capacity. So, the values for the heat capacity are the ones from the literature.

Depth (m)	**Layer Thickness (m)**	**Material**	**Thermal Conductivity ʎ ($Wm^{-1}K^{-1}$)**	**Volumetric Heat Capacity S_{vc} (MJ $m^{-3}K^{-1}$)**	**Horizontal Thermal Transmissivity per layer (W K^{-1})**	**Layer Thickness (m) * Volumetric Heat Capacity Svc (MJ $m^{-3}K^{-1}$)**
0,00	-	-	-	-	-	-
0,50	0,50	Topsoil	-	-	-	-
2,75	2,25	Moraine Clay	1,54	2,4	3,47	5,40
3,25	0,50	Silt	1,70	2,3	0,85	1,15
5,75	2,50	Moraine Clay	1,60	2,4	4,00	6,00
6,75	1,00	Gravelled Sand	2,30	2,0	2,30	2,00
10,25	3,50	Sand with flint and other hard rocks	2,36	2,1	8,27	7,35
14,25	4,00	Sand, locally rough	2,00	2,0	8,00	8,00
17,75	3,50	Sand, fine to medium grained	2,35	2,1	8,21	7,35
22,75	5,00	Fine Sand	2,30	2,1	11,50	10,50
26,25	3,50	Silted Fine Sand	2,50	2,1	8,75	7,35
28,25	2,00	Silt and Clay	1,74	2,4	3,48	4,80
35,00	6,75	Silt	1,70	2,3	11,48	15,53
41,00	6,00	Sand	2,30	2,1	13,80	12,60
47,00	6,00	Silt and Clay	1,31	2,4	7,89	14,40
51,00	4,00	Silt and Clay	1,10	2,4	4,41	9,60
52,00	1,00	Sand and Gravel	2,30	2,1	2,30	2,10
100,00	48,00	Sand	2,30	2,1	110,40	100,80
Total Horizontal Thermal Transmissivity T_{the} (WK-1)					209,11	-
Bulk horizontal TC $ʎ_{bh}$ ($Wm^{-1}K^{-1}$)					**2,1016**	-
Total Volumetric Heat Capacity (MJ $m^{-3}K^{-1}$)					-	**2,16**

Table 4.2-3: Summary of the stratigraphic column with the corresponding thermal conductivity measurements and volumetric heat capacity values per each layer. The λ values from the depths where there were not available samples have been assumed from literature.

Validation of Analysis

Regarding standard deviation values, it can be seen that the highest values are the ones corresponding to the measurements in depth 7 m when using guiding tubes. However, all the deviations have been considered acceptable.

Nevertheless, the values are not very stable, so it could be due to the sample execution which seems it requires to be improved in order to obtain better and more stable conditions for the measurements and this way make easier the obtaining of more similar values. This stability is more tangible in concrete samples. Which due to their compactness provide very constant values in all the measurements (Marcos, 2013).

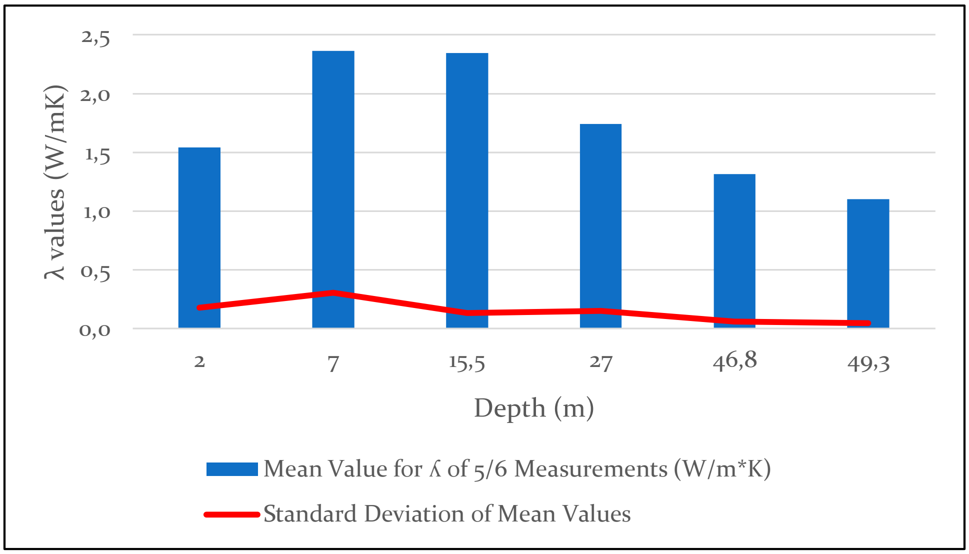

Figure 4.2-3: Graph sowing the different values for the thermal conductivities along the borehole depth and their standar deviations.

It has been considered the reliability of the results measured in the laboratory. Even though some errors seem to be too high, it has been asked the manufacturers and it has been considered that the results are correct and trustworthy.

Regarding the bulk thermal conductivity calculated (2,1016 W m^{-1} K^{-1}), seems to be acceptable but not completely reliable. As it has been possible the measurement of a 49 m depth sample, it has been checked in that profundity seems to be a thicker layer of silt and clay. However, the information given by GEUS Jupiter (2012) has been respected.

4.2.5. **Conclusions and Recommendations**

After executing the measurements, some problems and disadvantages have been found by the author in this methodology and in the proceeding way:

- Only individual and small samples are studied.
- The results have to be translated to a representative value for the entire profile.

- As small samples are studied comparing to the real scale, the non-homogeneities are not taken into account.
- The samples are modified, altered, are not analysed in the initial conditions since some of them were very old.
- The way of storing the samples also alter the results.
- This methodology does not bear in mind any influence of ground water flow on the thermal properties of the soil. So, the result cannot be considered as effective thermal conductivity.
- The author did not have access to samples in each layer. Just 6 samples from different depths have been studied. So the result is not as accurate as it should be and the need to rely on literature values has been compulsory, being completely aware that some information from the sources are not correct or are missing.

Regarding the time taken by this process, the good execution of the measurement for the six samples has taken more than one working week considering their preparation and the tempering time in the chamber. Of course, once everything was ready, the dedication to the measurements was between 1 and 2 hours per day. As five measurements were taken and having established a one day period for the repeatability of the test (Appendix 8.10), five more days have been necessary, what makes a total of at least seven days.

Considering that the equipment was used also by other researches, and that the author was not an expert in the field, the time required was higher.

On the other hand, the methodology seems reliable, simple and fast to execute and analyse once good conditions for measurements are reached. Of course, in perfect conditions (they are explained in Appendix 8.10) the accuracy will be higher, but the measurements have been executed trying to reach them.

4.3. Thermal Response Tests TRT

4.3.1. Background and Analysis Method

In VIA University College a machine to execute the TRT has been produced so as to impose a heat injection pulse into a BHE and be able to measure its temperature response in situ. The analysis of 3 detailed in situ tests in three different 100 m depth boreholes using Kelvin's Line Source approach is shown in this chapter.

There have been performed five tests in total, two tests with the previous equipment which has been improved (Tests 1 and 2) and three more with the new flow meter and temperature logger (Tests 3, 4 and 5). The latter ones are the ones that will be studied in this final dissertation since are the ones performed by the author.

The need to change those devices came from their breakdown. The next table shows a summary of the performed tests:

Test Number	Borehole Type	Date	Duration (h)	Used Equipment
1	Single U	08/04/2013	65,5	Old
2	Coaxial	16/04/2013	47,25	Old
3	Single U	03/07/2013	51,25	New
4	Double U	07/07/2013	52,25	New
5	Coaxial	30/07/013	64,25	New

Table 4.3-1: Summary table for TRTs

The test apparatus is sufficiently mobile and can be operated without supervision while the test is running.

The TRT delivers an integrated value of thermal conductivity over the length of the borehole as well as the borehole resistance R_b. So the soil around the borehole is studied as a whole. The result will be, then, an effective thermal conductivity.

While testing, the temperature difference between the inlet and outlet flows, as well as the flow rate are kept constant, allowing energy fluxes between 20 and 30 W/m. Besides, inlet, outlet, ambient and heater temperatures, apart from the heater consumption and low rate are monitored along time.

A manual for good practices for the use of the equipment available in the Geo Lab can be found in the corresponding Appendix 8.11, as well as a more detailed explanation about the problems in order to execute a good test and graphic documentation.

Even if several models are available in order to achieve soil thermal properties and evaluate the measured data of the TRT, the most widely used is the LSH model, apart from being the simplest one to perform. So, it will be the one used in this study. From now on, the basis of the theoretical background will be given:

Beginning from the consideration of a line source of heat in an infinite homogeneous medium with constant thermal properties and an initial ground temperature, the temperature variation around the line source in space and time can be described as (Banks 2008):

(4.3.1.1)

$$T\ (r,t) = T_0 + \left(\frac{-q}{4\pi\lambda} E\ i\ \left(\frac{-{r_b}^2}{4\alpha t}\right)\right)$$

Where T_o indicates the initial undisturbed ground temperature and r_b the borehole radius. It is being assumed that the grouting material around the borehole pipes is infinitely conductive (Banks 2008).

Minimum and maximum duration criteria in order to get the optimum conditions and where steady state situation can be checked in longer time to t_s is required. This demonstrations can be found in the explanations by Banks (2008) and Gehlin (2002):

(4.3.1.2)

$$\frac{5r_b^2 S_{VC}}{\lambda} < t < \frac{t_s}{10}$$

Where t_s is the break time for steady state situation.

For this time interval, it can be ensured a simplification of the previous equation (4.3.1.1) as provided in equation (4.3.1.3). So now, the formulation for a line source of length z, the average BHE temperature T_f in a borehole with a radius of r_b provoked by a specific radial heat flow rate q and considering the effect of the borehole thermal resistance R_b between the circulating fluid and the BHE wall is:

(4.3.1.3)

$$T_f\ (r = r_b, t) + qR_b = \frac{q}{4\pi\lambda}\ln(t) + \left\{qR_b + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha}{{r_b}^2}\right) - \gamma\right]\right\} + T_0$$

Where T_f corresponds to the average of inlet and outlet temperatures of the carrier fluid:

(4.3.1.4)

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

From equation (4.3.1.3) it can be deduced that:

(4.3.1.5)

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

Being k the slope of the function along the horizontal axis as logarithm of time t. Hence, the soil thermal conductivity can be derived from the slope k of the linear relation, the same way as in the thermal Needle Probe Method:

(4.3.1.6)

$$\lambda = \frac{q}{4\pi} \cdot \frac{\ln(t_2)-\ln(t_1)}{T(t_2)-T(t_1)} = \frac{q}{4 \cdot \pi \cdot k}$$

Once the thermal conductivity has been estimated, the R_b can be calculated along the time using the next equation:

(4.3.1.7)

$$Rb = \frac{T_f\,(t) - T_0}{q} - \frac{1}{4\pi\lambda} \cdot \left[ln\left(\frac{4\lambda t}{r_b^2 S_{VC}}\right) - 0{,}5772 \right]$$

However, some restrictions characterize the LSH theory, which will be later analysed. But the principal one is that the process requires an initial estimation of volumetric heat capacity.

4.3.2. **Process Summary**

The three TRTs carried out in this final dissertation have follow the same process: i) measurement of the undisturbed ground temperature before the heat injection, ii) injection of a constant heat power (kW) during at least 48 hours, iii) observation of the recovery of the ground allowing the water circulation without heating.

For the estimation of the results, just the data logged in phases i) and ii) have been taken into consideration for the determination of the soil thermal properties, leaving the data of the recovery tests for future analysis.

4.3.3. **Undisturbed Ground Temperature Measurement**

As previous steps for the TRT, some parameters of the ground are required. These are the measurements of the groundwater level and the undisturbed ground temperature.

For the measurement of the groundwater level a water level meter was used in an observation borehole of the Energy Park. The water level was measured between 15,35 m depth in April and 15,15 m depth in June.

Considering that each of the borehole is 100 m depth, this means that almost all the borehole can be assumed in saturated conditions.

According to Eskilson (1987) the undisturbed temperature increases from the ground surface down to the bottom of the borehole because of the geothermal gradient as it is shown in the graphs provided in Appendix 8.7 which show the results of the executed measurements.

According to Eskilson (1987) the average undisturbed temperature is normally with an enough accuracy equal to the undisturbed ground temperature at the mid-depth of the borehole:

(4.3.2.1)

$$z = D + \frac{H}{2}$$

Where z is the depth where the temperature is measured, D the depth of thermally insulated upper part of the borehole and H the borehole length over which heat extraction takes place.

In the case of the studied boreholes, the author does not have the opportunity to know whether there is an insulated layer or not, so it has been considered that there is not an insulating material placed.

According to Eskilson (1987) for the thermal performance of the extraction borehole the temperature variations in the ground surface and the considerations about the variations of the thermally insulated upper part between 1 to 5 m are negligible. However, the whole length of the borehole has been considered in all the calculations, being aware of the error this causes.

Following the procedure proposed by Gehlin (2002) to measure the undisturbed ground temperature. The borehole has to be at thermal balance with the surrounding. Then, temperature logging of the borehole is recorded each meter along the pipe through all the depth (100 m) using a temperature sensor on a graduated tape, and taking an average (Banks, Withers & Freeborn 2010). This way, the readings are used to calculate the arithmetic mean of the borehole temperature.

The results obtained are shown in the graphs in Appendix 8.7. It has not been considered necessary giving the tables. The measured temperature profiles and their gradients are available and they are all within the expected values for Denmark.

Another way to calculate directly the average undisturbed temperature is making circulate the carrier fluid through the borehole for about 30 minutes before starting the heating for the TRT. However, some authors do not rely on this procedure since it is considered an alteration of the initial undisturbed temperature due to the pump work (Gehlin 2002).

Before executing the measurement, the pipes in the boreholes were filled with water at least 2 days before. For the mean temperature calculation, all the range of temperatures were taken into account.

The following table shows the summary for the Undisturbed Mean Temperatures used for the three TRTs performed.

Test Number	Borehole Type	Date	Undisturbed Mean Temperature (ºC)
3	Single U	03/07/2013	9,90
4	Double U	18/06/2013	9,67
5	Coaxial	27/07/2013	9,86

Table 4.3-2: Summary for Undisturbed Mean Temperatures for the 5 tests performed.

From the table above, it can be appreciated the uniformity of the measurements, since the mean undisturbed ground temperatures have a standard deviation of 0,12 ºC and a mean temperature of 9,81 ºC.

From the graphs provided in Appendix 8.7, it could be deduced that the first 10 to 15 m are influenced by ambient conditions, and the temperature gradients start to be positive around the 40 m depth. These gradients are in the range between 0,013 and 0,014 ºC.

For Test 3, there was not enough time to execute a meter by meter measurement, so for the undisturbed ground temperature was considered the temperature of the circulating water without heating it one hour before the heating started for the TRT.

Besides, for Tests 4 and 5 the undisturbed temperature has been measured by means of the two methods, and in the following table a comparison of the results is given:

Test Number	Borehole Type	Date	Undisturbed Mean Temperature measuring each meter (ºC)	Undisturbed Mean Temperature circulating water (ºC)	Difference (%)
3	Single U	03/07/2013	-	9,90	-
4	Double U	18/06/2013	9,67	9,79	-1,24
5	Coaxial	27/07/2013	9,86	10,23	-3,75

Table 4.3-3: Comparison of Undisturbed temperature measurements by different methods.

It can be perceived that the difference is not high. However, since it is considered that the meter by meter measurement is more accurate (Gehlin 2002) those results have been the ones used for the TRT result interpretation.

4.3.4. Experimental Setup for TRT

Experimental Apparatus

The experimental apparatus used maintains a fixed temperature difference between the inlet and outlet ones.

The components of the system available at VIA University College can be seen in the following scheme as they are configured:

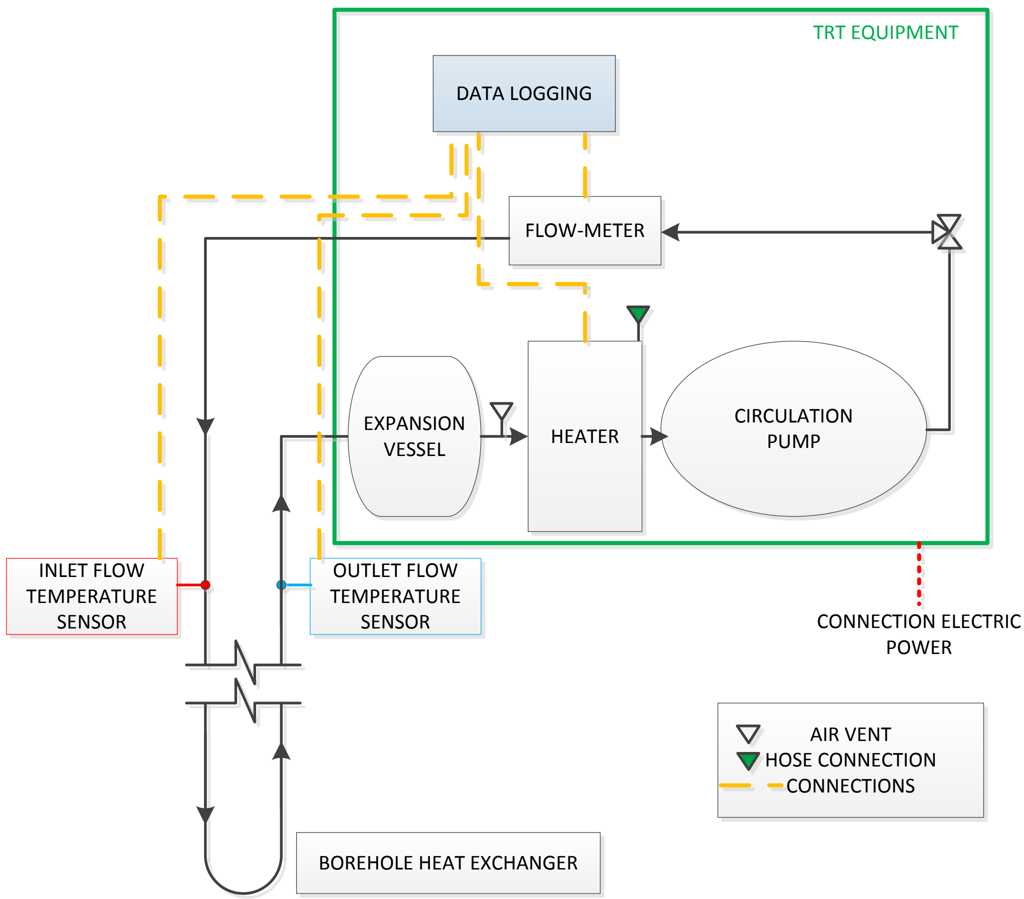

Figure 4.3-1: TRT equipment configuration scheme.

The two temperature sensors that measure the fluid temperature at the inlet and outlet pipes are thermocouple sensors connected to a data logger. The ultrasonic flow meter has a +/- 0.001 m^3/h accuracy and there is a consumption meter as well. The data is recorded in 10 s intervals.

The heater generates a supply of warm water. Using the temperature sensors in the entering and exit of the closed-loop, a specified difference is maintained. In this system the difference goes up to 3ºC approximately. The amount of energy injected or extracted from the ground is a function of the flow and temperature difference selected (Witte, Gelder & Spitler 2002).

(2.2.7.1)

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

For further information about the equipment and to know more about the technical features, the reader could address to Appendix 8.11.

Assembling and Working of Thermal Response Test Equipment

Before running the tests, some initial decisions and assumptions need to be done:

- *Power supply*
  It has been considered, looking to previous test observations, that putting the heater at 25 – 26 ºC it is enough in order to obtain injection rates around 25 W/m.

- *Flow*

  It has been considered the obtaining of a turbulent flow, so the Reynolds number *Re* had to be higher than 5000 in order to ensure the turbulence inside the pipes.

  (2.2.7.2)

$$Re = \frac{\rho \cdot v \cdot \emptyset}{\mu}$$

  Where ρ is the density of the carrier fluid [kg/m³], v is the speed of the carrier fluid inside the pipes [m/s], Ø is the inner diameter of the pipe [m] and μ is the dynamic viscosity of the carrier fluid [Pa·s] (VAXA Software 2013).

  For the calculations have been considered: ρ = 1000 kg/m³, $v = Q/A$, being A the surface of the pipe section (different for each configuration), μ = 0,001002 Pa·s (at 20ºC).

  In table 4.3-4 the calculated Reynolds values are provided, together with other test parameters.

- *Data collection interval*
  10 s intervals are used. Later, the data is treated in excel in order to reduce the data quantity making mean values for each 15 minutes.

- *Test length*
  Following the international guidelines established in Geotrainet (2011a) and the advices by Gehlin (2002) at least 50 hours.

- *Borehole depth considered*
  All the borehole length has been considered without taking into account the corrections required to be done to consider the depth affected by the ambient conditions or the insulated most superficial layers.

Whereas the test is being performed, the following data has been logged:

- Circulating water flow
- Temperature of the input flow
- Temperature of the output flow
- Temperature of the heater
- Ambient temperature

Logging Data and Gathering it all together

Once the test has been executed, the data is ready to be downloaded into the PC and gather it all in the same excel file in order to analyse it. Hereby the data logged in each of the tests will be provided in graphs.

For each of the test will be given the temperatures logged, the flow measured and the heat power injected along the time in the following chapter 4.3.6. Results.

Regarding the heat flux, once all the values are put together, the power quality can be checked. Following the equation (4.3.4.1) (Banks 2008) the evolution of the injected power rate can be known. This parameter is calculated in function of the temperature difference, the heat capacity of water and the borehole length and the circulation flow:

(4.3.4.1)

$$q = F \cdot S_{VC} \cdot (T_{in} - T_{out})/D$$

Where F is the flow in the pipes.

It has been assumed a constant heat power along the heating phase. And following the recommendations about the power quality advised by the ASHRAE (2007) in its HVCA Applications Handbook, it is stated: "the standard deviation should be equal to or less than 1,5% of the average power and the maximum power variation should be less than 10 % of the average power. The average heat flux should fall the 15W/ft range to best simulate the expected peak loads in the borehole". This mean in SI, that the heat influx should be between 49 to 82 W/m. This statement has been considered too high, since other authors advice a heat injection in the order of 30 W/m (Gehlin 2002).

It must be pointed that, as later will be explained, the first hours of the test are neglected, and the heat power in the circulation fluid provoked by the circulation pump is considered null. So the fluctuations in the input heat during the initial minutes is considered negligible.

4.3.5. TC and Borehole Resistance Calculations

During this dissertation, three tests have been run by the author. Before, there were executed two more tests (in the coaxial heat exchanger and in the single U one), with a slightly different equipment. It has been decided to do the analysis of just the three TRT executed by the author due to the lack of information about the execution procedure of the previous ones and the change of equipment. This is why the test numbering starts directly from 3 to 5, in order to be easier the future identification of the tests performed in the studied boreholes.

Heat Exchanger Type	Single U-tube 2	Double U-tube 1	Coaxial 2
Installation Number	VIA 14	VIA 13	VIA 15
Test Number	3	4	5
Grout Type	Dantonit	Dantonit	Dantonit
Grout Thermal Conductivity (W m^{-1} K^{-1})	2,35	2,35	2,35
Borehole Diameter (mm)	160	160	160
Active Length (m)	100	96	102,5
External Pipe Material	PE 100 -RC S5 PN16	PE 100 -RC S5 PN16	PE 100 -RC S5 PN16
External Pipe Outer Diameter (mm)	40	32	40
External Pipe Inner Diameter (mm)	32,6	26,2	32,7
External Pipe Wall Thermal Conductivity (W m^{-1} K^{-1})	0,42	0,42	0,42
Internal Pipe Material	-	-	PE 100 - S5 PN16
Internal Pipe Outer Diameter (mm)	-	-	20
Internal Pipe Inner Diameter (mm)	-	-	16,2
Internal Pipe Wall Thermal Conductivity (W m^{-1} K^{-1})	-	-	0,42
Undisturbed Soil Temperature (ºC)	9,90	9,67	9,86
Soil Volumetric Heat Capacity (MJ m^{-3} K^{-1})	2,16	2,16	2,16
Water Volumetric Heat Rate or Flow (m^3/h)	1,122 ± 0,038	1,134 ± 0,009	1,063± 0,009
Reynolds number	12138,78	21119,50	7760,69
Duration (h)	47,25	51,25	64,25
Average Heat Input Rate (W/m)	21,80 ± 0,90	23,72 ± 0,77	21,74 ± 0,52

Table 4.3-4: Summary table with main characteristics of the borehole heat exchangers and the TRT performed.

Once all the logged data was put together in an excel file, several columns have been executed along the time in order to analyse them: time (seconds, minutes and hours), flow (m^3/h), input temperature (ºC), output temperature (ºC), the ambient temperature (ºC), difference between input and output temperatures (ºC), mean temperature T_f (ºC), temperature displacement (difference between mean temperature and initial undisturbed ground temperature) and the power input rate (W/m) following equation (4.3.4.1).

Then, it is required to know which data has to be analysed. It is usual disregarding the first hours measured. This is done to avoid the evaluation of the transient heat transfer process in the borehole and to use a period when the ground thermal properties have a larger influence on the thermal response (Gehlin 2002).

According to Gehlin (2002), the line source model fits better to the observed data when around ten hours of the initial data are discarded. If less than 30 hours are used, the convergence seems to be inaccurate. However, the data to discount could be from the initial 4 hours up to 10 hours depending on the author (Gehlin 2002).

The minimum time criterion for the evaluation of a geothermal response test, which to evaluation differences may occur due to measurement disturbances reduce is (Banks 2008):

(4.3.5.1)

$$\frac{5r_b^2 S_{VC}}{\lambda} < t_s$$

Being r_b the radius of the borehole, which in these cases is 0,08 m. So, the time discarded has to be in the order of 9 hours. Notice this value is approximate since the volumetric heat capacity and thermal conductivity values are the ones have been calculated in the second approach I chapter 4.2. Thermal Conductivity Measurements: S_{vc} = 2,16 MJ m^{-3} K^{-1} and λ = 2,18 W m^{-1} k^{-1}.

However, in order to check the sensitivity of the results, it has been decided to study different periods starting at different times and obtaining the results for each of them. These periods start from hour 6 on, with 3 hour steps lag: hour 6 to ending (period 1), hour 9 to ending (period 2), hour 12 to ending (period 3), hour 15 to ending (period 4) and hour 18 to ending (period 5).

With this different starting periods the sensitivity of the thermal conductivity variation along time can be checked.

Even though some of the curves starting at hour 6 fit better to the real curve since the standard deviations are lower (Appendix 8.7), it has been considered that the ones obtained from the curves with the beginning at hour 9 (period 2) have enough accuracy. This way it is respected the criteria for the minimum time to take into account. In all the tests, this period 2 is the first or the second best approximation to the real situation and this way the steady state is more feasible to happen.

Once all the information is organised, the following algorithm should be followed in order to obtain the thermal conductivity and the borehole resistance:

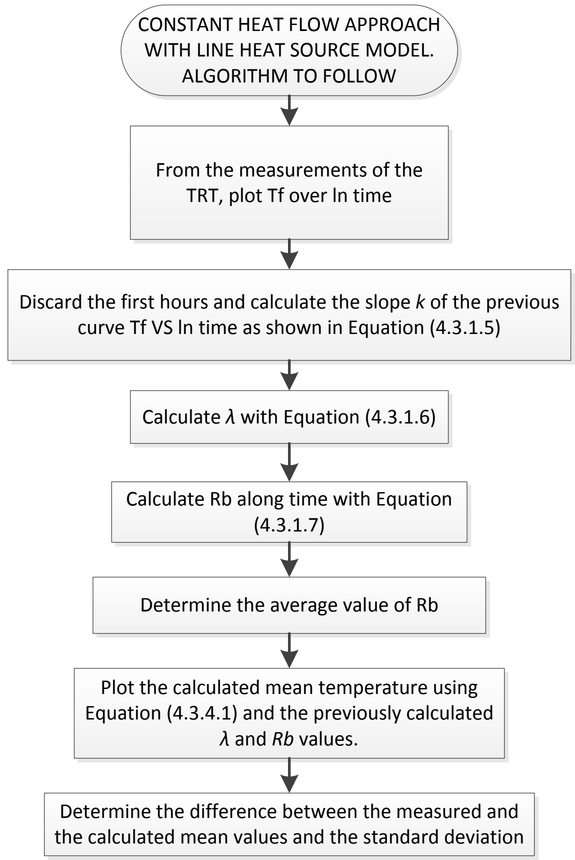

Figure 4.3-2: Algorithm to follow for the evaluation of the data obtained the TRT.

For the calculation of the trend line, the least squares method has been followed. The graphs are provided in Appendix 8.8 where the trend lines for each period can be found. For the period starting at hour 9, the graphs are shown in this chapter.

Regarding the last two steps, the measured mean temperature curve is plot together with the real one (the measured one) and it is checked if it fits or not. This way, comparing the values along the time, the deviations can be calculated.

4.3.6. **Results**

In this chapter the results and the main conclusions are given for each of the tests. For further information and analysis more data is provided in Appendix 8.8.

Test 3: Single U_2

Applying the LSH theory it has been calculated a ground thermal conductivity of 1,7539 ± 0,0472 W m^{-1} K^{-1} and a borehole resistance of 0,1128 ± 0,0049 K m W^{-1}.

Hereby the measured inlet and outlet temperatures are shown, together with the mean temperature between them, the circulating flow rate (m^3/h) and the input power rate (W/m).

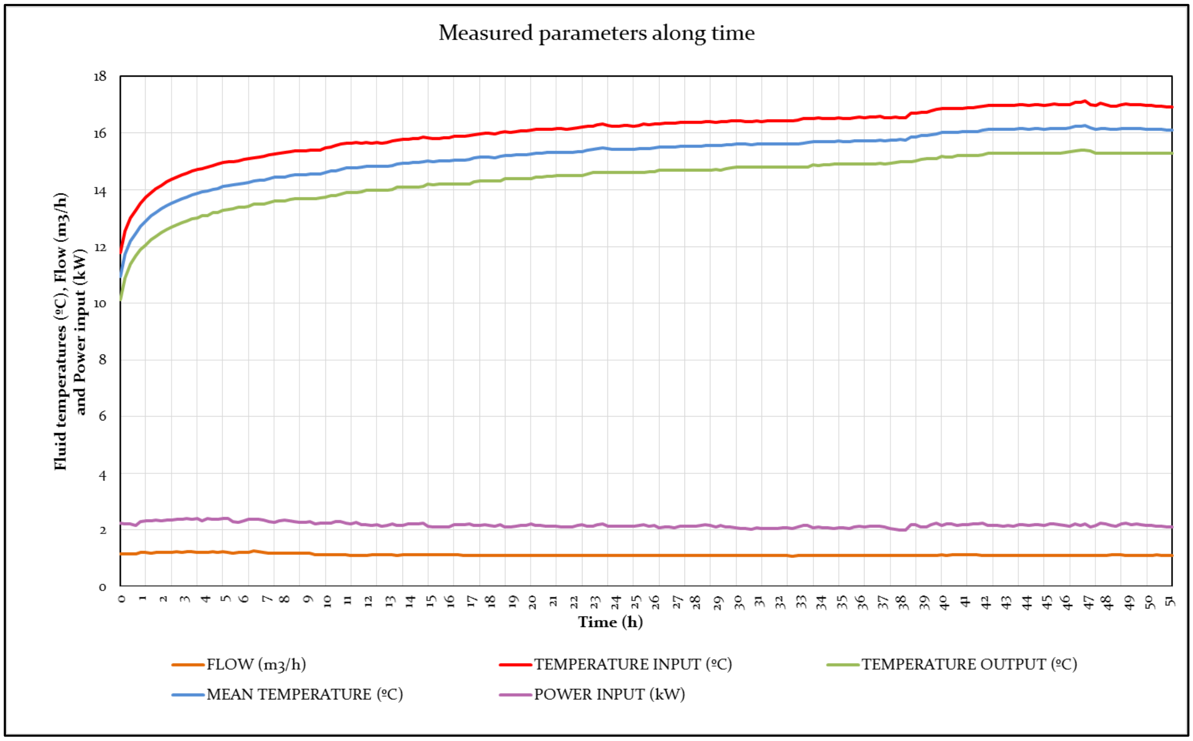

Figure 4.3-3: Measurements along test time for Test 3.

In Figure 4.3-4, the mean temperature is plotted along the natural logarithm of time, and the trend line equation is shown for Period 2, which is calculated by the least squares method. After, following the proposed algorithm, the results are determined in Appendix 8.8.

The analysis for the evolution of the borehole resistances and the thermal conductivities have been done in Appendix 8.8 and no remarkable aspects have been considered.

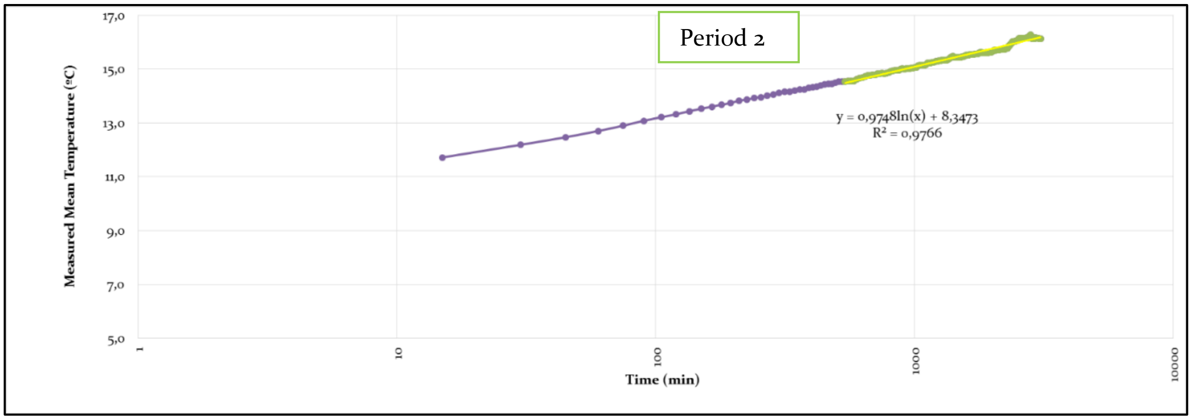

Figure 4.3-4: Measured mean temperature VS time logarithm and trend line for Period 2.

Once the thermal conductivities and the boreholes resistances are calculated for each period, the mean temperatures can be calculated using equation (4.3.4.1). For this Period 2, the fitting curve is the one showed in the next figure. It has a standard deviation of 0,0098 ºC. It is considered accurate enough.

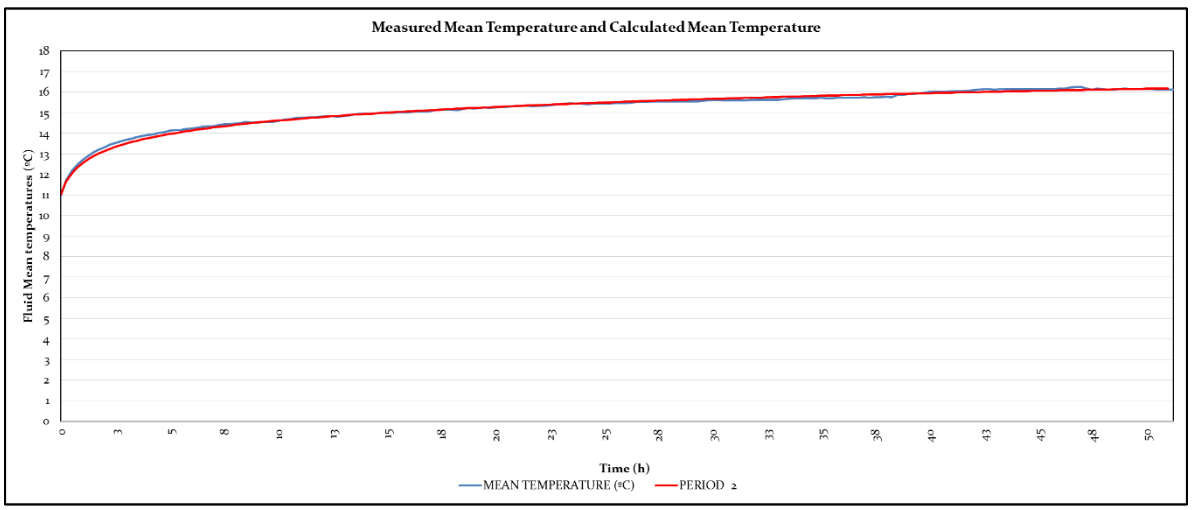

Figure 4.3-5: Fitting curve between measured mean temperature and the calculated one for period 2 in Test 3.

Test 4: Double U_1

The results for this test, are provided: for the ground thermal conductivity 2,0234 ± 0,0656 W m^{-1} K^{-1} and for the borehole resistance 0,0906 ± 0,0049 K m W^{-1}.

Hereby the measured inlet and outlet temperatures are shown, together with the mean temperature between them, the circulating flow rate (m^3/h) and the input power rate (W/m).

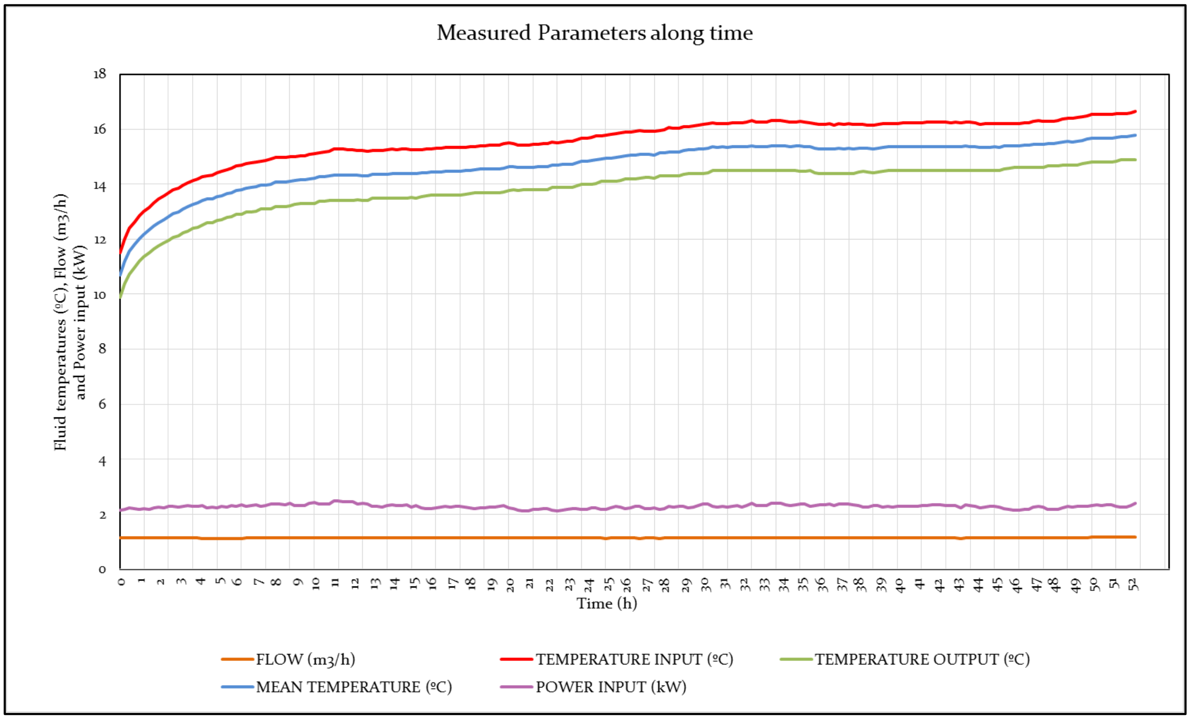

Figure 4.3-6: Measurements along test time for Test 4.

In Figure 4.3-7, the mean temperature is plotted along the natural logarithm of time, and the trend line equation is shown for Period 2, which is calculated by the least square method. After, following the proposed algorithm, the results are determined in Appendix 8.8.

The analysis for the evolution of the borehole resistances and the thermal conductivities have been done in Appendix 8.8 and no remarkable aspects have been considered.

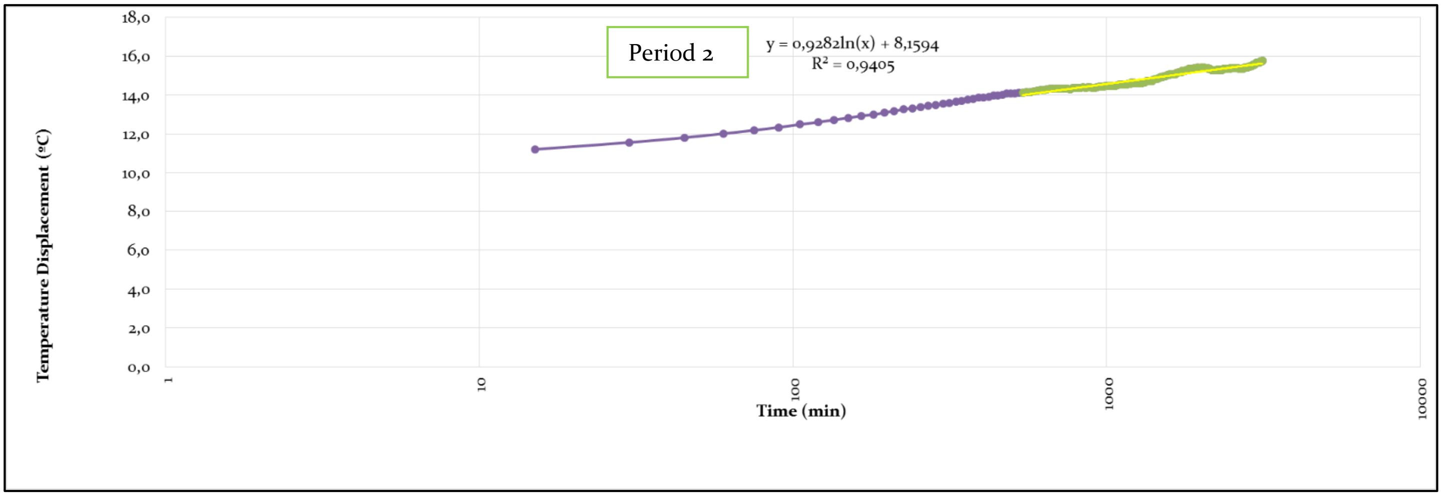

Figure 4.3-7: Measured mean temperature VS time logarithm and trend line for period 2 for Test 4.

For Period 2, the fitting curve is the one showed in the next figure. It has a standard deviation of 0,0055 ºC. It is considered accurate enough.

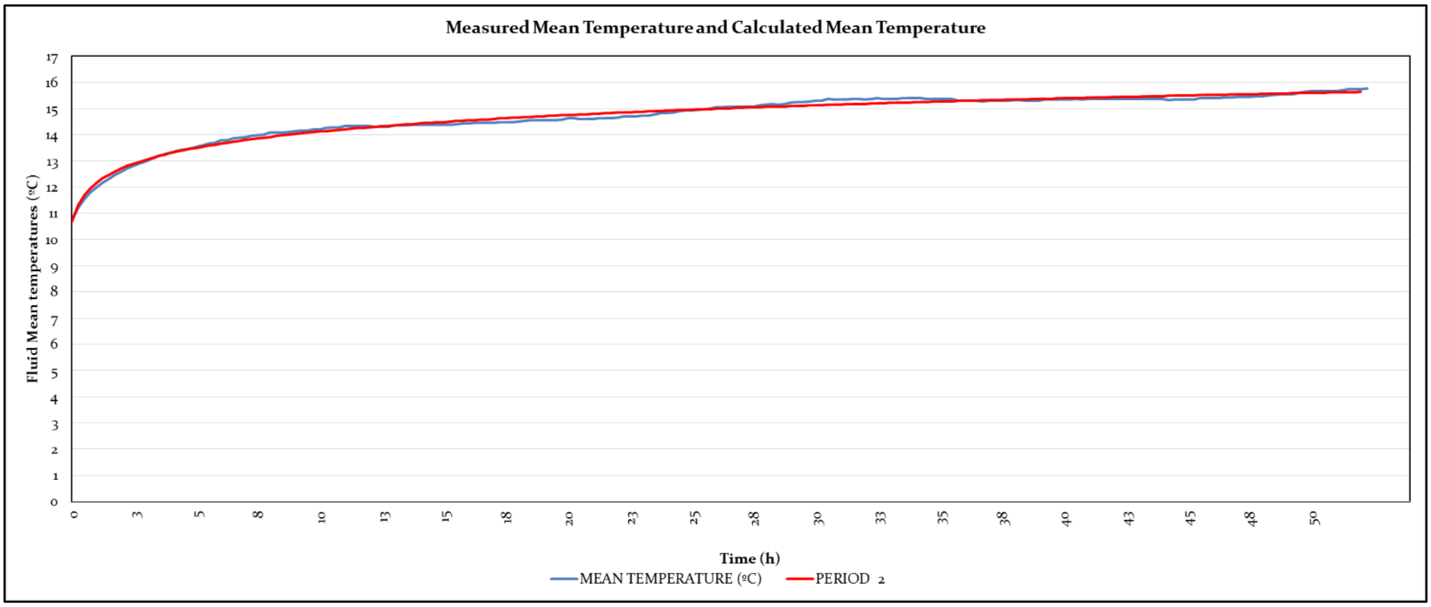

Figure 4.3-8: Fitting curve between measured meand temperature and the calculated one for period 2 in Test 4.

Test 5: Coaxial_2

The results for this test, are provided: for the ground thermal conductivity 1,9649 ± 0,0472 W m^{-1} K^{-1} and for the borehole resistance 0,1827 ± 0,0037 K m W^{-1}.

Hereby the measured inlet and outlet temperatures are shown, together with the mean temperature between them, the circulating flow rate (m^3/h) and the input power rate (W/m).

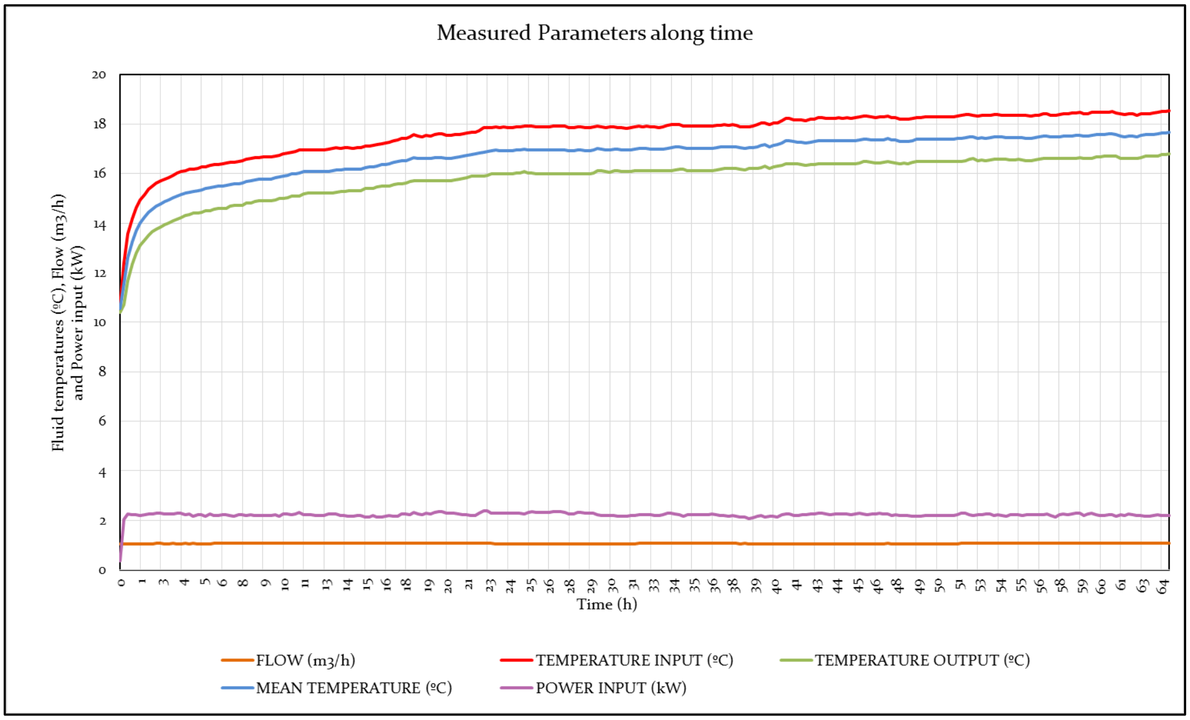

Figure 4.3-9: Measurements along test time for Test 5.

In Figure 4.3-10, the mean temperature is plotted along the natural logarithm of time, and the trend line equation is shown for Period 2, which is calculated by the least square method. After, following the proposed algorithm, the results are determined in Appendix 8.8.

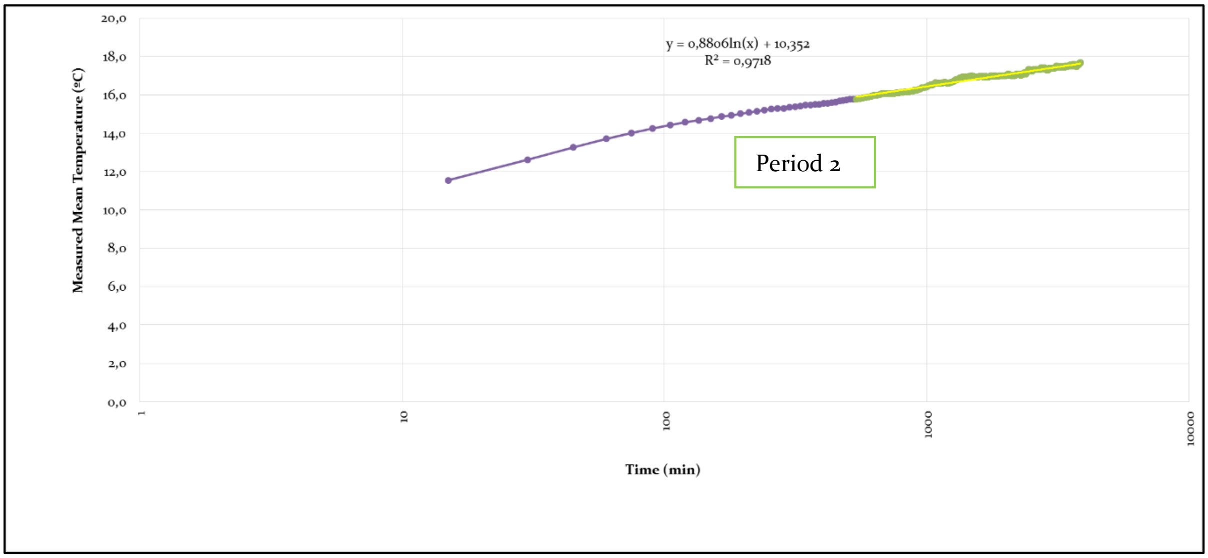

Figure 4.3-10: Measured mean temperature VS time logarithm and trend line for period 2 in Test 5.

The analysis for the evolution of the borehole resistances and the thermal conductivities have been done in Appendix 8.8. The main highlighting point is that the estimations of the thermal conductivity progressions become higher when the starting point is postponed (Figure 4.3-11). According to Witte (2001) and Chiasson (2001), this can be interpreted as the existence of groundwater.

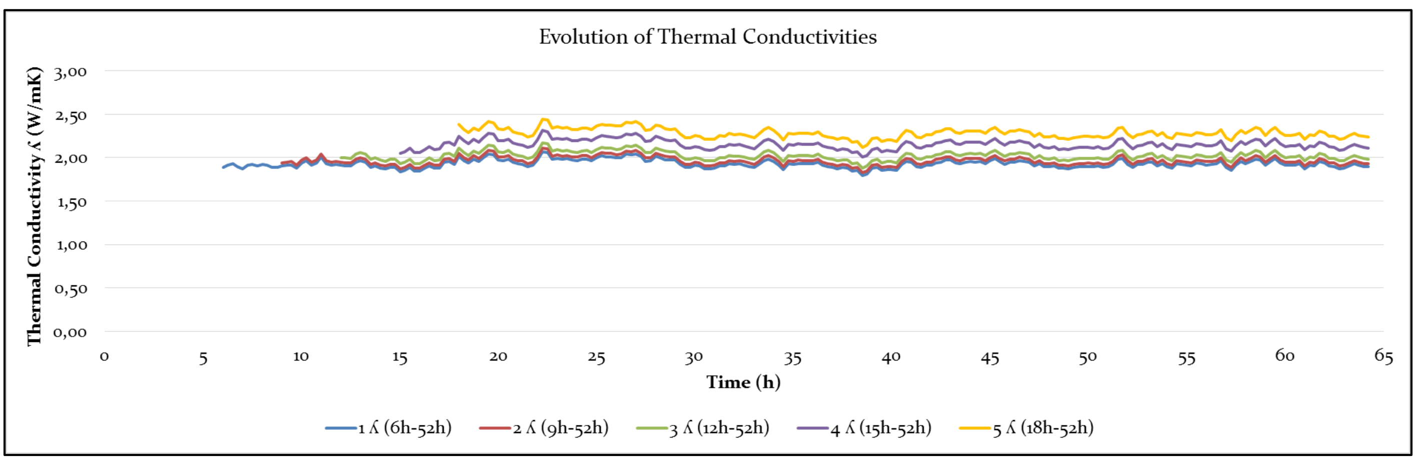

Figure 4.3-11: Evolution along time of thermal conductivities for each period in Test 5.

For the chosen period 2, the fitting curve is the one showed in the next figure. It has a standard deviation of 0,0016 ºC. It is considered accurate enough.

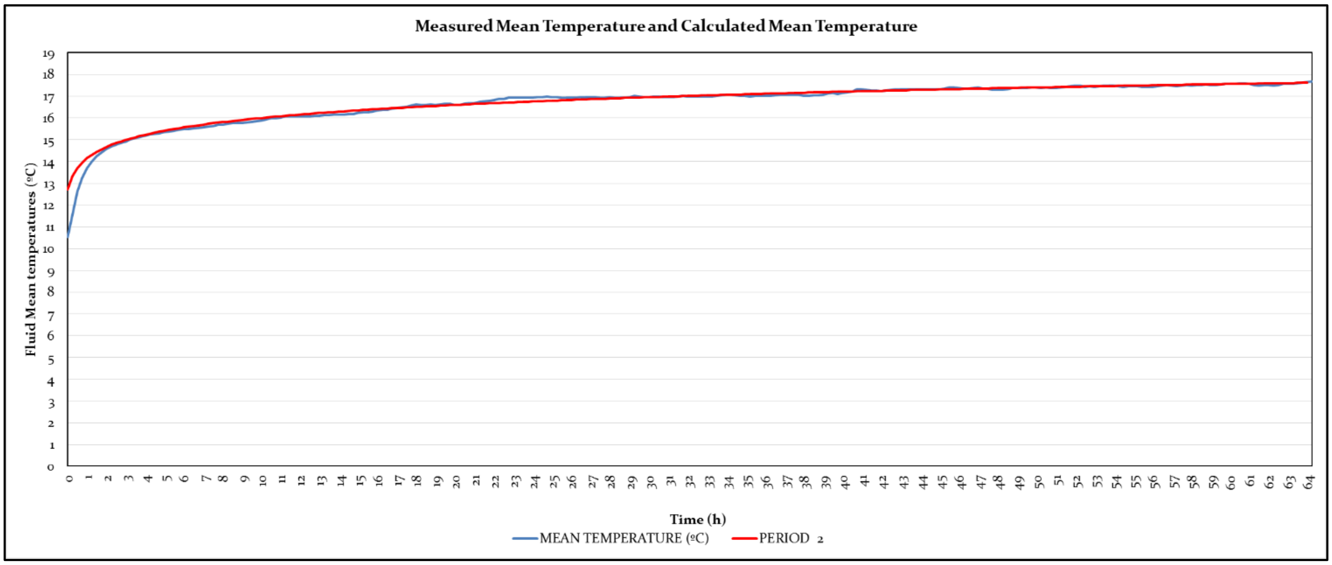

Figure 4.3-12: Fitting curve between measured meand temperature and the calculated one for period 2 in Test 5.

4.3.7. Result Interpretation

As a summary for the results, the next table is provided:

Heat Exchanger Type	Single U-tube 2	Double U-tube 1	Coaxial 2
Installation Number	VIA 14	VIA 13	VIA 15
Test Number	3	4	5
Active Length (m)	100	96,5	102,5
Borehole Diameter (mm)	160	160	160
Soil Thermal Conductivity Line Source/Mean Temp. ($W\ m^{-1}\ K^{-1}$)	1,7539 ± 0,0472	2,0340 ± 0,0660	1,9649 ± 0,0472
Borehole Resistance Line Source/Mean Temp. ($K\ m\ W^{-1}$)	0,1128 ± 0,0049	0,0899 ± 0,0049	0,1827 ± 0,0037

Table 4.3-5: Summary of results of in-situ TRT.

In this chapter, a result interpretation will be done for the TRT but also for the determination of the undisturbed ground temperature, together with a result comparison and an analysis of the main problems of the followed methodology.

Result Analysis

Regarding the measurements of the undisturbed ground temperature:

- The temperature measurement is considered correct from both approaches, although it is more realistic the determination taking measurements each meter, since disturbances from the circulation pump can be avoided. But a high ambient temperature might affect the determination.

Regarding the TRT results:

- The collected data seems to be correct for the three tests as it can be seen in the first graph provided for each case in the Appendix 8.8. Besides, the data quality analysis done fulfils the ASHRAE recommendations.
- A factor which directly affect the results is the ambient temperature. Insulation was used for Test 5 which has been the less influenced one by the ambient conditions because the temperature curves were not extremely altered.

  This affections of ambient conditions have an influence around 0,2 ºC and although it does not look a big alteration, the thermal conductivity results are directly modified.

  Another factor that must be considered in this aspect could be the use of the protection tent. In order to protect the equipment, the tests have been run inside an impermeable tent which is the originator of the overheating noticed in the analysis of the ambient temperatures.
- It has been seen that while the Tests 4 and 5 give similar values of thermal conductivity, the Test 3 gives a lower value. The higher the slope of the trend line, the

lower the thermal conductivity. So a descendent tendency in the thermal conductivity values could be expected as a lower data period is studied.

While for Tests 3 and 4 the trends of the thermal conductivities are descending, for Test 5 the tendency is ascendant. So, for Tests 3 and 4 it is accomplished that the lower the data period taken, the lower the thermal conductivity with the time, as the slope is each time lower since the steady state situation is obtained.

However, for Test 5 this does not happen. So, it means that there may be a convection phenomenon provoked in the ground. This ascent in the thermal conductivity values could be attributed to the existence of groundwater movement according to Chiasson (2001). This is an important factor worthy bearing in mind since the thermal conductivity values determined from this in-situ measurements could appear too high, leading to over or under designs.

On the other hand, this convection in Test 5 could be caused by the length of the heating time in the test, which is 12 hours higher than for Test 3 and 4.

- Regarding the values of the borehole resistances look more constant or stable for the different periods than the thermal conductivity values. This might be due to the fact that the heat exchanger's characteristics are more homogeneous than the soil properties. The ground cannot be considered as a homogeneous medium, since there are too many factors involved in its behaviour.
- The fitting the approximations of the fitting curves are considered good enough for the three tests since the errors look acceptable: not higher than 6 % in any case.

Result Comparison

Comparing the results obtained, it can be done a clear difference in the values obtained. Because the only difference between the three boreholes is the use of different heat

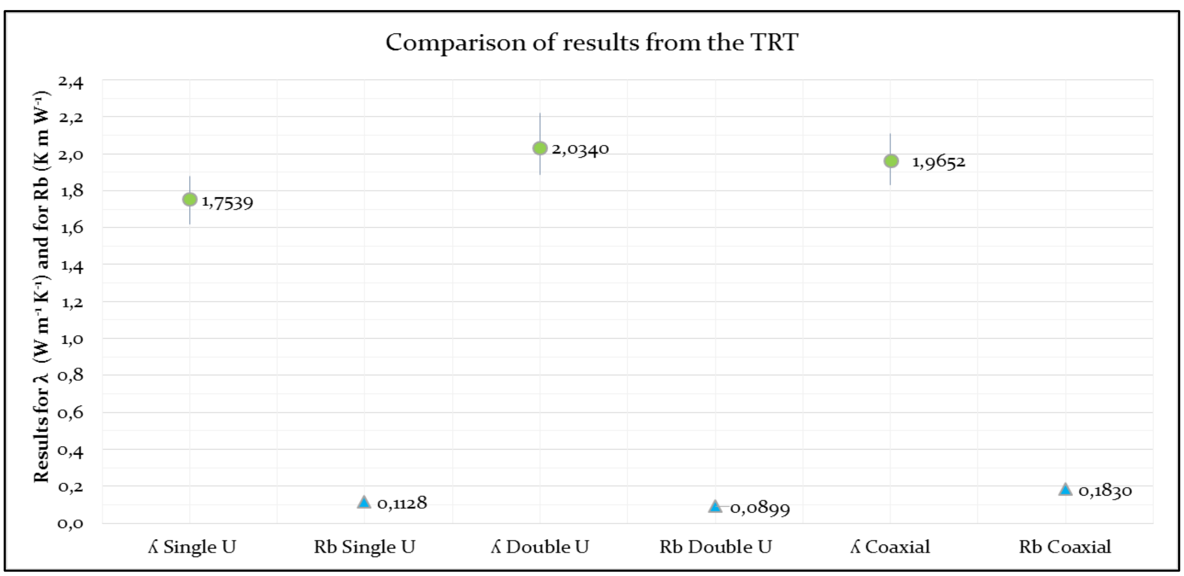

Figure 4.3-13: Comparison of results for the three TRT.

exchangers due to the fact that the geology, the drilling method, the grouting material and the borehole depth and diameter are the same.

Regarding the thermal conductivity values, while for the Double U and Coaxial ones the results are very similar, 2,0340 ± 0,0660 W m^{-1} K^{-1} and 1,9649 ± 0,0472 W m^{-1} K^{-1} respectively, for the Single U the thermal conductivity looks lower, 1,7539 ± 0,0472 W m^{-1} K^{-1}. The difference seems to be too high considering that the geology of the area is considered very similar for the three boreholes. However, even being aware of the dissimilarities, the results are logical and in the order of the expected values for this kind of geological conditions.

This variation can be due to different causes:

- Errors in the execution of the TRT due to the fact of the inexperience of the author, the existence of some air in the circuit or a combination of many aspects.
  For the execution of Test 5 an improvement was made, assembling an air valve just in the circulation pump exit. This way the air was extracted completely and the problem has been overcome.
  So, it could have happen that in Tests 3 and 4 some air was in the circuit. Indeed, in Test 4 this is tangible as shown in the flow drop in Figure 8.9-9.
- Some non-recorded geological aspect which breaks the uniformity of the expected geology.
- An error in the borehole execution during the injection of the grouting material.

Regarding the borehole resistances, the higher one is achieved in the coaxial heat exchanger (0,1827 ± 0,0037 K m W^{-1}), followed by the Single U one (0,1128 ± 0,0049 K m W^{-1}). Hence, the best result, is for the Double U heat exchanger (0,0899 ± 0,0049 K m W^{-1}), since it has the lower borehole resistance, what makes an improvement of the performance of the GSHP system translated as a reduction of the borehole dimension and of the economic cost.

The Double U heat exchanger has a rise in the effective contact surface what leads into a decrease in the borehole resistance comparing to the Single U one. Comparing to the Coaxial heat exchanger, the one used is an ordinary one, whose relative heat exchanging surface comparing to the one of the Double U is 0,5 approximately (Oberdorfer, Maier & Holzbecher 2011). This is in total accordance with the obtained results, since the borehole resistance of the Coaxial borehole is the double of the Double U one.

Making a deeper analysis of the temperature evolutions along time in the different heat exchangers can be perceived that in general the evolution of the mean temperatures is higher for the coaxial heat exchanger than for the single U and double U ones.

Trying to find a reason for this more elevate trend in the mean temperatures of the coaxial heat exchanger, a comparison against the injected power rate (kW) and the circulation flow (m^3/h) has been done in Figures 4.3-14 and 4.3-15.

The heat input rate is very uniform and similar for the three tests, so it does not seem the cause of the fact that the mean temperatures for the coaxial heat exchanger are higher.

On the other hand, analysing the circulation flow it can be perceived a relation between the higher temperatures and the flow, since the flow for the coaxial heat exchanger is lower, and this could have made easier the heat transfer between the liquid, the borehole and the ground.

Besides, an indicator for the order of the borehole resistances might be deduced from the first hours of the mean temperature curves, showing direct relation between the slope of the mean temperature and the borehole resistances. The higher the slope in the first part of the curve, the higher the borehole resistance is, what means a lower interaction between the borehole and the ground in the first hours. This is why an approximation to the thermal conductivity of the borehole as a whole can be done as shown in Appendix 8.8.

Another point to consider is the maintenance of the difference between the inlet and outlet temperatures, which must be maintained constant along the time in order to follow the basic premises of the TRT guidelines (Figure 4.3-16).

These temperature differences between the inlet and outlet temperatures look similar in the three tests, and the deviations look reasonable. However, they are very low reductions (between 1,67 and 1,80 ºC), what they can be translated as low heat injections into the ground (between 2,1 and 2,3 kW). These power inputs are lower than the ones recommended by the ASHRAE and slightly lower than the ones recommended by Sanner et al. (2005). The guidelines are provided in Appendix 8.11. In addition, ASHRAE (2007) requires temperature differences around 3 to 7 ºC.

A reason to explain these low differences could be the high flow provoked in the circulating fluid. So, for next tests, a slight reduction in flow should be done. This decrease might not be too high, but enough to cause an acceptable temperature difference (look at equation (4.3.4.1)).

Furthermore, another reason for the low power input is the limited power of the heater: 3 kW. Besides, the useful power is lower, since a performance of the 80 % has been calculated from the consumption study. Thus, in order to work in the intervals proposed by the guidelines aforementioned, a heater of 6 or 7 kW of power is suggested.

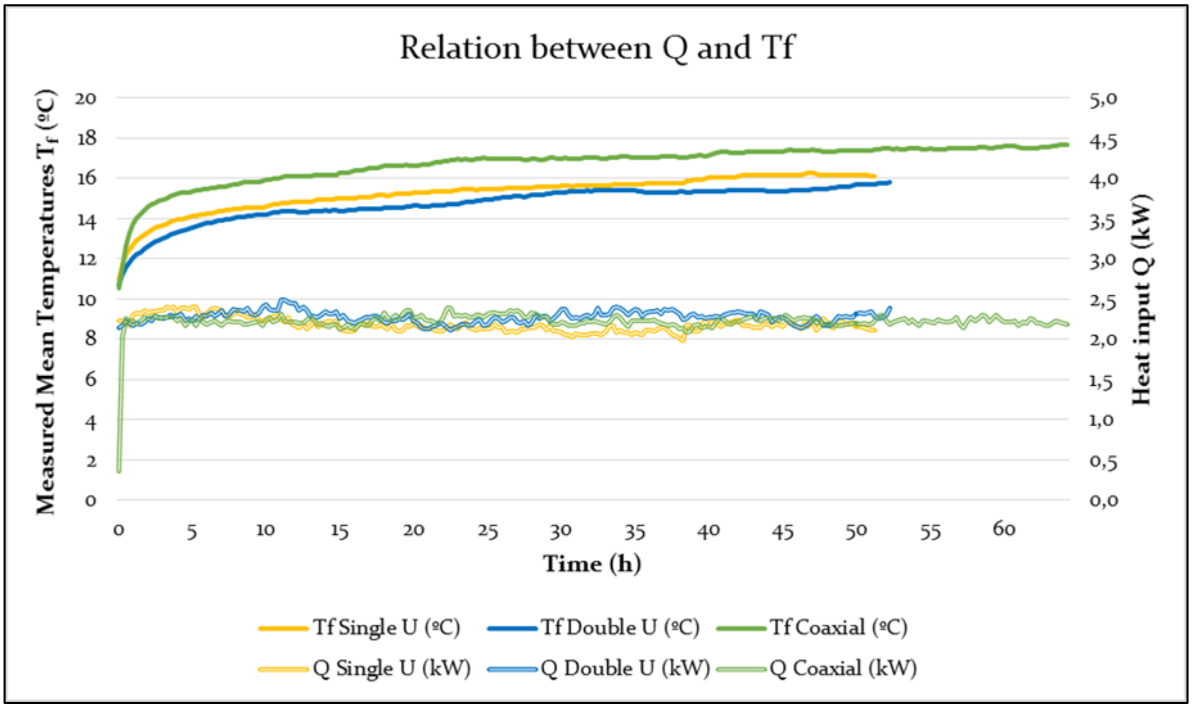

Figure 4.3-14: Graph showing the measured mean temperatures and the heat injection rate for the three tests.

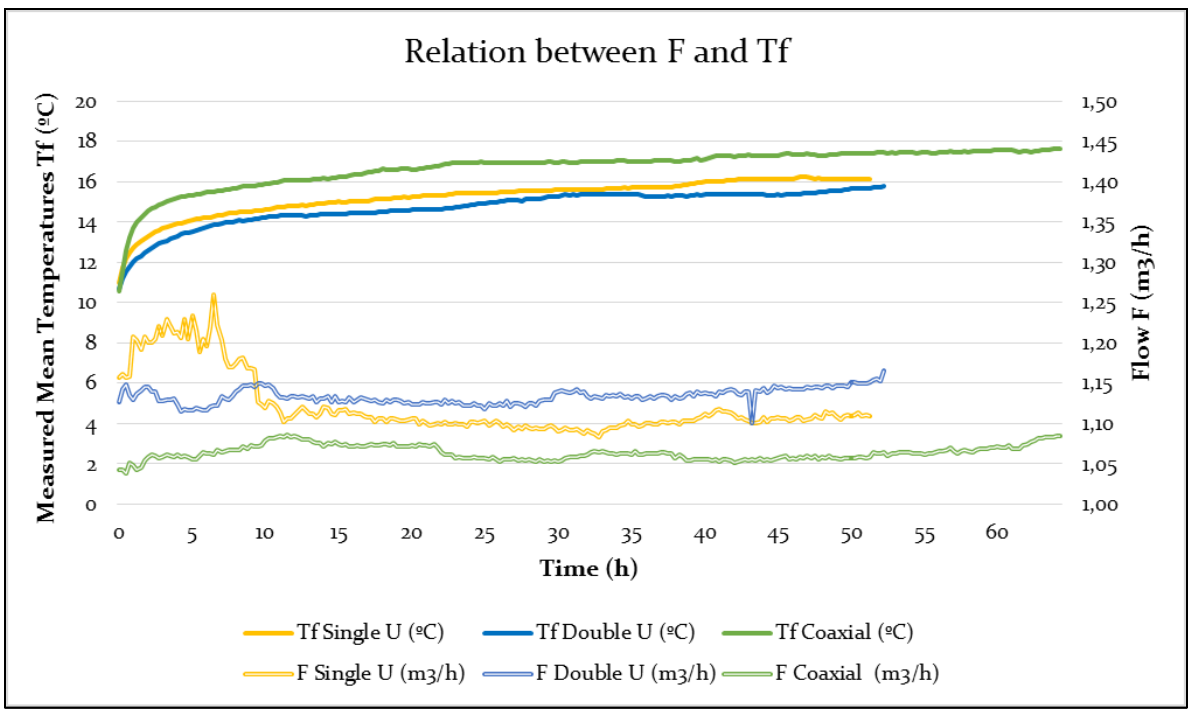

Figure 4.3-15: Graph showing the measured mean temperatures and the flow rate for the three tests.

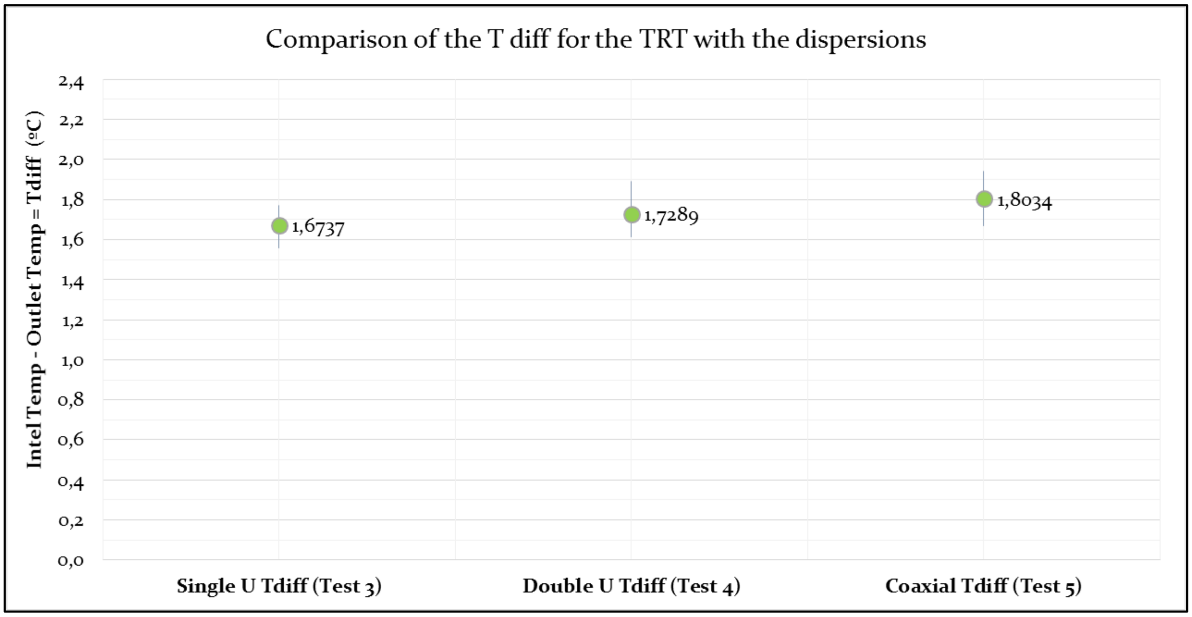

Figure 4.3-16: Comparison of the mean deduction values between the inlet and outlet temperatures together with their dispersions.

In order to check the obtained values, the repeatability of more thermal response tests is suggested, so as to be able to do a statistical study of the properties determined.

Methodology Problems

After executing the tests, some problems and lags have been found regarding both, the data evaluations method and the way of performing the TRT.

Regarding the disadvantages of the evaluation methodology based on LHS have to be considered the limitations of the methodology itself given in the state of the art, in point 2 of this dissertation. Next points must be highlighted:

- The assumption of pure conductive heat transport, that can lead into substantial deviations (Wagner et al. 2013).
- TRT is based on Line Source theory whose main limitation is that it does not allow the determination of the volumetric heat capacity independently from the thermal conductivity. So the thermal capacity of the soil is assumed constant. However, this can give an error up to 33% on the production temperature of a real TRT (Wagner & Clauser 2005).
- In order to be aware about more uncertainty sources linked to the used LHS approach, the reader can address to chapter 12.3 of the book "An Introduction to Thermogeology" by Banks (2008).

Regarding the problems derived from the way of executing the TRT the next aspects need to be considered:

- Limitations already explained in the introduction of this MSc Final Dissertation.
- Influence of outside perturbations: diurnal temperature cycles…
  This aspect is directly linked to the estimation of thermal conductivity due to two factors: i) the selection of the data to study and ii) the fact that the total heat flux could not be balanced (Witte, Gelder & Spitler 2002).
  This influence can be avoided partly choosing right experimental parameters: maintaining the fluid temperature as closer as possible to the outside temperature and forcing a high energy input. Besides, a good insulation of the apparatus is recommended.
- A big difficulty perceived in the setting up of the test was the extraction of the air inside the circuit. The installation of an air valve was required for Test number 5 and that way the execution was easier.
- There has not been done an error analysis in order to check the inaccuracies due to the used instruments. This has to be done so as to give a better description of the equipment used.

4.3.8. Conclusions and Recommendations

In this chapter 4.3 the study of three TRT in the facilities of VIA University College has been carried out. It has been found that the results obtained look logical and the machine seems to work correctly. So, so far it is considered reliable enough. There can be executed long tests (65 hours heating and more without it) without being controlling it on site. Besides, for its use at university it is quite manageable.

These tests allow acceptable values of the soil thermal conductivity and of the borehole thermal resistance.

After the execution of the three tests, some equipment improvements are proposed:

- Heater of 6-7 kW.
- Insulate the machine so as to avoid ambient temperature affections
- Put the equipment in a trolley in order to make easier the transportation.
- Install a bypass or a small water tank in order to preheat the water.

When it comes to future recommendations for the TRT and its evaluation a lot of research ways can be developed:

- Before doing more tests, the evaluation of the measured recovery curves is suggested in order to have a second source of checking the results obtained. Besides, numerical simulations verify that the borehole Thermal Resistance is determined with a higher accuracy using a combination of recovery and heat injection data (Raymond, Therrien & Gosselin 2011).
- Other evaluation methods can be applied: infinite cylindrical source.
- From the data gathered, more information about the soil properties and the heat exchanger's performances can be obtained if numerical simulation is added.
  However, for this dissertation there were not resources and time enough to perform a numerical model. That is why this option is considered for further investigations, taking as reference a performed TRT.
- The repeatability of the tests is proposed in order to be able to carry out a statistical analysis and confirm the reliability of the three tests performed in this dissertation.
- In order to record and evaluate the affection of ambient temperature fluctuations, there can be used a DTRT with fiber optics in order to plot the temperatures along the borehole's depth. E.g. a temperature vertical profile could allow the possibility to determine the influences of the ambient temperature along the depth as well as a determination of the different thermal conductivity values along the soil layers passed.
- The previous proposal can be used as well to account the influence of the effects of the groundwater flow and consider it for the design of the BHE.
- New machines can be assembled in order to perform different types of TRT.

5. Comparison of Results from the Different Approaches

In this chapter the three developed approaches to the soil thermal conductivity value are compared, so the borehole resistance results are not treated. This parameter has already been analysed in point 4.3 of this final dissertation.

One of the main objectives of this final dissertation was the validation of the reliability of the tests facilities at VIA University College either for the non-steady state probe method or for the TRT equipment.

For this, firstly a traditional approach to the thermal conductivity value for a set geological profile from literature values has been carried out. Later, and following the known stratigraphic column to complement the information missing, the laboratory measurement of six owned samples at different depths have been executed. This measurements have been used to obtain a global thermal conductivity value of the soil around the borehole through the whole length. Finally, as a third approach the execution of three in situ tests has been developed.

As a summary of the results obtained from the three different approaches the next figure is given:

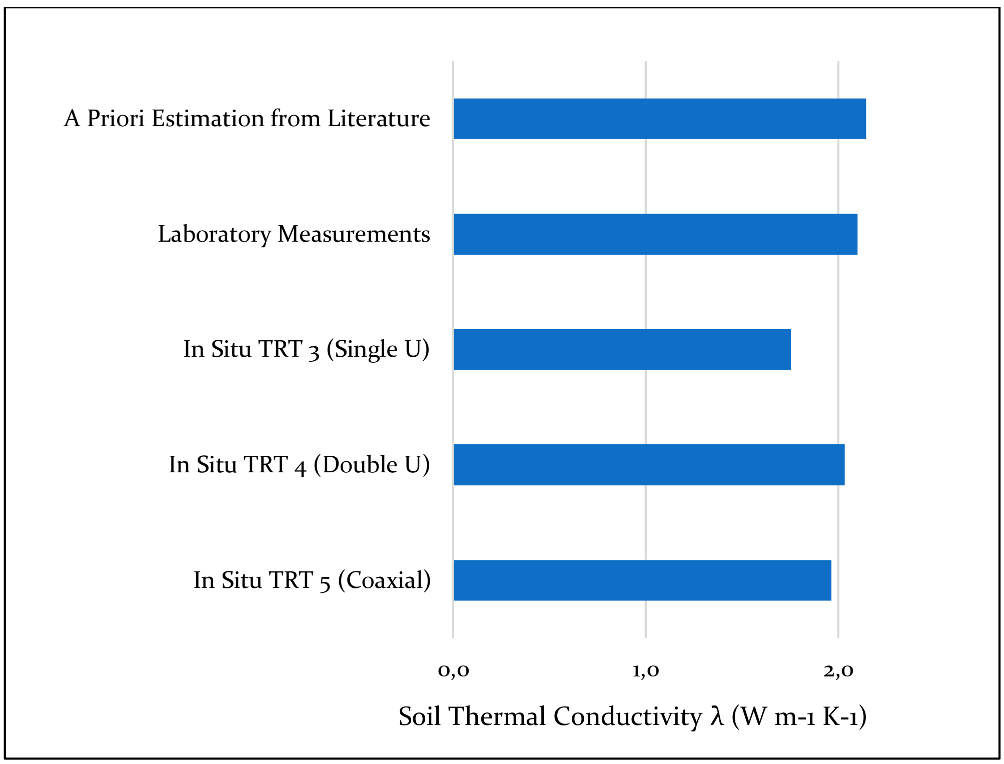

Figure 5.1-1: Comparison between thermal conductivity values estimated from the literature, laboratory measurements and in situ TRT.

According to Witte (2001) in experiments with heat injection convection could happen in the borehole, what can lead into a higher estimation of the thermal conductivity. Besides, in laboratory estimations it is not taken into account the groundwater flow what theoretically should provide a lower estimation of the thermal conductivity.

However, in the results from this final dissertation happens the opposite situation, where estimations from literature and laboratory measurements give higher results, although the order is very similar for the different approaches. Nevertheless, a difference of around 18 % can be perceived between the literature approximation and the TRT 3 which seems not rational.

What it is clear, is that in order to do a good and a reasonable approximation from a priori estimation from literature or from a laboratory measurement series, the good determination of the stratigraphic profile is vital.

The error from the literature approach is considered higher, since the data used is not from local soils.

The determination from the non-steady state probe method, the accuracy is considered better than the previous case, but as just six samples were available, the method could not be applied to the whole length of the borehole, what reduces the trustworthiness of the procedure. However, it would be considered a good approach if the author had been able to access to each layer (or at least to a significant part of the core samples).

Consequently, it must be pointed out the importance of a good knowledge about the existing soil and layers. Sometimes information is missing, as it happens in this case, so the results are not as reliable as it could be thought. This is why the in-situ approach is in some cases required. The TRT gives a more accurate overview about what really happens in the subsoil when a heat injection occurs. In addition, the TRT gives an extra result: the borehole resistance.

Moreover, having a reference TRT allows the chance to apply and validate numerical simulations and obtain more information of the soil if the required tools are owned. Despite more experience in the field is required for such a level of research.

An advantage of laboratory measurements against in situ TRT might be the length of the tests. The TRT take too long in order to determine a reliable values of the thermal conductivity. But it must be highlighted that the laboratory measurements require a repeatability of the measurements in order to have enough confidence in the results obtained. Besides, requires a good extraction of a core and a correct preparation of the samples. Consequently, the save in time does not look remarkable.

Summarising, in view of the results, the reliability of the equipment at VIA University College is validated.

In order to have an idea of the performance of a GSHP installation connected to each of this boreholes, a specific heat extraction rate of 60 W/m can be expected for an installation running 1800 hours per year, or 50 W/m for an installation running 2400 hours per year. This data has been taken from the German Standard VDI (2010). These values have to be taken as a guide since for a deep design of a system, more aspects have to be considered, such as the expected demand, the heat pump's evaporator capacity…

Regarding the design for BTES, according to (VDI 2001), one of the most important properties is the heat capacity of the soil. So, further investigation is required in order to find a better approach to the obtained heat capacity values. The achieved values have been used as a guide, but the author is aware of the error this can cause.

Author Hypothesis

The results show a close accordance between the laboratory measurements and the TRT, being the estimation from literature slightly higher.

The explanation the author finds to this fact is that the geological acquirable information from the different sources is incomplete.

From the maps provided in Appendix 8.1 the expected depth of the quaternary sediments ranges between 50 and 80 m. This confirms correspondence with the used geological profile which indicates a thickness around 50 m. Nevertheless, in view of the results of the tests executed by the Thermal Needle Probe Method, it has been checked that at approximately depth 50 m the expected thermal conductivity is around 1,2 W m^{-1} K^{-1}. Which is lower than the one expected from the literature values.

This might entail the idea that some of the coming meters, deeper than 50 m, are formed of the same formation, what would lead into a lower bulk thermal conductivity of the soil surrounding the borehole.

If this hypothesis would be correct, the second approach to the thermal conductivity value would have likely given a lower value than the ones from the TRTs. What would be in accordance to the conclusions of Witte, Gelder & Spitler (2002).

6. General Conclusions and Future Research Proposals

Too much work can be done in the field of GSHP systems, and the facilities at VIA University College provide the possibility to test them and try to apply and spread them in Denmark, which seems to be a potential user of shallow geothermal systems.

Regarding the projects that can be run out at VIA University College which are aimed to the solar energy storage, a proposal in order to establish some procedures is given. An organised team is proposed in order to monitor undisturbed ground temperatures each month, execute TRT changing different parameters, measurement of more soil samples corresponding to the extracted cores which are stored in the deposit, study of different solar thermal panels and their performances, etc.

Another research way can be the attempt to obtain a procedure or test in order to determine the heat capacity of soil samples. An approach to the heat capacity can be the previous calculation of the thermal diffusivity.

Besides, in the coming months the installation of the heat pump in the WorldFlex House will be executed, so the testing of the real performance of the system will be possible. This will be the way to check the accuracy of the obtained results.

BHE and BTES seem to have a promising future since they give a feasible alternative to fossil fuel as a combination with other energy systems, particularly with solar thermal energy. These systems have much to say in nearly zero energy buildings approach and they are focused on the same aims the European Union aspires: reduction of GHG and improvement of the energy efficiency of buildings.

Finally, and returning to the beginning, it has been expected the reading of this dissertation has given an understandable introduction to the GSHP world in general and to the BHE in particular, contributing to the accessibility of this topic in order to make easier its deployment and make it part of a sustainable world.

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