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Geothermal energy: Model development and analysis of a pilot project

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Submission date: June 2016
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Norwegian University
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Department of Energy
and Process Engineering

EPT-M-2016-104

MASTER THESIS

for

Student
Cecilie Rindahl

Spring 2016

Geothermal energy: Model development and analysis of a pilot project

Geotermisk energi: Modellutvikling og analyse av et pilotprosjekt

Background and objective

A pilot geothermal installation based on two 800 m deep borehole heat exchangers (BHEs) and using a heat pump for temperature lift is under planning in Asker, Norway.

The main objective with the pilot project is to test whether the BHEs can be successfully installed and operated, and to provide practical experience and operational data which will be used in the planning of a larger ground source heat pump system (GSHP) for the Føyka- Elvely area in Asker commune.

The construction of the pilot project will start during spring – 2016. The boreholes will be equipped with coaxial borehole heat exchangers and will be instrumented with fiber-optical cables for temperature measurements.

The first objective of the thesis is to develop a calculation method to account for the thermal interaction between deep borehole heat exchangers. The calculation method can be developed using either analytical or numerical methods.

The second objective is to model the BHEs in the pilot project. This may be achieved using an existing numerical model developed at NTNU with further developments. Provided that measurement data are available from the pilot project within the time frame of the master thesis, the data shall be used to enhance and validate the model of the BHEs.

The following tasks are to be considered:

1. A literature study shall be performed regarding methods to account for the thermal interaction between borehole heat exchangers. This survey will form the basis for the development of a calculation method that can account for the thermal interaction between deep borehole heat exchangers. The methods shall be presented and discussed.
2. A calculation method taking into account the thermal interaction between several deep boreholes shall be developed. The model shall be based on previous works presented in the literature survey. The approach shall be decided in cooperation with the supervisors.
3. Use the interaction model developed in Pt. 2 to analyze the thermal interaction between deep boreholes, and to quantify the influence of the separation distance between deep boreholes. These results will result in basic criteria's for siting of deep boreholes. The results shall be presented and discussed.

4. A model for the performance of the BHEs in the pilot project shall be developed. An existing numerical model developed at NTNU can be used as the platform for further development. The model will initially be used to study the thermal and hydraulic performance of different collector solutions. In addition, strategies for thermal response tests will be studied. Alternative strategies for thermal response testing in deep boreholes (>500 m) shall be proposed and tested against the numerical model. Based on the results, recommendations for thermal response testing of the pilot project shall be made.
5. Suggestions for further work shall be made.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 13. January 2016

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Acknowledgements

This master's thesis has been written at the department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). The thesis is a continuation of the work done in the project report.

I would like to thank my supervisor Erling Næss for his guidance and support during the past year.

A special thanks to my co-supervisor Henrik Holmberg at NTNU/Asplan Viak, his help and knowledge has been invaluable during the work with this thesis.

I would also like to thank Otto K. Sønju at NTNU/Rock Energy and Randi Kalskin Ramstad at NTNU/Asplan Viak for their involvement and contributions.

Trondheim, June 2016

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Abstract

The objective of this study is to develop a calculation method taking into account the thermal interaction between several deep boreholes. Based on a literature study on heat transfer models, a hybrid model combining an existing numerical model with the analytical line source solution is developed. The main advantage of this model is that the accuracy of the numerical solution is maintained, but the grid complexity and computation time remains small when modelling a field with several boreholes. Time-varying heat loads are accounted for by using a temporal superposition technique. The model is used to study the thermal interaction between deep boreholes (> 500 m). The influence of separation distances between boreholes and heat rate are evaluated for operation periods up to 20 years. All the simulations are performed using a coaxial collector in the boreholes due to their good thermal performance and large flow area, which is especially important in deep boreholes. Doubling the heat extraction rate is shown to have a larger influence on the fluid outlet temperature than reducing the separation distance by half.

This thesis is written in parallel with the construction of a pilot project with deep boreholes in Asker, Norway, which are intended to cover a part of the base load demand for heating. Based on this pilot project, a case study of two 800 m deep boreholes with typical values for ground thermal conductivity and geothermal gradient is performed. Criteria regarding the minimum distance between the boreholes and maximum heat extraction rates are suggested, based on the resulting temperature level in the boreholes. When assuming an initial average borehole temperature of 13 °C and a constant heat extraction rate throughout the year, the two boreholes combined can provide a total energy amount of 340 MWh per year.

Thermal response testing using a constant heat injection rate is a common method to estimate the thermal properties of the borehole. In this work a numerical model is used to simulate thermal response tests, and the results are analyzed with the line source solution to obtain the ground thermal conductivity. An evaluation of the traditional response test showed that this method is not accurate for deep boreholes, mainly due to the significant temperature and heat rate variations along the borehole axis. Additionally, a large power source would be required to conduct this type of test in a deep borehole. Alternative methods are tested, first using a constant inlet temperature and a variable heat rate through the direct use of cold tap water as circulation fluid. Due to unsatisfactory results, the method is improved by using a variable mass flow and thereby obtaining a constant heat rate throughout the test. The tests are simulated and analyzed with local borehole wall and fluid temperature measurements. It is shown that a minimum difference of 10 degrees between the inlet temperature and the undisturbed ground temperature is required to avoid large mass flows and inaccurate conductivity estimations. Applying this criterion, the thermal conductivity is estimated with an error of less than 3 %. However, an actual field test will naturally contain additional sources of errors.

Sammendrag

Formålet med dette arbeidet er å utvikle en beregningsmetode som tar hensyn til den termiske interaksjonen mellom flere dype borehull. Basert på et litteraturstudie om varmeoverføringsmodeller er en hybrid modell blitt utviklet, som kombinerer en eksisterende numerisk modell med den analytiske linjekildemodellen. Den viktigste fordelen med denne modellen er at nøyaktigheten i den numeriske løsningen er opprettholdt, mens kompleksiteten i det numeriske rutenettet og beregningstiden fremdeles er lav ved modellering av et felt med flere borehull. Variasjoner i varmeraten over tid blir superposisjonert. Modellen brukes for å studere den termiske interaksjonen mellom dype borehull (> 500 m). Påvirkningen av avstanden mellom borehullene og varmeraten blir evaluert for operasjonstider opp til 20 år. Alle simuleringene blir utført med en koaksial kollektor i borehullet grunnet den gode termiske ytelsen og store strømningsareal, noe som er spesielt viktig i dype borehull. En dobling av varmeuttaksraten viste seg å ha en større innflytelse på utløpstemperaturen fra borehullet enn en halvering av avstanden mellom borehullene.

Denne oppgaven er skrevet parallelt med utviklingen av et pilotprosjekt med dype borehull i Asker, Norge, som skal brukes til å dekke en del av grunnlasten av oppvarmingsbehovet. Basert på dette pilotprosjektet er et casestudie av to 800 m dype borehull utført, med typiske verdier for berggrunnens termiske konduktivitet og geotermisk gradient. Kriterier for minimum avstand mellom borehullene og maksimal varmeuttaksrate blir foreslått, basert på det resulterende temperaturnivået i brønnene. Under antakelsene om en gjennomsnittlig initial borehullstemperatur på 13 °C og en konstant varmeuttaksrate gjennom hele året, blir det beregnet at de to borehullene til sammen kan levere en total energimengde på 340 MWh per år.

Termisk responstesting ved bruk av en konstant varmetilførselsrate er en vanlig metode for å estimere de termiske egenskapene til borehullet. I dette arbeidet blir en numerisk modell brukt til å simulere termiske responstester, og resultatene fra disse blir analysert med linjekildemodellen for å bestemme berggrunnens termiske konduktivitet. En evaluering av den tradisjonelle responstesten viser at denne metoden ikke gir nøyaktige resultater i dype borehull, hovedsakelig grunnet de betydelige variasjonene i temperatur og varmerate langs borehullsaksen. I tillegg vil det kreves tilgang på en stor strømkilde for å kunne utføre denne typen test i et dypt borehull. Alternative metoder blir derfor testet, først ved bruk av en konstant innløpstemperatur og en variabel varmerate ved direkte bruk av kaldt nettvann som sirkulasjonsvæske. Grunnet utilfredsstillende resultater blir metoden forbedret ved å bruke en variabel massestrøm for å oppnå et konstant varmeuttak gjennom hele testen. Testene blir simulert og analysert med lokale temperaturmålinger fra borehullsveggen og sirkulasjonsvæsken. Det blir vist at en minimum differanse på 10 grader mellom innløpstemperaturen og den uforstyrrede bergtemperaturen er nødvendig for å unngå store massestrømmer og unøyaktige estimeringer av konduktiviteten. Ved anvendelse av dette kriteriet blir konduktiviteten estimert med en feil på under 3 %. Imidlertid vil en reell test i felt naturligvis inneholde flere feilkilder.

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Nomenclature

Symbols

B	Borehole width	[m]
c_p	Specific heat capacity of the ground	[J kg^{-1} K^{-1}]
$c_{p,water}$	Specific heat capacity of water	[J kg^{-1} K^{-1}]
d_1	Outer diameter of center pipe	[mm]
d_2	Inner diameter of external pipe	[mm]
dr	Radial element in numerical grid	
D_h	Hydraulic diameter	[m]
E_1	Exponential integral	
f	Friction factor, Eq. 10	
Fo	Fourier number $= \alpha t/r^2$	
H	Borehole depth	[m]
J_0	Bessel function of the first kind	
J_1	Bessel function of the first kind	
k_g	Ground thermal conductivity	[W m^{-1} K^{-1}]
$Lstep$	Number of days between update of border condition	
$\dot{m}$	Mass flow	[kg s^{-1}]
N_r	Number of radial elements in the numerical grid	
P	Pressure	[Pa]
Q	Heat rate	[W]
$\dot{q}$	Heat rate per unit length of borehole	[W m^{-1}]
$\dot{q}_{gen}$	Generated heat per unit volume	[W m^{-3}]
Re	Dimensionless Reynolds number, defined in Eq. 9	
R_b^*	Effective borehole thermal resistance, defined in Eq. 7	[m K W^{-1}]
r	Radius or radial coordinate	[m]
r_b	Borehole radius	[m]
s	Pipe thickness	[mm]
T	Temperature	[°C]
t	Time	[s]
t_s	Steady state time, $t_s = H^2/9\alpha$	[s]
V	Fluid velocity	[m s^{-1}]
Y_0	Bessel function of the second kind	
Y_1	Bessel function of the second kind,	
z	Axial coordinate	[m]

Greek letters

α	Ground thermal diffusivity	[m^2 s^{-1}]
ε	Surface roughness height	[m]
φ	Circumferential coordinate	[rad]
μ	Dynamic viscosity	[kg m^{-1} s^{-1}]
ρ	Density	[kg m^{-3}]

Subscripts

b	Boundary
bh	Borehole wall
f	Circulation fluid
g	Ground
in	Inlet
out	Outlet

Abbreviations

BHE	Borehole heat exchanger
COP	Coefficient of Performance
DTRT	Distributed thermal response test
PE	Polyethylene
PP	Polypropylene
TRCM	Thermal resistance and capacity models
TRT	Thermal response test

1. Introduction

The use of geothermal energy is increasing, and new and more efficient ways to utilize this large renewable energy source are in constant development. The ground coupled heat pump system utilizes boreholes in the ground as heat source or heat sink for heating or cooling of buildings. The temperature in the ground is only affected by the fluctuations in the ambient air temperature down to a depth of about 15 to 20 m [1]. Below this depth the temperature will usually increase due to the geothermal gradient, and it is more or less constant throughout the year and independent of the seasonal fluctuations. This property makes the ground a suitable source for heating and cooling of buildings, and ground source heat pumps provide a higher energy efficiency than for example air source heat pumps.

There are several ways to utilize the geothermal energy, and both horizontal and vertical ground heat exchangers are common [2]. Vertical heat exchangers are usually classified either as open or closed loop systems. In an open loop the groundwater is used directly as heat source for the heat pump, while a closed loop utilizes a heat carrier fluid which circulates in pipes within the drilled boreholes. The aim of this thesis is to model and evaluate vertical, closed loop systems.

The drilling of the boreholes represents a significant part of the high initial costs of ground coupled heat pump systems. Accurate performance simulations are therefore important to avoid an unnecessary over dimensioning of the system, but still ensure that the system will cover the heating or cooling demand. Large geothermal systems usually consist of more than one borehole, which after some time of operation will interact with each other. Knowledge of the heat transfer process is necessary to avoid excessive thermal interaction between the boreholes and by that a reduction in the performance and the energy efficiency of the system over time.

Since the temperature increases with depth, an advantage of drilling deeper boreholes is that a large amount of energy can be extracted within a small surface area. Systems with many boreholes require a lot of space, and in areas where this is not available, a solution can be to increase depth and thereby reduce the number of required boreholes. Additionally, the temperature level in deep boreholes is higher, which increases the amount of energy available per borehole meter. The heat pump efficiency is also improved since the required temperature lift is reduced. However, this increased temperature level also makes deep boreholes less suitable for cooling.

1.1. Objectives

The objectives of this work is to develop a calculation method to study the thermal interaction between several deep boreholes. Based on the results, the goal is to be able to define a criterion for a minimum distance between the boreholes of an installation to obtain the desired long term performance. In addition, the thermal and hydraulic performance of the borehole collector is to be evaluated, along with a study of existing and possible future methods for thermal response testing for deep boreholes. The findings were supposed to be validated against field data, but due to a delay in the development of the pilot project, data from the boreholes was not available within the time frame of this thesis.

1.2. Structure

This thesis is divided in two main parts; Chapter 2-5 consists of a model development and a study of the thermal interaction between boreholes, while Chapter 6 and forward will focus on the performance and response testing of the borehole heat exchangers.

Chapter 2 provides background information regarding the ground as an energy source and methods to evaluate and utilize this energy.

The literature study in Chapter 3 will form the basis for the development of the calculation method to be used in the evaluation of the thermal interaction between multiple boreholes.

In Chapter 4 the proposed calculation method is described, and the results from this model are presented in Chapter 5.

Chapter 6 contains an evaluation of the thermal and hydraulic performance of the coaxial borehole heat exchanger.

In Chapter 7 current methods for thermal response testing are evaluated, and new methods for deep boreholes are examined.

Chapter 8 contains conclusions and suggestions for further work.

2. Background

A vertical, closed loop geothermal heating or cooling system consists of three principal components; the boreholes containing the ground heat exchanger, a heat pump and a distribution system in the buildings. This thesis focuses on the first component, which provides the heat transfer from the ground to the entrance of the heat pump.

2.1. Collector types

The collector serves as a heat exchanger between the circulation fluid and the surrounding ground, and the two main types are U-tube and coaxial collectors [3]. However, for commercial applications the U-tube is the most common, and most of the existing literature focuses on the modelling of the U-tube.

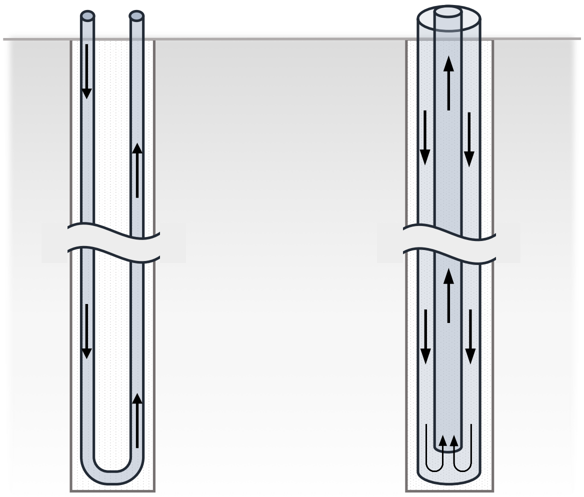

Figure 1. U-tube collector (left) and coaxial collector (right). Based on Gehlin [1]

Newer studies indicate that the coaxial collector may have better thermal performance than the traditional U-tube. U-tube collectors may experience thermal shortcutting due to undesired heat transfer between the upward and downward flow, which will reduce the overall efficiency of the borehole heat exchanger (BHE). In a coaxial collector the inner pipe can be isolated to reduce heat transfer between the flows, and the flow area for the circulation fluid is also larger, thereby reducing the pressure losses in the collector.

Expressions for the thermal resistance between the circulation fluid and the borehole wall have been developed by Hellström [4] for different types of collectors. Lower effective thermal resistance will mean a lower temperature difference between the circulation fluid and the surrounding ground and therefore a higher outlet temperature from the collector.

2.2. Thermal response testing

A thermal response test (TRT) evaluates the temperature change in the ground as a function of an injected or extracted heat rate, with the objective of determining the most important thermo physical properties of the geothermal system [1]. A field test usually last for about 72 hours, and the typical setup of equipment in a traditional response test is shown in Figure 2. The circulation fluid temperatures T_{f1} and T_{f2} are measured at the inlet and outlet of the borehole.

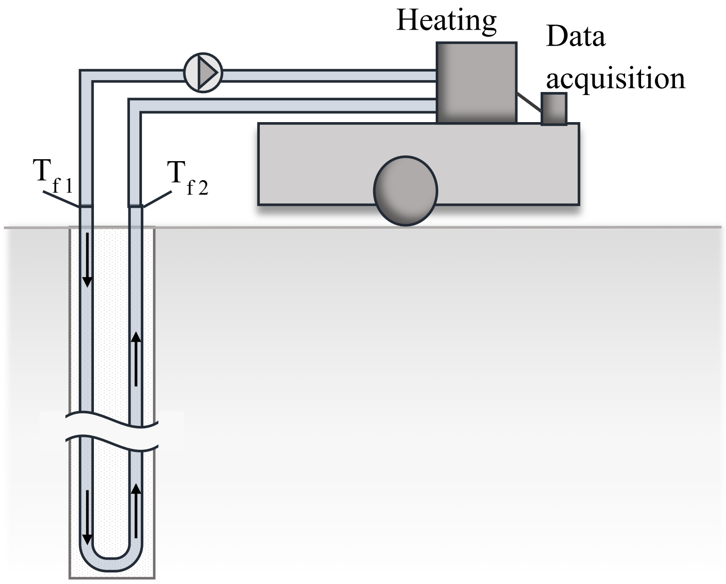

Figure 2. Typical setup of a field TRT with heat injection. Based on Gehlin [1]

This method allows the determination of the thermal conductivity of the ground and the thermal resistance between the circulation fluid and the ground. Before initiating the heat extraction/injection, the undisturbed temperature of the ground is usually measured. This can be done either by circulating the fluid and measuring the average temperature, or by manually measuring the temperature at different sections of the borehole to obtain the temperature profile. The response test can be performed either by injecting or extracting heat. However, for practical reasons, heat injection is the most common since less equipment is required to heat the circulation fluid than to cool it down.

Newer methods for field testing of boreholes include distributed thermal response tests (DTRT), which consists of using an optical fiber cable to measure the temperature profile in the borehole during the test [3]. As opposed to a traditional TRT, which only provides average values, a DTRT can provide valuable information about the different sections along the depth of the borehole.

2.3. Thermal interaction between boreholes

In an area with multiple boreholes close together the boreholes will be influenced by each other, which in the long term affects the performance of the system. The amount of thermal interaction will depend on the distance between the boreholes, the extracted or injected heat rate and the operation time of the system [5].

3. Heat transfer models

In this chapter various methods to model the heat transfer in the ground and evaluate the thermal interaction between borehole heat exchangers are presented. The models are divided into analytical and numerical methods. The modelling of the transfer in ground coupled heat pump systems is normally divided into two separate regions, which are then coupled through a common parameter, usually the borehole wall temperature [6]. The first region is within the borehole, consisting of the circulation fluid, the collector and the grout or groundwater surrounding the collector pipes. The second region consists of the ground surrounding the borehole. The borehole wall temperature is determined by the heat transfer analysis of the ground outside the borehole, and this temperature is then used to determine the heat transfer process within the borehole. The heat transfer in the ground is usually analyzed as a pure conduction process, neglecting the effects of possible groundwater movements.

Although the ground surrounding the borehole is non-homogeneous, a common simplification is to assume that the ground is homogeneous with constant thermal properties, using mean values for thermal conductivity and diffusivity. These values can be obtained from a field thermal response test, as described in Chapter 2.2.

When assuming pure conduction in the ground surrounding the borehole, the heat transfer analysis is reduced to solving a single equation. The general heat conduction equation has the following form in cylindrical coordinates

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}_{gen}}{k_g} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

The first to terms in this equation represent the radial heat flux. The third and fourth term represent the heat flux in the circumferential and axial direction, respectively, which are usually considered negligible in the analytical models. Axial effects can usually be neglected for short-time simulations without introducing large errors, but they become increasingly important as the simulated operation time increases.

3.1. Analytical methods

The most common analytical solutions to the heat conduction equation used for borehole heat exchangers are presented in the following chapters. Analytical models are extensively used due to their high flexibility, simplicity and short computational time. However, these benefits are achieved at the expense of the level of detail in the analysis and a larger amount of simplifications and assumptions. In most analytical models the ground surface temperature is assumed to be constant and equal to the ground temperature, and variations in temperature and heat rate along the borehole axis are usually neglected.

3.1.1. Infinite line source solution

One of the simplest solutions to the heat equation is Kelvin's line source solution, which assumes that the borehole is an infinite line with a constant heat flow rate, in an infinite medium. The ground initially has a uniform temperature T_g, and a relation derived by Ingersoll and Plass [7] provides the temperature change at a given point and time with respect to the undisturbed initial temperature. The equation yields

$$T(r,t) - T_g = \frac{\dot{q}}{4\pi k_g}\int_u^{\infty}\frac{e^{-u}}{u}du = \frac{\dot{q}}{4\pi k_g}E_1\left(\frac{r^2}{4\alpha t}\right) \tag{2}$$

where $u = \frac{r^2}{4\alpha t}$, k_g is the ground thermal conductivity and α the thermal diffusivity. E_1 is the exponential integral.

The assumption of negligible heat transfer in the axial direction is justified by the fact that the diameter of the borehole is very small compared to the length, and the assumption is valid at depths far from the surface. The infinite line source is commonly used to evaluate thermal response tests, by assuming that the average between the inlet and outlet temperature represents the average circulation fluid temperature. The exponential integral is then evaluated with r being equal to the borehole radius, and by introducing a borehole thermal resistance the circulation fluid temperature can be expressed by the following equation.

$$\bar{T}_f(t) = \frac{\dot{q}}{4\pi k_g}E_1\left(\frac{r_b^2}{4\alpha t}\right) + \dot{q}R_b^* + T_g \tag{3}$$

For a constant heat rate the last to terms of this equation are constant over time, so the thermal conductivity k_g can therefore be determined by the slope of the temperature development of the circulation fluid over time. Once the thermal conductivity is known, the effective thermal resistance can be determined by using a curve fitting method. To simplify the analysis, the exponential integral is usually solved by a linear expansion.

A disadvantage of the infinite line source solution is that it never reaches a steady-state condition, that is, the temperature tends to infinity as time tends to infinity, due to the constant heat rate. This is obviously not the case for a real process, as the heat flow between the borehole collector and the ground requires a temperature gradient in the opposite direction.

3.1.2. Cylindrical source solution

In the solution presented by Carslaw and Jaeger [8], the borehole heat exchanger is represented by a cylinder with a constant heat extraction rate over the cylinder surface. As in the line source solution, the borehole is assumed to be infinitely deep. Considering only radial heat transfer, the temperature change at a given time and radius is given by

$$T(r,t) - T_g = \frac{\dot{q}}{k_g} G(Fo,p) \tag{4}$$

where

$$Fo = \frac{\alpha t}{r^2}$$
$$p = \frac{r}{r_b}$$

The G-factor is given by Equation 5, where J_0 and J_1 are Bessel functions of the first kind, and Y_0 and Y_1 are Bessel functions of the second kind.

$$G(Fo,p) = \frac{1}{\pi^2} \int_0^{\infty} \frac{\left(e^{-\beta^2 z} - 1\right)}{\beta^2 [J_1^2(\beta) + Y_1^2(\beta)]} [J_0(p\beta) Y_1(p\beta) - Y_0(p\beta) J_1(\beta)] \partial\beta \tag{5}$$

Neither the infinite line source nor the cylindrical source solution are accurate for large time periods of several years, as they neglect the axial heat transfer.

3.1.3. Finite line source solution

The finite line source was first applied to the study of borehole heat exchangers by Eskilson [6], and later further developed by Zeng et. al [9], Diao et. al [10] and Lamarche and Beauchamp [11]. Considering the borehole as a line source of finite length, the model gives an analytical solution of the transient heat conduction around the borehole [9]. In this solution the surrounding ground is considered a homogeneous semi-infinite medium, with the boundary being the ground surface. The temperature is assumed constant at the boundary surface. Mathematically this is achieved by superimposing a virtual line with negative strength above the surface and opposite to the borehole, thereby including the effect of the ground surface and achieving the isothermal boundary condition. As in the infinite line and cylindrical source solution, the heat rate is assumed to be constant. However, the finite line source will approach a steady state condition as time tends to infinity.

3.1.4. Temporal and spatial superposition

Temporal superposition can be applied to account for variations in the heat extraction rate, while the effect of multiple boreholes can be included in the analysis by spatial superposition. The superposition technique requires that the equations are linear, which for the case of the heat conduction equation means assuming that the thermal properties of the ground are independent of the temperature [4]. Koohi-Fayegh and Rosen [12] compared a numerical solution and a solution using the line source with the superposition method, and obtained similar results with both methods. They concluded that for constant heat rates, the analytical solution can be just as accurate as the numerical. This conclusion is in accordance with the findings of Eskilson [6], who determined that the error when using the superposition principle is negligible.

3.2. Numerical methods

The three main methods for solving the heat conduction equation numerically are through finite differences, finite elements and finite volumes. Numerical models have fewer limitations than the analytical models. However, many of the same simplifications are often maintained, for example neglecting groundwater movement and assuming a homogeneous ground.

3.2.1. Eskilson's g-functions

Combining numerical and analytical methods, Eskilson [6] defined the dimensionless temperature response function g, which gives the temperature drop/increase at the borehole wall for a given heat extraction/injection rate, as a function of various non-dimensional factors.

$$T_b - T_g = \frac{\dot{q}}{2\pi k_g}\, g(t/t_s, r_b/H, B/H) \tag{6}$$

Eskilson calculated the g-functions for several borehole configurations using the numerical finite difference method, assuming a uniform borehole wall temperature along the whole borehole depth. For the case of multiple boreholes, the temperature was calculated by superimposing the temperature distribution of each borehole. However, these solutions are only valid for the given configuration, and interpolation is therefore required when applying the g-functions in a design process. Further contributions to this method were made by Lamarche and Beauchamp [11] and Cimmino and Bernier [13], using the analytical finite line source solution to generate g-functions.

3.2.2. Two-dimensional models

A two-dimensional model can be applied under the assumption that the heat transfer in the axial direction is negligible. Koohi-Fayegh and Rosen [5] solved the transient heat conduction equation in two dimensions using a finite volume approach in FLUENT. For the analyzed system with two boreholes the effects of circumferential heat transfer were included as well as the radial heat transfer. The model showed good agreement with the analytical line source solution. Further comparison with a three-dimensional model [14] showed that the solution in two dimensions was valid for about 96 % of the borehole length. However, the axial heat transfer was found to not be negligible at the upper and lower part of the borehole.

3.2.3. Three-dimensional models

Three-dimensional models are able to include the axial effects in the heat transfer analysis, but naturally these methods usually require larger computation time. Several models have been developed by different authors. Lee and Lam [15] applied the finite difference method using a rectangular coordinate system, assuming quasi-steady state conditions inside the boreholes. The ground surrounding the boreholes was discretized, and each borehole was represented by a square column. Koohi-Fayegh and Rosen [14] applied a finite volume method using FLUENT software. Utilizing the symmetry in the heat transfer both in the vertical and horizontal direction, the solution domain can be reduced to one eighth of the total borehole field. The initial undisturbed temperature was assumed to be equal for the entire field, and the heat flux across the borehole wall was also assumed to be constant along the borehole depth.

3.2.4. Hybrid models

Wetter and Huber [16] developed a quasi three-dimensional model by dividing the borehole into different vertical sections, and solving the heat transfer in the ground numerically within a radius of two meters around the borehole. The outer boundary conditions were defined by using the analytical line source to calculate the temperature on a weekly basis, and this boundary condition was held constant for the following week. This method reduces the necessary size of the numerical grid and hence the number of elements, and it also reduces the complexity of the grid when evaluating a system of boreholes. Heat extraction rates starting at different time steps were superimposed to account for variations over time.

3.3. Heat transfer inside the borehole

In most of the solutions for the heat transfer inside the borehole, the borehole wall temperature is required, which is obtained from the previous analysis of the heat conduction in the surrounding ground. The heat transfer analysis between the circulation fluid and the borehole wall can then be solved with different approaches. The simplest solution is based on the effective borehole thermal resistance first presented by Hellström [4], which can be defined by the average circulation fluid temperature and the average borehole wall temperature.

$$\bar{T}_f - \bar{T}_{bh} = \dot{q} R_b^* \tag{7}$$

R_b^* is the effective thermal resistance per unit length, which includes the convection between the circulation fluid and the collector, conduction in the collector pipes and conduction in the grout or groundwater surrounding the collector. The borehole resistance will depend on the type of collector and the position of the collector in the borehole, among other factors.

3.4. Discussion

An advantage of the analytical models is that they are simple to use and easily applied to different borehole configurations, but when including temporal variations, the computation time becomes large for long simulation periods. On the other hand, numerical methods have a higher accuracy and can take into account many of the processes that are excluded in the analytical models. However, this increased complexity also increases the computation time, which is why the numerical models are usually more suitable for a theoretical analysis rather than in a design process. The borehole geometry also presents challenges in the numerical modelling, mainly related to the high aspect ratio, that is, the length of the borehole compared to the width. For long term simulations the size of the solution domain becomes very large, and a large number of grid elements is required to achieve an accurate solution.

The linearity of the heat equation allows for the use of superposition methods. This property has been utilized by many authors, both to account for temporal variations in heat rate and also to evaluate multiple boreholes. However, an analysis of a three-dimensional simulation performed by Lee and Lam [15] showed that superimposing the results obtained from a single borehole would not predict precisely the performance of a borehole field. They conclude that a better solution for systems with multiple boreholes is to discretize and simulate the whole field simultaneously.

In a real borehole the temperature and the heat rate will vary along the axis of the borehole and both will usually increase with increasing depth. The variations from top to bottom will therefore be more significant for deep boreholes, and this will also influence the amount of thermal interaction between a group of boreholes.

3.5. Conclusion

For the reasons mentioned above, a numerical model is considered to be the most suitable for the applications in this work. Precision is given a higher priority than short computation time, since the main purpose is to analyze a given borehole configuration rather than designing and optimizing a system. A model which can account for the changes in heat rate and fluid outlet temperature as a result of thermal interaction is required to accurately evaluate the influence of surrounding boreholes. This also justifies the choice to use a numerical model in this work. In order for the numerical simulation to be accurate, the grid has to be sufficiently large so that the solution is not affected by the boundary conditions, which in this case is the ground temperature being constant at a distance far from the borehole. However, this requires a large grid and hence a large simulation time. The geometry of a radial grid is also a challenge when including multiple boreholes, due to the requirement of a high resolution close to the borehole. The principles used in the hybrid model described in Chapter 3.2.4 will therefore be used to deal with the challenges related to the numerical grid in a field with multiple boreholes. Since the heat rate variations along the borehole depth will be significant as the depth increases, it is desirable to have a model that can take into account the effect of both temperature and heat rate variations, since one of the objectives of this work is to study deep boreholes. Both temporal and spatial superposition will be applied, but for each time step the whole borehole field will be modeled simultaneously.

4. Development of calculation method

One of the main objectives of this thesis is to develop a calculation method for the heat transfer for multiple deep boreholes, taking into account the thermal interaction between them. The main reason for developing a new method instead of basing the research on existing models is to have full flexibility in terms of borehole geometry and configurations, in addition to having full transparency in the calculations. This will also facilitate the study of the thermal interaction and the influence of the separation distance between the boreholes, which is one of the main goals of this work.

4.1. Model formulation

The proposed model in this work is a hybrid method combining numerical and analytical models, and using the superposition technique to account for the influence of surrounding boreholes. The challenges regarding the numerical grid are solved by using the line source solution to calculate the temperature at a given radius, allowing for the boundary conditions of the numerical model to change according to the time and heat flux in the BHE. The analytical line source solution is applied at certain radius from the borehole, through the equations presented in Chapter 3.1.1. The line source is preferred due to its simplicity and short computation time, given that the line source and the cylinder source provide the same solution for large time scales.

Since the temperature at some distance from the borehole is not affected by the heat flux variations on a short time scale, the temperature at the boundary will be calculated with a larger time step than the numerical part of the model. This is achieved by using the average heat flux in the evaluated period and superimposing the contribution from each time step, as shown in the figure below.

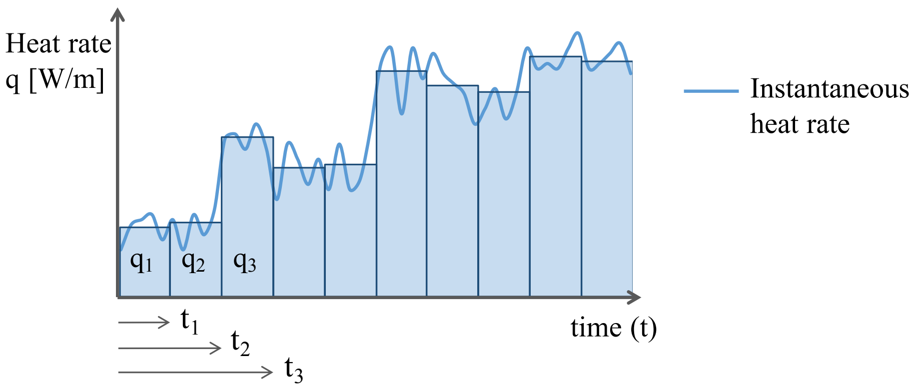

Figure 3.Time-averaged heat rate and temporal superposition

Using average values within a certain time period will greatly reduce both the required memory and the computation time, and the maximum time step will be decided through an evaluation of the temperature change. The resulting choice will be a compromise between computation time and error in the solution.

The superposition technique [17] used to account for variable heat rates with the line source solution is given by Equation 8. The resulting equation when applying this to the three time intervals from Figure 3 is shown below, where t_0 is equal to cero.

$$\Delta T = \frac{1}{4\pi k_g}\sum_{i=1}^{n}\dot{q}_i[E_1(t_n - t_{i-1}) - E_1(t_n - t_i)] \qquad (8)$$

$$= \frac{1}{4\pi k_g}\left[\dot{q}_1\big(E_1(t_3) - E_1(t_3 - t_1)\big) + \dot{q}_2\big(E_1(t_3 - t_1) - E_1(t_3 - t_2)\big) + \dot{q}_3\big(E_1(t_3 - t_2)\big)\right]$$

To minimize the error, the exponential integral in the line source solution is computed numerically using the *integral* function in Matlab for each time step.

The heat transfer within a certain radius of the BHE as well as the inside of the borehole is computed numerically. This solution will be based on an existing three-dimensional finite difference model, developed by Henrik Holmberg [18]. This model uses the concept of thermal resistance and capacity models (TRCM), a simplification which represents the different parts of the borehole by single nodes with associated thermal capacities and resistances. The thermal processes within the borehole are then coupled to a two-dimensional axisymmetric cylindrical grid in the surrounding ground. The heat transfer in the ground is assumed to be pure conduction, thereby neglecting possible contributions from groundwater movement.

A significant difference between Holmberg's model and other existing models is that it takes into account the effects of the non-grouted borehole, that is, a borehole filled with groundwater instead of a grouting material, which is common practice in Norway. Research has shown that the differences between a grouted and a groundwater filled borehole are significant, mainly due to the effects of natural convection in the water [19]. The natural convection is caused by the density gradients in the water, which are induced by extracting or injecting heat through the BHE. Natural convection is accounted for by introducing the non-dimensional Nusselt number, which is the ratio between the pure conduction heat transfer coefficient and the effective heat transfer coefficient including the contributions from natural convection. The effects of natural convection are primarily important for U-tube collectors, and not as important for coaxial collectors.

In order to achieve a more realistic representation of the temperature in the ground and the resulting heat rates, a geothermal gradient is assumed, with the average initial temperature being equal to the undisturbed temperature in the ground. Both the temperature and the heat flux across the borehole wall will therefore vary along the borehole depth. The axial heat transfer is considered negligible for operation periods of less than five years, but it is included when simulating larger time periods.

Figure 4 illustrates the difference between Holmberg's numerical model and the proposed model using a boundary condition calculated with the line source solution. The number of radial elements is greatly reduced, resulting in a shorter simulation time.

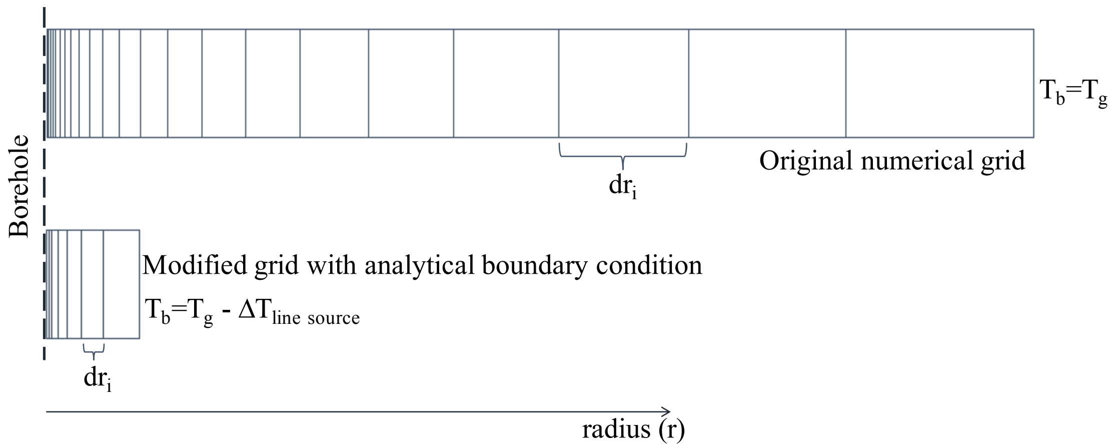

Figure 4. Comparison of grid and boundary condition in original and proposed model

The figure also illustrates the use of the line source solution to define the boundary condition at the border of the numerical grid. The temperature changes at this border caused by heat injection or extraction from the BHE is added to the undisturbed ground temperature to obtain the actual temperature.

4.1.1. Modeling a borehole field

The model described in the previous chapter is used to evaluate the thermal interaction in a field with multiple boreholes. The additional temperature change caused by a neighboring BHE is calculated at the border of the numerical grid, thereby modifying the boundary condition of the first borehole. The total temperature rise is obtained by adding the contribution from each borehole to the boundary condition of the first borehole, and the line source calculation is therefore performed once for each borehole. This is illustrated in the figure below for the case of two boreholes.

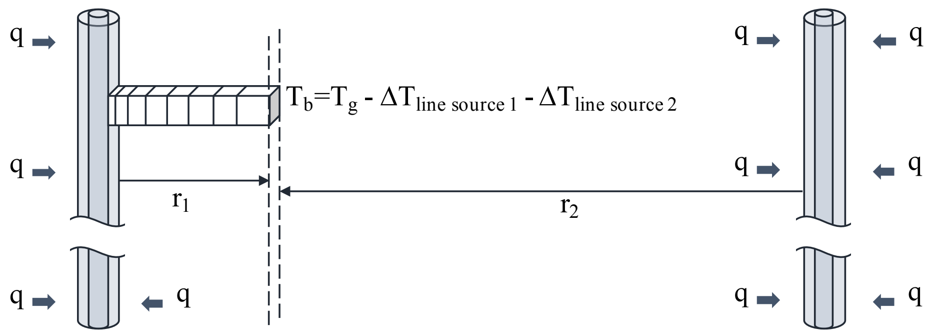

Figure 5. Change of boundary condition due to neighboring boreholes

The border of the numerical grid is a circle around the center of the borehole. However, the boundary condition is only calculated for a single point at a given distance, even though the influence from a neighboring BHE will be different at different positions on this circular border. For example, the point in between the two boreholes will experience a larger temperature change than the point at the opposite side of the borehole. To simplify, it is assumed that using the distance between the centers of the two boreholes in the line source calculation gives a sufficiently good approximation of the average influence on the border surrounding the borehole. This is illustrated in the Figure below, where the color represents the temperature influence from the adjacent borehole.

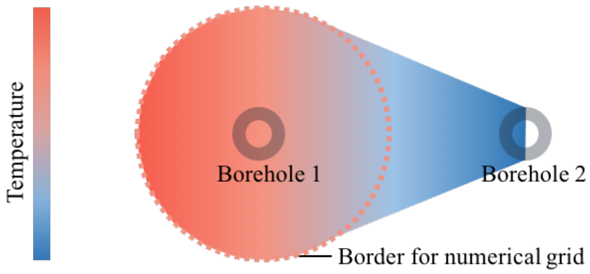

Figure 6. Temperature influence on the border of the numerical grid

To verify that this simplification is acceptable, an analysis of the boundary condition calculation is performed. The radial size of the numerical grid is set to 2 m, and the average specific heat extraction rate to 30 W/m. The temperature decrease caused by a neighboring borehole at a distance of 20 m is calculated for the two points of the border of the numerical grid that are closest and furthest away, and compared to the influence at the center of the borehole.

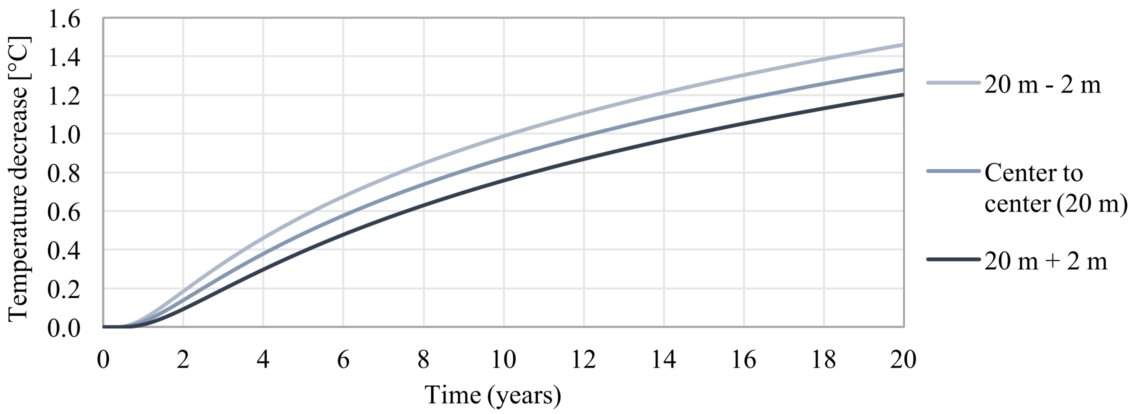

Figure 7. Average temperature decrease caused by neighboring BHE at different points in the numerical grid

Figure 7 shows the average temperature decrease over time, and it can be observed that the difference in temperature change at the different points is relatively small. After 20 years of operation, the difference between the point furthest away and closest to the neighboring borehole is only about 0.26 degrees.

Figure 8 shows the distribution of the temperature decrease along the borehole depth caused by the neighboring borehole, after a simulated operation time of 20 years.

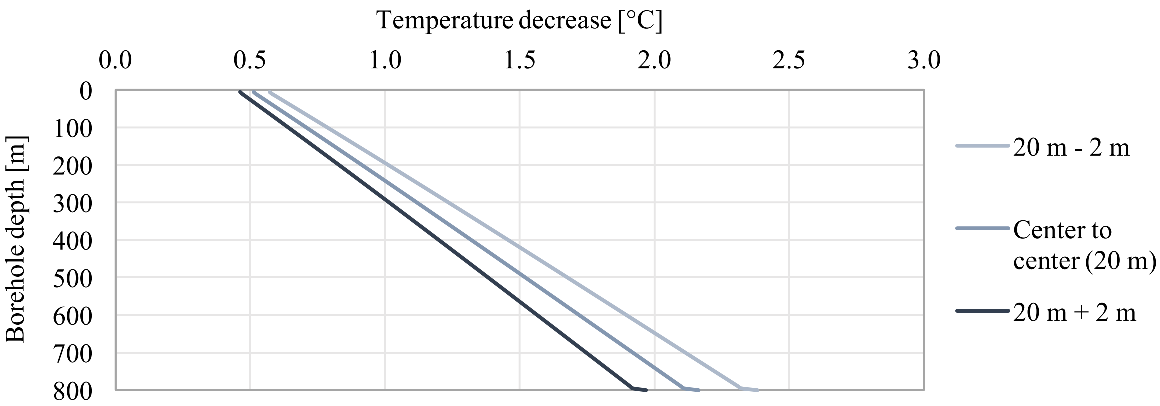

Figure 8. Distribution of temperature decrease caused by neighboring BHE after 20 years

The largest differences are at the bottom of the borehole, where the point closest to the neighboring borehole experiences a temperature decrease of 2.38 degrees, and the point furthest away experiences a temperature decrease of 1.97 degrees. The temperature decrease calculated at the center of the borehole is 2.16 degrees, which is a little less than the average of the two points. This gives a maximum deviation of 0.22 degrees between the center of the borehole and the border of the numerical grid. Naturally this value will increase if the heat rate or the size of the numerical grid is increased, or if the distance between the boreholes is reduced. However, the values used in this analysis are realistic in terms of future application of the model in this work. Based on this, using the temperature change at the center of the borehole is considered a reasonable estimation of the average influence on the boundary condition.

4.2. Verification of the model

To verify the accuracy of the proposed model, the results of the simulations are compared to the original numerical model. Holmberg´s numerical model has previously been evaluated using measurements both from a distributed thermal response test and from heat pump operation [20]. It showed good agreement with the measured data, and will therefore be used as a basis to evaluate the accuracy of the model proposed in this work.

Since each simulation with different input parameters creates a new radial grid, the resulting temperature outputs are interpolated in Matlab in order to compare the temperature at the same distance from the borehole. This interpolation will introduce some small errors in the comparison of the two models, but it will not affect the comparison of the wall temperatures.

Increased resolution in the numerical grid, that is the ratio between the number of radial elements (N_r) and the size of the grid (r) will improve the accuracy of the model, but a large number of radial elements will also increase the computation time. For the numerical part of the calculation, it would therefore be an advantage to use use a short radius on the numerical grid. However, this would also require the boundary condition to be updated more frequently. The final choice of values will therefore be a tradeoff between different considerations, and the model is therefore analyzed further to evaluate how much each parameter affects the accuracy of the calculations. As opposed to the numerical part of the model, the calculation time of the line source solution is not proportional to the simulated operation time, since the equation to be solved will have an extra term for each time step. Reducing the frequency of the boundary condition calculation is therefore given higher priority than reducing the size of the numerical grid.

The results from six simulations are shown in Figure 9, for a simulated operation period of five years. Lstep is the number of simulated days between each update of the boundary condition. It is observed that when using a fine grid with high resolution, there is a very good agreement between the two models, but the error increases significantly when either increasing the grid radius or reducing the number of radial elements. The time interval between the update of the boundary condition is shown to have little influence on the final result, and can therefore be increased to reduce the computation time.

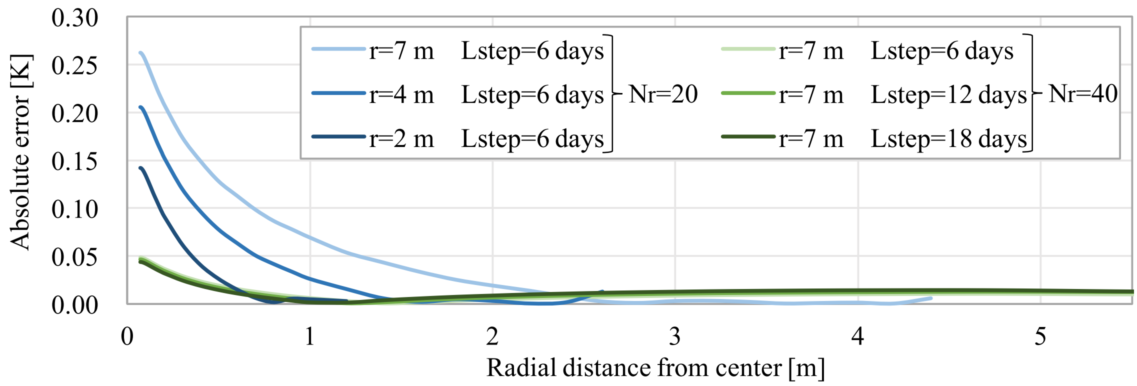

Figure 9. Error in proposed model compared to original numerical model

Based on the results shown in the figure above, it can be concluded that the most important factor to achieve high accuracy in the proposed model is the grid resolution. A small radius is therefore chosen, combined with a relatively high number of radial elements and a low frequency for the update of the boundary condition.

A maximum temperature deviation of 0.02 °C between the full numerical and the proposed model is considered to be acceptable, and this criterion is used to define the values to be used for the three parameters. The simulations in the following chapters are therefore performed with N_r=30 elements, r=2 m and Lstep=30 days.

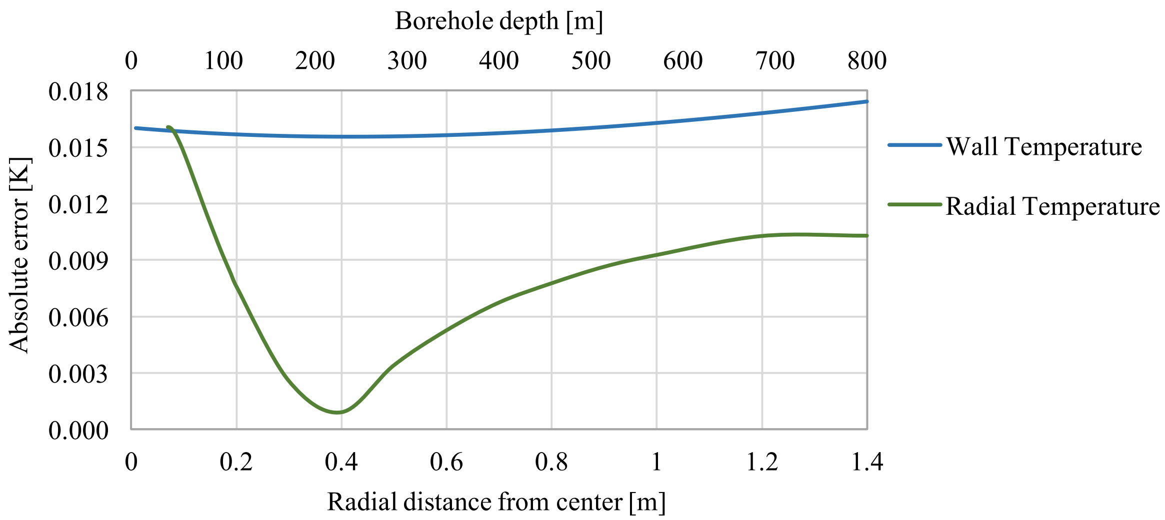

Figure 10. Error in proposed model using N_r=30 elements, r=2 m and Lstep=30 days

Figure 10 shows the absolute error in the temperature calculations when using the chosen parameters for a simulation period of five years. An average specific heat rate of 20 W/m is used in these simulations. The resulting maximum error of 0.018 degrees is considered to be acceptable for this application. The error in the wall temperature increases slightly with increasing borehole depth since the specific heat rate is larger towards the bottom of the borehole. This will increase the temperature change at the numerical border for each time step, and therefore also increase the error introduced by not using an updated boundary temperature. For this reason, is also important to point out that applying a larger average heat rate would give a larger error than the one obtained in this analysis. To maintain the same accuracy with a larger heat rate, the boundary condition would have to be updated more frequently.

5. Evaluation of thermal interaction

The placement and quantity of boreholes in a system will depend on the application, available space and energy demand. In this chapter different configurations are presented, starting with the simplest case of two boreholes.

5.1. Thermal interaction between two boreholes

The model described in the previous chapter is used to evaluate the thermal interaction between two boreholes with coaxial collectors, each with a depth of 800 m. The circulation fluid enters through the annular space between the two pipes and returns through the center pipe. This flow direction has been shown to give the best thermal performance for deep boreholes [18]. The choice of dimensions for the collector pipes is based on commercially available sizes, and the material of the center pipe is assumed to be polyethylene (PE) with a thermal conductivity of 0.42 W/m·K. The line source calculation is performed twice for each time step, where the input in the second calculation is the distance between the two boreholes. The resulting temperatures are then compared to the case of a single borehole. The specific heat extraction rate in the two boreholes is assumed to be equal and is set to an average of 20 W/m, with a mass flow rate of 3 kg/s. This means that for two 800 m deep boreholes, the total power extracted is 32 kW. The values used for the properties of the ground is thermal conductivity k_g = 3 W/m·K, density ρ = 2600 kg/m^3 and specific heat capacity c_p = 840 J/kg·K. The initial undisturbed temperature profile is assumed to be linear, with an average temperature of 13 °C and a geothermal gradient of 0.02 K/m. Since the heat rate is assumed to be the same in both boreholes, the radial temperature distribution will symmetrical in this case. The numerical calculation is therefore only performed once for each time step. The thermal interaction is first evaluated in terms of temperature changes at the border of the numerical grid, which is the boundary condition in the calculation. In the next section, the influence on the borehole wall and the circulation fluid is presented.

5.1.1. Influence on the boundary condition

The temperature changes on the numerical border will vary with depth, and depend on the heat rate at each point along the borehole axis. Figure 11 shows how the heat rate distribution along the borehole changes for different distances between the two boreholes, for a simulated operation period of 20 years. It is clear that most of the heat extraction is from the lower part of the borehole where the temperature is higher, and in this case 75 % of the total amount of energy is extracted in the bottom half. At the upper 100 m there is very little heat extraction, and for the case of a single borehole, heat from the circulation fluid is actually transferred back into the ground in the upper part. Adding a second borehole will contribute to a more vertical profile, and the maximum heat rate at the bottom of the borehole is therefore reduced. The heat loss that occurs at the top of the borehole is also reduced or eliminated. The sudden increase in heat rate at 800 m is due to the additional axial heat transfer from the bottom of the borehole and downwards into the ground. The line source calculation does not take into account the direction of the heat transfer, but in a real BHE this axial heat transfer at the bottom would naturally not affect the horizontal temperature changes.

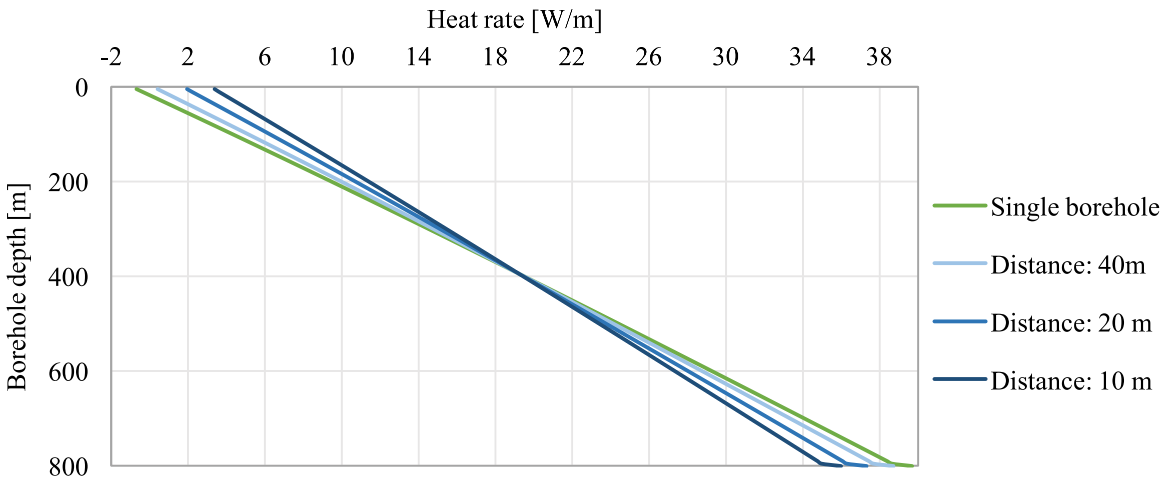

Figure 11. Heat rate distribution after 20 years for different distances between boreholes

The temperature profiles shown in Figure 12 are at the border of the numerical grid, at a distance of two meters from the center of the borehole. The undisturbed temperature is the initial temperature profile in the ground, before any heat is extracted, while the other temperature profiles are after 20 years of heat extraction at an average rate of 20 W/m. The influence of thermal interaction on the temperature profile is clear, especially for short distances between the boreholes.

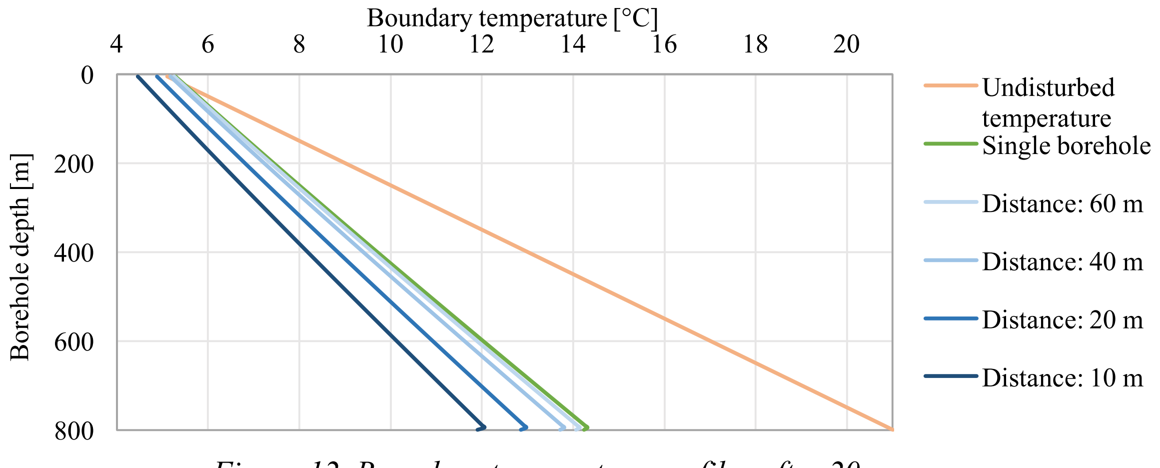

Figure 12. Boundary temperature profiles after 20 years

As can be observed in the figure, the heat extraction from the boreholes makes the temperature profile in the ground more vertical, since the amount of heat extracted is proportional to the temperature difference between the ground and the circulation fluid. Adding a second borehole will decrease the temperature further, and enhance this effect.

Figure 13 shows the difference between the temperature profiles in Figure 12, obtained by subtracting the profiles for the case of two boreholes from the profile for a single borehole.

This shows clearer the influence from the neighboring borehole on the boundary condition, and also that the effect at the bottom of the borehole is larger than at the top. The large decrease in temperature at the bottom is due to the line source calculation of the boundary condition, which as mentioned, does not take into account that some of the heat flow is in the axial direction.

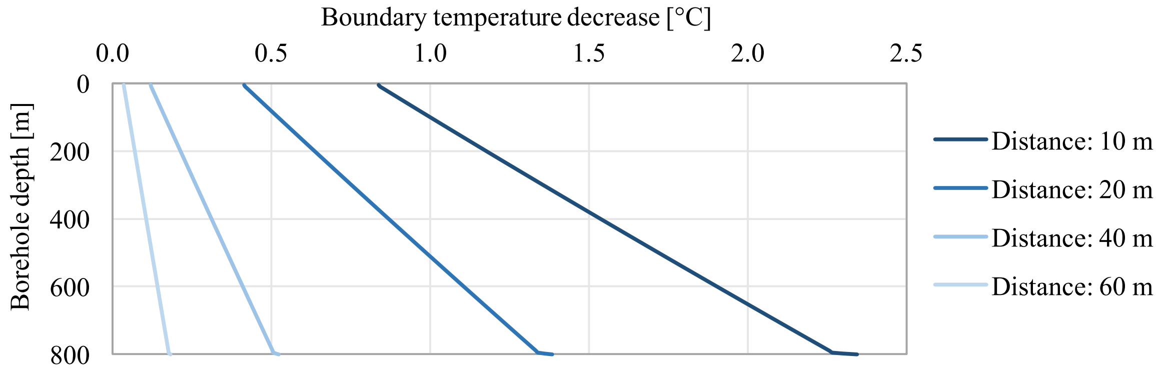

Figure 13. Temperature changes on boundary after 20 years due to thermal interaction

It is also useful to see how the boundary condition changes over time for a certain separation distance. Figure 14 shows the development of the temperature at the border of the numerical grid, for simulated operation times from 1 to 20 years and a separation distance of 40 m between the boreholes. The temperature changes during the first are large, but then the temperature stabilizes and decreases at a lower rate after some years of operation.

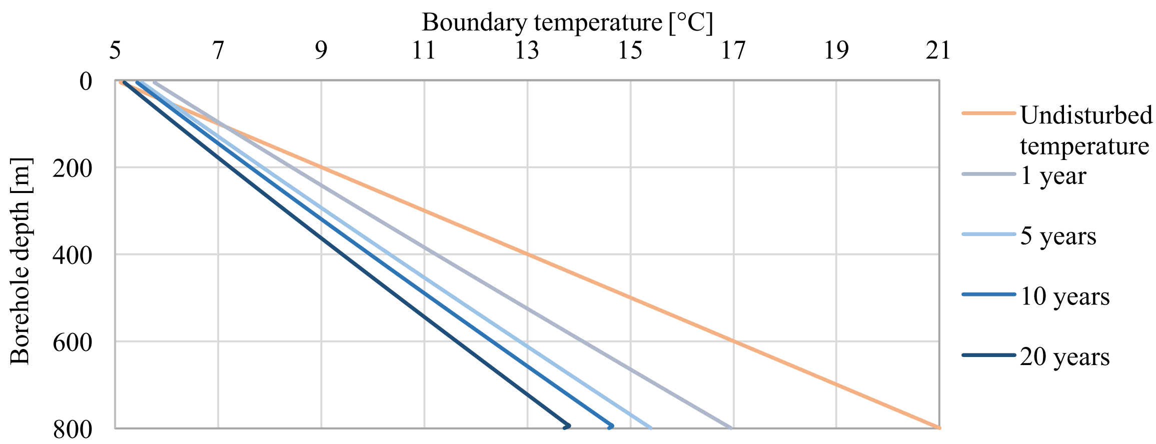

Figure 14. Boundary temperature profiles with 40 m between the boreholes

For this separation distance, there is little difference between the temperature development of the two boreholes compared to a single borehole. The contribution from the neighboring BHE is very small during the first few years, and after 10 years the average temperature decrease due to thermal interaction is only 0.15 degrees. After 20 years the average decrease has reached 0.31 degrees, with a maximum of 0.52 degrees at the bottom of the borehole. This shows that a 40 m separation distance is enough to ensure almost no thermal interaction between the boreholes, even for relatively long operation periods.

5.1.2. Influence on the borehole wall

A neighboring borehole will also influence the temperature profile at the borehole wall. The temperature distribution at the borehole is different from the profile at the border of the numerical grid, due to the circulating fluid in the collector.

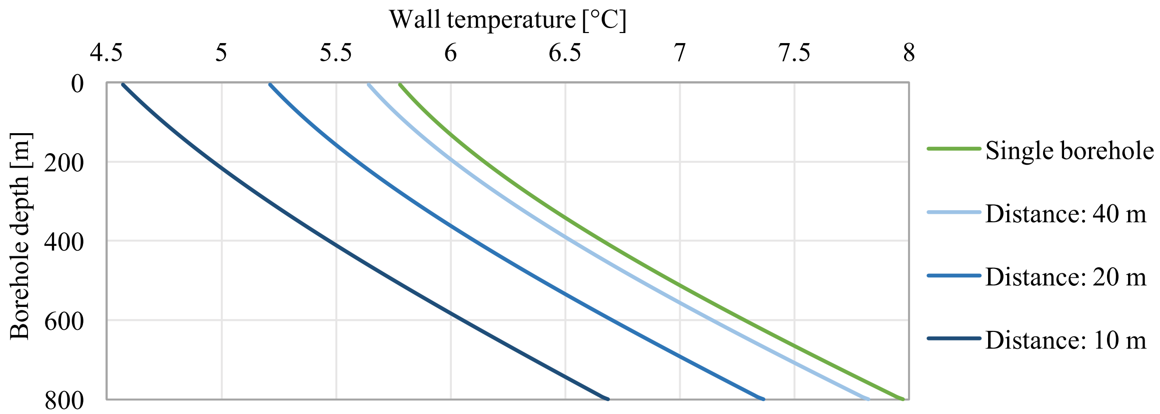

Figure 15. Temperature on borehole wall after 10 years for one borehole and two boreholes with different separation

As can be observed in Figure 15, the temperature decrease caused by a neighboring BHE can be significant already after 10 years, depending on the distance between the two boreholes. Figure 16 shows the change in wall temperature when comparing the simulation of a single borehole to the case of two boreholes, for different separation distances. The average temperature decrease along the borehole is the same as on the border of the numerical grid, but the distribution is very different.

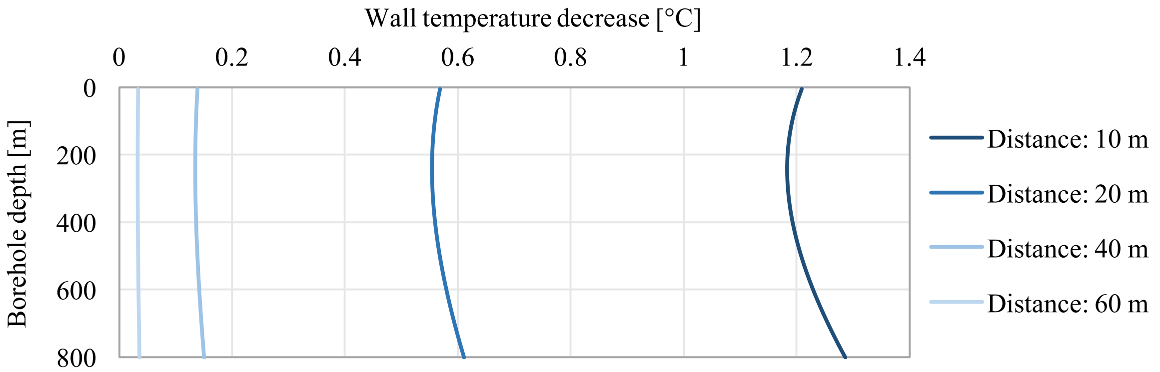

Figure 16. Temperature changes after 10 years due to thermal interaction

At the borehole wall, the influence of thermal interaction is more equally distributed along the axis, and the maximum temperature changes occur at the top and bottom of borehole. As seen for the evaluation of the numerical border, it is clear that neighboring borehole at a distance of more than 40 m will have no practical influence on the operation of the BHE.

Figure 17 shows how the temperature profile at the borehole wall develops over a period of 20 years, for a separation distance of 40 m between the boreholes. The largest changes occur during the first year, and the temperature will then decrease at a slower rate.

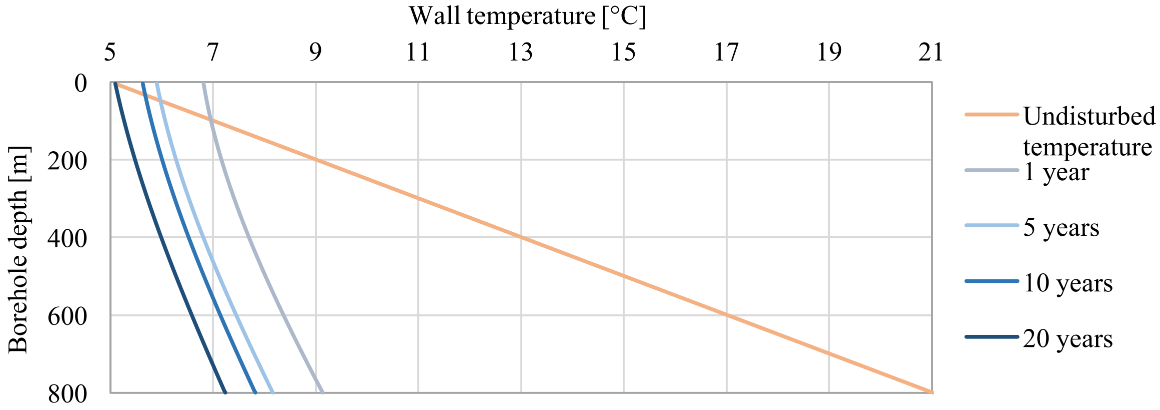

Figure 17. Borehole wall temperature for two boreholes with 40 m separation distance

For a separation distance of 40 m between the boreholes, the effect of the thermal interaction between the boreholes is quite small. Even after 20 years of operation the average temperature decrease along the borehole wall is only about 0.31 degrees for this separation distance. If the separation distance is reduced to 20 m, the temperature decrease would be 0.87 degrees after 20 years.

5.1.3. Influence on the circulation fluid

The temperature of the circulation fluid at the inlet and outlet of the collector is an important factor for the overall performance of the system, given that it directly affects the operating conditions of the heat pump. A higher temperature level on the circulation fluid will improve the coefficient of performance of the heat pump and thereby also increase the energy savings.

Figure 18 shows the circulation fluid temperature along the borehole depth after 10 years of operation, for various separation distances. The arrows indicate the flow direction of the circulation fluid. The profiles show that all the heat from the ground is gained in the downward flow, and the fluid reaches the maximum temperature at the bottom of the borehole. The upward flow experiences a decrease in temperature, and this undesired heat loss is due to the heat transfer between the collector pipes. About 30 % of the heat gained on the way down is transferred back on the way up. This means that there is room for improvement regarding the thermal isolation of the center pipe.

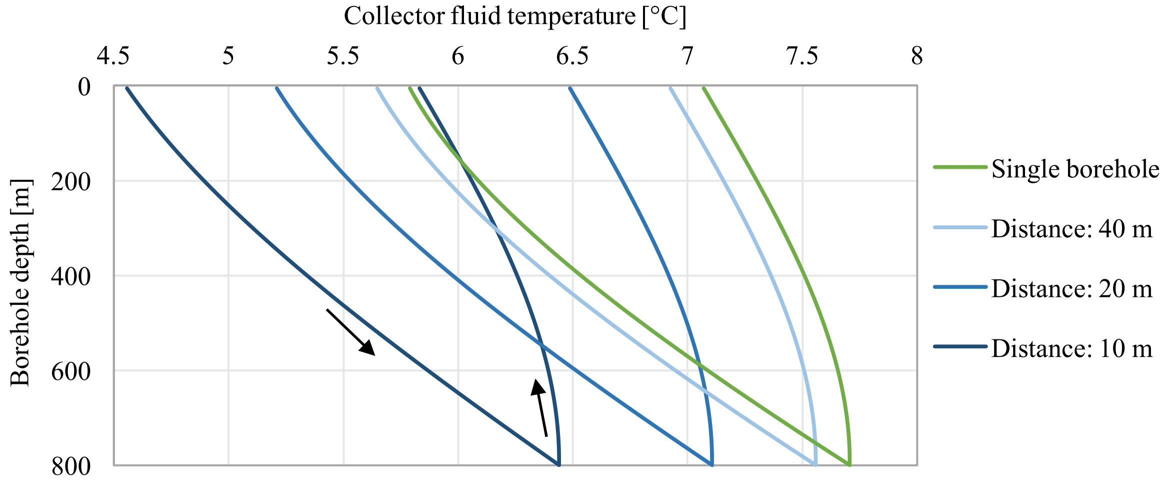

Figure 18. Temperature profiles downwards and upwards after 10 years

As can observed in Figure 18, the temperature difference between the inlet and the outlet of the BHE remains constant and equal to 1.3 degrees, since the amount of heat extracted is the same for each case. However, the overall temperature level decreases as the distance between the boreholes becomes smaller. The shape of the temperature profile in the collector is also shifted slightly to the left since the amount thermal interaction is larger towards the bottom, and also because the thermal interaction changes the heat rate distribution along the axis.

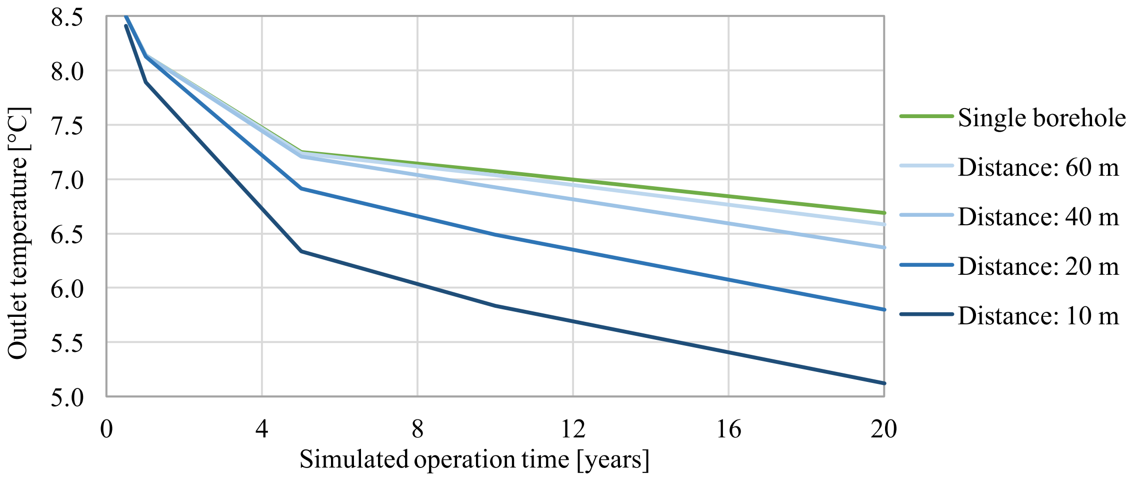

Figure 19. Fluid outlet temperature over time for different distances between boreholes

Figure 19 shows how the outlet temperature of the circulation fluid decreases over time. The changes on the outlet temperature are about the same as the average values obtained at the borehole wall. For a separation distance of 10 m the influence of the neighboring BHE is large, and the outlet temperature will have decreased with almost 1.6 degrees more than for a single BHE after 20 years. After less than 4 years of operation, these two boreholes will have reached the same outlet temperature as a single borehole operated for 20 years. Two boreholes separated by 20 m will reach the same temperature after about 7 years, which means that the amount of thermal interaction is large in both cases and this will reduce the efficiency of the system within few years of operation.

5.1.4. Case study

Based on the results of the simulations, it is possible to conclude that an acceptable separation between two boreholes is in the range of 20 to 40 m, in order to avoid an excessive temperature decrease on the circulation fluid due to thermal interaction. Considering only distances within this range, further analysis is made to evaluate the possible amount of heat that can be extracted from the two boreholes. Studies by other authors conclude that varying the heat rate has a larger influence on the thermal interaction between the boreholes than varying the distance between them with the same ratio [5], which gives reason for further investigation. This case study will be largely based on the pilot project that is under development in Asker, Norway. The installation will be used to cover a part of a base load, so the main focus of this study is therefore on the average heat extraction rate over time and not on possible peak loads.

In this analysis the specific heat rate is increased by 50 % while the other parameters remain the same. The main objective is to find out how an increased heat rate affects the long term performance and the temperature level in the borehole. Increasing the heat extraction rate will also increase the thermal shortcutting between the collector pipes, since the temperature difference between the upward and downward flow will increase. This effect will reduce the performance of the BHE, but it can be counteracted by increasing the mass flow. Figure 20 shows the temperature profiles in the collector for different separation distances and specific heat rates. The temperature difference between the inlet and outlet is increased to 1.9 degrees by increasing the heat rate to 30 W/m, while for a heat rate of 20 W/m the temperature difference is 1.3 degrees.

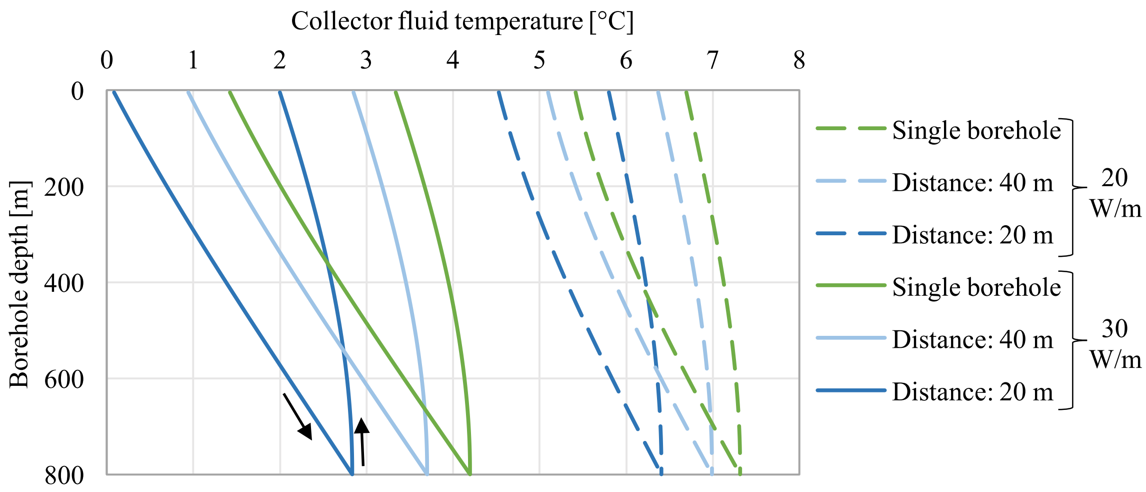

Figure 20. Temperature profiles downwards and upwards after 20 years

The circulation fluid temperature is significantly reduced when increasing the heat extraction rate. It is also clear that the amount of thermal interaction increases for larger heat extraction rates, but this has a smaller influence on the fluid temperature.

The development of the fluid outlet temperature over time is shown in Figure 21. Increasing the heat rate from 20 to 30 W/m will cause the outlet temperature to drop an additional 3.4 degrees for a single borehole and 3.8 degrees for two boreholes separated by 20 m.

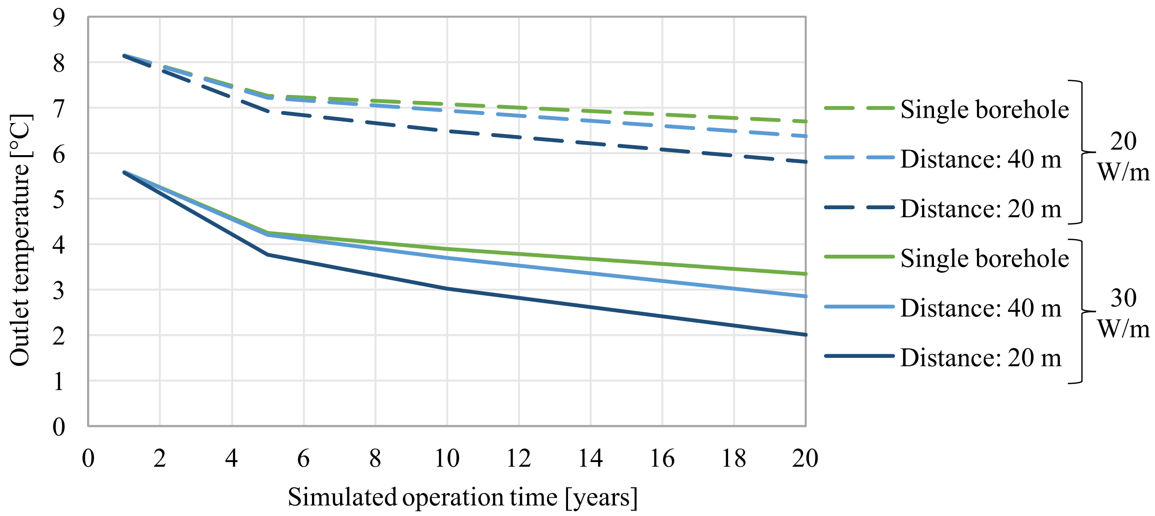

Figure 21. Outlet temperature over time for different distances and heat rates

It is clear from both the previous figures that increasing the heat rate by 50 % has a much larger effect on the outlet temperature than reducing the separation distance in half. For this particular case an average heat extraction rate larger than about 25 W/m is not recommended, since the temperature in the borehole becomes quite low within only a few years of operation for larger heat rates.

Due to seasonal variations in the heating demand, a more realistic representation of the operation of the pilot project would be to have a constant heat extraction during the period with a heating demand, and zero heat extraction for the rest of the year. For this case study the heating demand period is assumed to be 8 months, and the two boreholes are simulated with a separation distance of 20 m and a specific heat extraction rate of 30 W/m during these 8 months of the year. The total amount of energy extracted in this case is 280 MWh per year. The resulting circulation fluid outlet temperatures are shown in Figure 22.

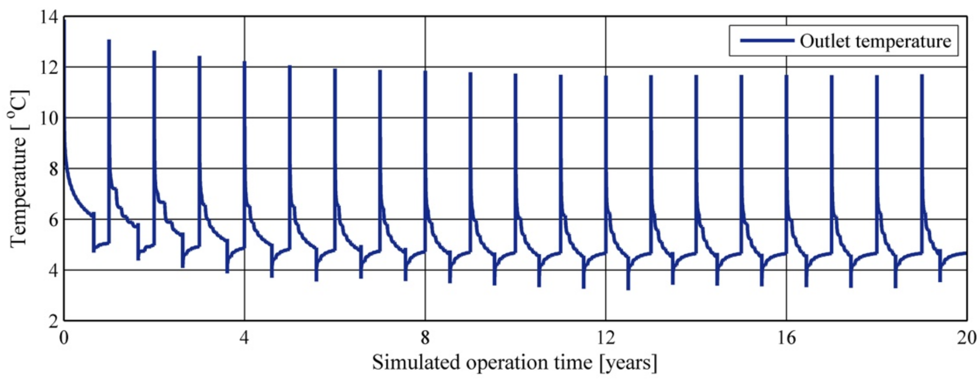

Figure 22. Outlet temperature from the collector with seasonal heat load variations

Temperature peaks can be observed for the first circulation at the beginning of each heat extraction period. These occur after a certain recovery period, since the circulation fluid temperature will be the same as the average borehole temperature. The thermal recovery during the summer allows for a larger heat extraction rate during the winter without causing an excessive temperature drop. With seasonal heat load variations, the outlet temperature after the last heat extraction period is about 2 degrees higher than the temperature obtained if the same heat extraction rate were to be maintained constant throughout the whole year.

5.2. Thermal interaction between a group of boreholes

For a group of boreholes, the numerical part of the model still only has to be calculated once for each unique temperature field, by taking advantage of the symmetry in the arrangement of the boreholes. For a geometry where the influence between all of the boreholes is completely symmetrical, the only additional calculations to be made are the temperature changes caused by each borehole. This property is very beneficial in terms of computation time. The influence from the surrounding boreholes is calculated with the line source solution with the corresponding radiuses, and each contribution is added to the boundary condition of the first borehole, as illustrated in the figure below.

Figure 23. Examples of configurations with identical temperature fields for each borehole

The configuration to the left in Figure 23 is chosen for this analysis, consisting of four boreholes in a square formation. The length of the sides of the square formed by the boreholes (r_2) will be varied from 10 to 60 m, which means that the length of the diagonal (r_1) varies between $10\sqrt{2}$ and $60\sqrt{2}$ m. As for the case of two boreholes, the simulations are performed with coaxial collectors and a borehole depth of 800 m. The heat specific rate and mass flow for each BHE is still maintained at 20 W/m and 3 kg/s, respectively. The total power extracted from the four boreholes will therefore be 64 kW, which equals a total energy amount of 561 MWh for one year of operation.

5.2.1. Influence on the boundary condition

As expected, the changes in the heat rate distribution along the axis are much more pronounced for a group of boreholes than for the case of two boreholes. The profiles are less inclined and the difference between top and bottom is significantly reduced, as can be seen in Figure 24.

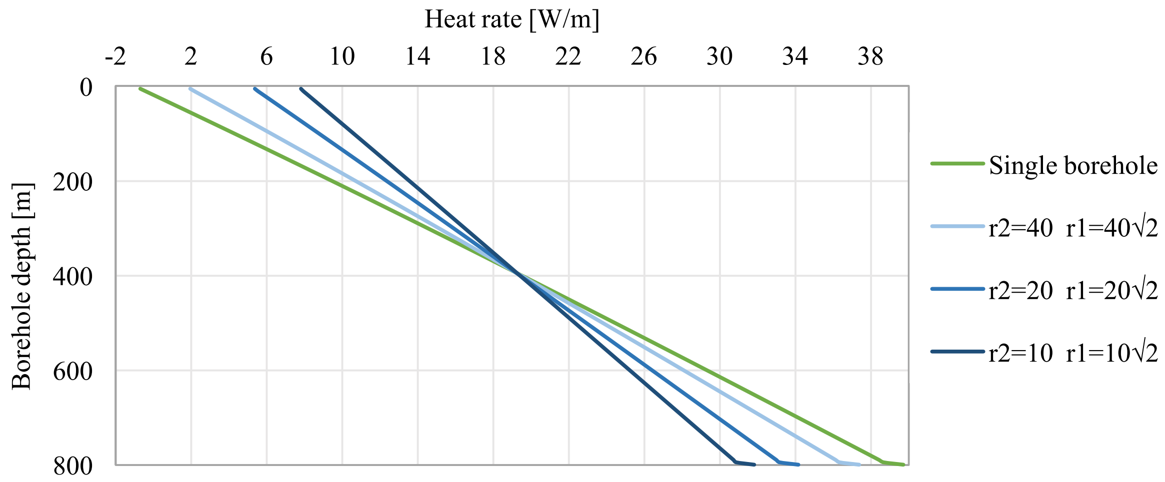

Figure 24. Heat rate distribution after 20 years for different distances

The temperature changes on the border of the numerical grid are shown in Figure 25. Similar to the case of two boreholes, the influence of the thermal interaction is very small for separation distances larger than 40 m. For shorter distances, however, the influence is significant, and the effect of having four instead of two boreholes becomes notable.

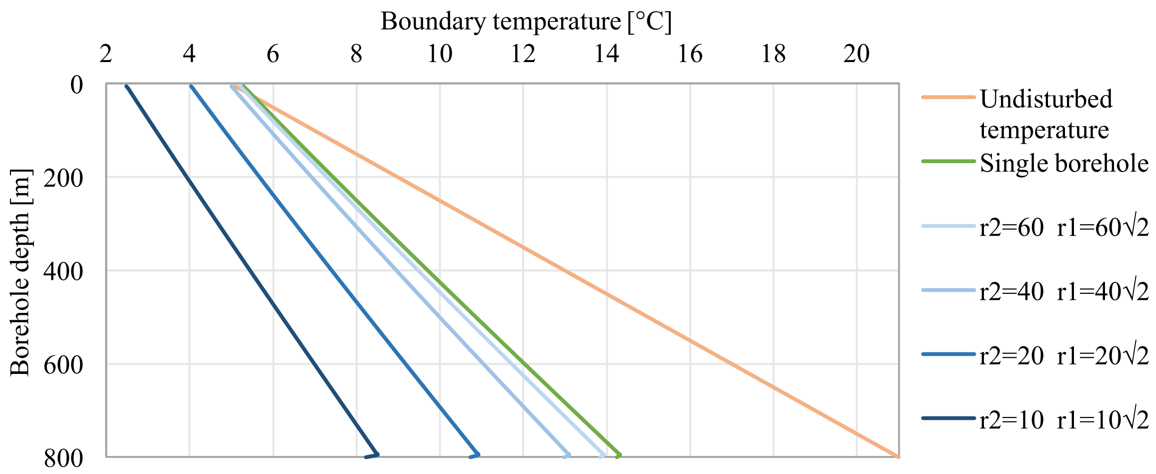

Figure 25. Boundary temperature profiles after 20 years

For a single borehole the average reduction in temperature at the border of the numerical grid is 3.3 degrees after 20 years, while for a group of four boreholes with r_2=10 m the average reduction is 7.6 degrees.

The distribution of the additional temperature change caused by the surrounding boreholes is shown in Figure 26.

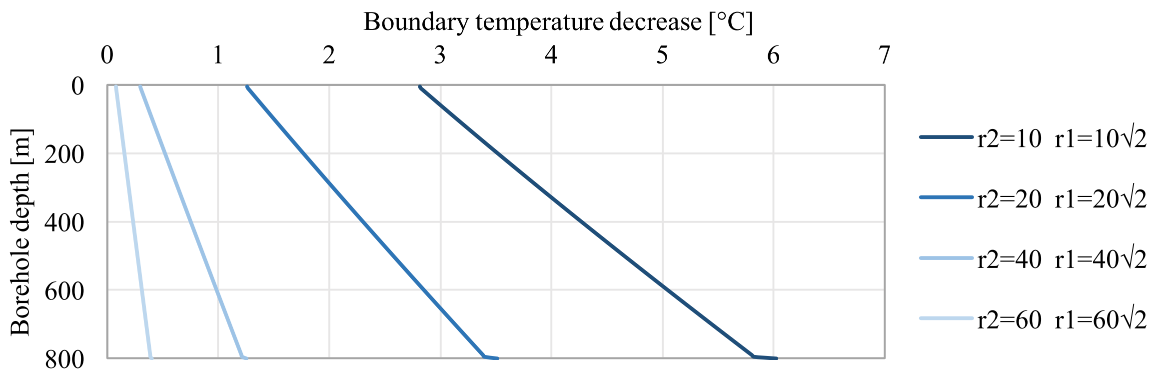

Figure 26. Temperature changes after 20 years due to thermal interaction

For the shortest separation distance, the temperature of the boundary condition will decrease with almost 6 degrees in the lower part, as a result of the thermal interaction between the boreholes.

5.2.2. Influence on the borehole wall

As observed for the case of two boreholes, the thermal interaction contributes to making the temperature profile at the borehole wall more linear, since the temperature influence is largest at the top and bottom. This effect will counteract the originally parabolic shape of the temperature profile, as can be observed in Figure 27.

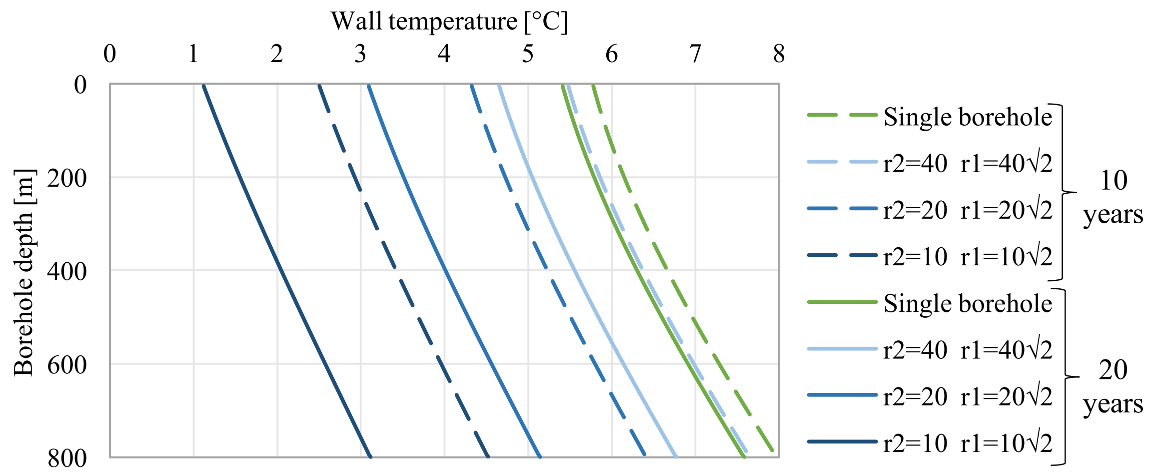

Figure 27. Wall temperature for one borehole and four boreholes with different distances

The difference between 10 and 20 years of operation is quite small for a single borehole, while for a group of four boreholes the changes are much larger. As opposed to the linear temperature profile at the boundary, the temperature along the borehole wall varies in a non linear manner.

The temperature change caused by the surrounding boreholes will therefore also have a different shape, and the result is shown in Figure 28.

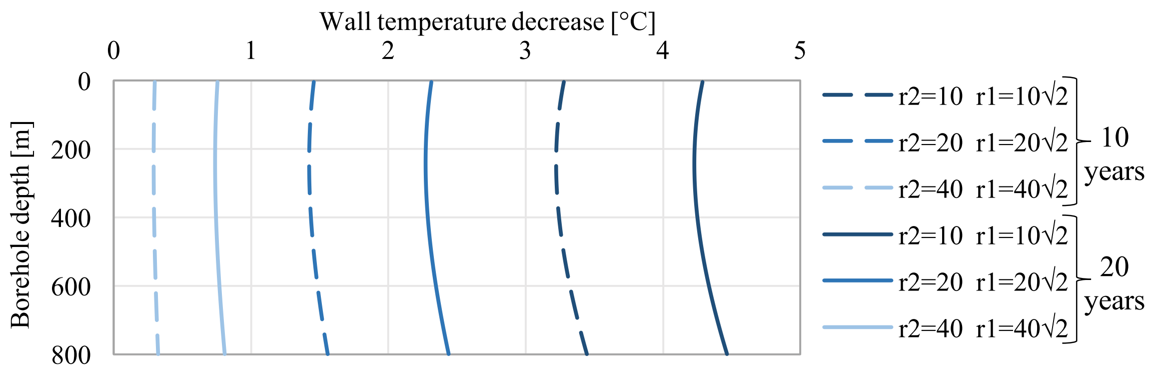

Figure 28. Temperature changes on borehole wall due to thermal interaction

The largest amount of thermal interaction still occurs at the upper and lower part of the borehole, with the minimum influence being at a depth of about 240 m. However, compared to the case of two boreholes, the amount thermal interaction is more equally distributed along the borehole depth. This occurs since the heat rate distribution along the axis also becomes more equally distributed when increasing the number of boreholes.

5.2.3. Influence on the circulation fluid

The effects observed in the analysis of two boreholes are amplified when adding two more boreholes to the field, both regarding the temperature decrease and distribution in the borehole.

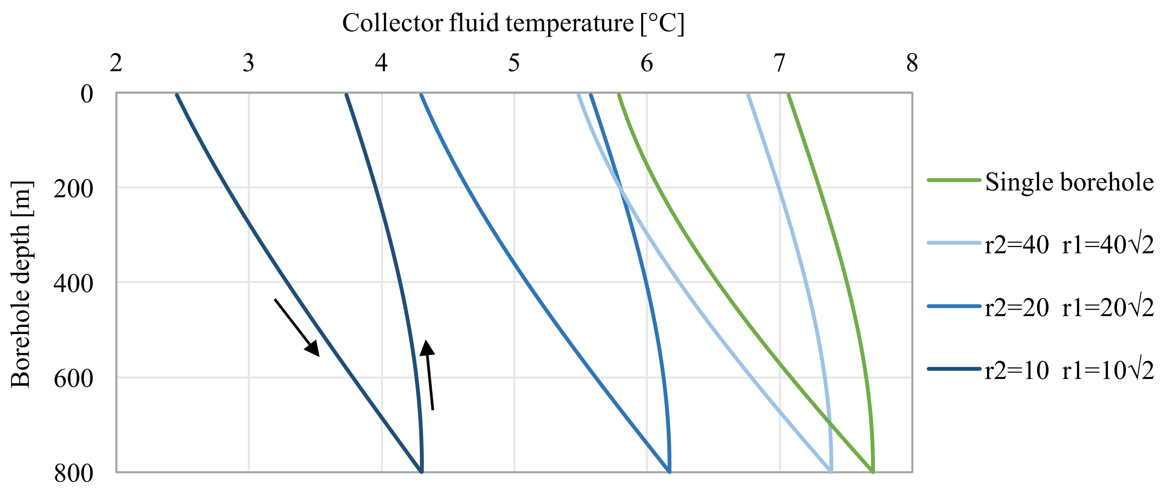

Figure 29. Upward and downward temperature profiles after 10 years

It is clear from Figure 29 that the thermal interaction between the four boreholes is significant after 10 years, even for relatively large distances between the boreholes. With the values for the heat extraction rate and mass flow used in these simulations, the temperature difference between the inlet and outlet is about 1.3 degrees. The outlet and inlet temperatures of the borehole decrease with more than 3 degrees for the shortest distances, and the inlet temperature approaches 0 °C, which is undesirable since the borehole and circulation fluid could freeze. On the other hand, the temperature profile of the upward flow becomes straighter, meaning that the heat loss towards the top of the collector is reduced. This is due to a more equally distributed heat rate along the axis, with smaller differences between top and bottom.

The development of the circulation fluid outlet temperature over time is shown below. This shows that for distances larger than 60 m, the influence of the three neighboring boreholes is negligible even after 20 years of operation.

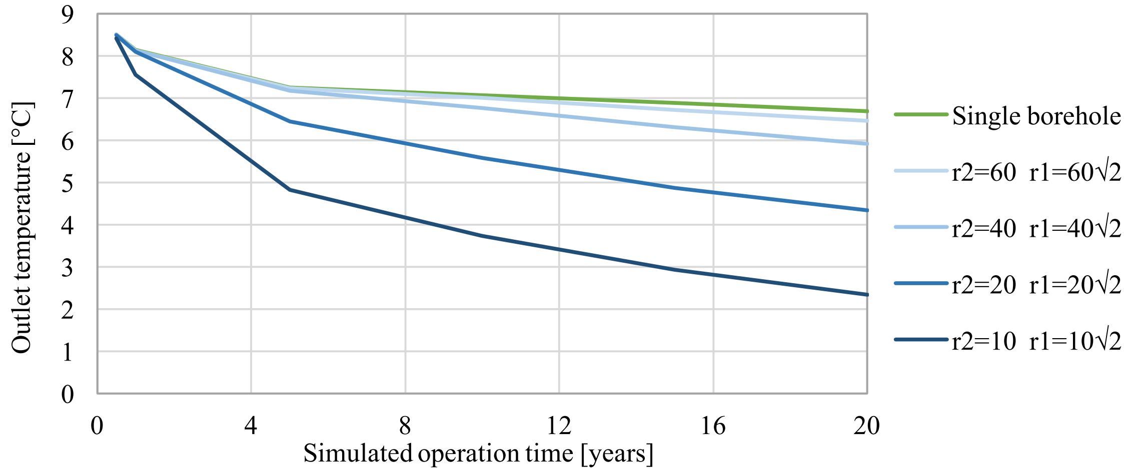

Figure 30. Outlet temperature over time for different distances between boreholes

For the shortest distances of 10 and 20 m, the circulation fluid temperature decreases with an additional 2.4 and 4.3 degrees compared to the case of a single borehole. According to Acuña and Palm [21], an increase of 1 degree on the circulation fluid temperature can give an increase on the heat pump performance of about 3 %. The temperature decrease caused by thermal interaction in these cases will therefore have a significant influence on the energy efficiency of the system. Based on the results presented in Figure 30, it is possible to conclude that a minimum separation distance of 30 m is considered acceptable for this specific configuration and with the parameters used in the simulation.

5.3. Discussion

The results of the simulations show that a neighboring BHE will greatly affect the long term temperature level in the borehole, and that performing only simulations of a single borehole will not accurately predict the performance of the system. For the given heat rate, the results from the simulations of multiple boreholes can be used to define a minimum distance between the boreholes in order to maintain the temperature level in the borehole above a certain limit. Since the amount of thermal interaction will depend on the heat rate as well as the separation distance, these results are not directly applicable for other heat rates. In addition, there are other factors that will affect the heat transfer and the performance of the borehole heat exchanger, for example the thermal conductivity of the ground. For these simulations a conductivity of 3 W/m·K was used, which was held constant along the depth of the borehole. However, the ground thermal conductivity will depend on the location and in a real borehole it is likely to vary with depth. The same applies to the temperature profile and the average temperature in the borehole, which also are site-specific properties.

For the reasons mentioned above, it is difficult to make general recommendations and criteria regarding the placement of deep boreholes. However, the simulations give a good indication of how the separation distance and the heat extraction rate influence the amount of thermal interaction and the temperature changes in the borehole.

The model can also be modified and used for inclined boreholes. The distance between the boreholes would increase with depth, and this has to be taken into account in the line source calculation. An example of this is shown in the figure below.

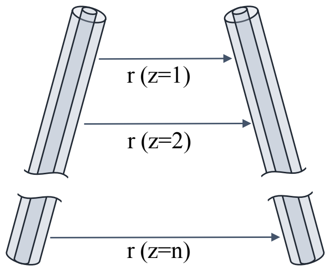

Figure 31. Two boreholes with inclination

The ground volume available for each borehole is increased with this type of configuration. The amount of thermal interaction between the boreholes is also significantly reduced, especially when the boreholes are used for heat extraction since the thermal interaction increases with depth.

6. Borehole heat exchanger performance

This chapter presents an evaluation of the thermal and hydraulic performance of the coaxial collectors that will be used the boreholes of the pilot project. This type of coaxial collector design which can be applied to deep boreholes has been described and tested both through simulations and field measurements by Acuña and Palm [22]. The collector consists of a center pipe which is inserted into a larger, flexible external pipe that is pressed against the borehole wall by the water in the borehole. The influence of the center pipe dimensions and materials is analyzed in this chapter. Other factors that affect the BHE performance, such as the mass flow rate, are discussed, but not studied in depth in this work. The simulations in this chapter are performed using an existing numerical model [18], considering only the performance of a single borehole.

6.1. Thermal and hydraulic performance

The pressure drop in the pipes is proportional to the power consumed by the circulation pump, and will therefore directly affect the overall energy efficiency of the system. The pressure drop in the pipes increases with increased velocity, but a higher velocity will also improve the thermal performance of the collector and provide a higher outlet temperature. Therefore, all of these factors have to be taken into consideration when determining the optimal dimensions and mass flow rate for a system.

To ensure good heat transfer between the circulation fluid and the collector walls, the fluid velocity is maintained high enough to ensure turbulent flow. The flow regime is determined by the dimensionless Reynolds number defined in Equation 9, using the hydraulic diameter D_h as the characteristic length.

$$Re = \frac{\rho V D_h}{\mu} \tag{9}$$

For turbulent flow, the Darcy friction factor can then be calculated with the following expression

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{2.51}{Re\sqrt{f}} + \frac{\epsilon}{3.7D_h}\right) \tag{10}$$

This implicit equation is solved by iteration. The roughness of the plastic pipes is low, and the value used in these simulations is $\varepsilon = 0.003$ mm. Once the friction factor for each pipe is known, the pressure drop can be calculated by Equation 11.

$$\Delta P = f\frac{H}{D_h}\frac{\rho V^2}{2} \tag{11}$$

The total pressure drop in the collector will be the sum of the pressure drops in the annular space and in the center pipe. A cross section of the collector is shown in Figure 32.

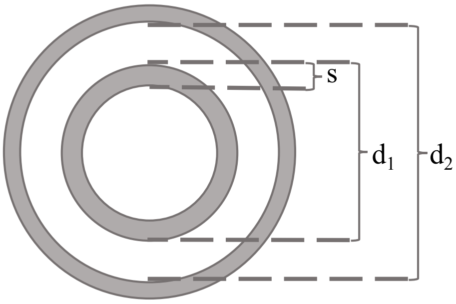

Figure 32. Cross section of the coaxial collector

Since the performance of the collector is evaluated for heat extraction mode, the circulation fluid will enter through the annular space between the pipes and return through the center pipe. Both the mass flow and heat extraction rate are maintained constant in this analysis, while the center pipe dimensions and material are varied. The four different cases from the table below are studied, and the chosen dimensions are based on pipe sizes that are commercially available [23].

	Case 1	Case 2	Case 3	Case 4
d_1	110 mm	90 mm	75 mm	63 mm
s	10 mm	8.2 mm	6.8 mm	5.8 mm
d_2	140 mm	140 mm	140 mm	140 mm

Table 1. Pipe dimensions

The diameter of the borehole and the external pipe is the same for all four cases. The simulations are performed with two different materials for the center pipe; polypropylene (PP), which has a thermal conductivity of 0.24 W/m·K, and polyethylene (PE), which has a thermal conductivity of 0.42 W/m·K. The simulations are performed with a mass flow and specific heat rate of 3 kg/s and 30 W/m, respectively.

6.1.1. Results and discussion

The thermal performance is evaluated by studying the temperature profiles in the collector. The optimal case would be to have a constant temperature on the returning flow in the center pipe, meaning that no heat is being transferred from the upward to the downward flow. In reality, since the thermal resistance of the center pipe is not infinite, some heat will be lost on the way up. This is clear from Figure 33, which shows the circulation fluid temperature along the borehole for both pipes, for the different center pipe dimensions and materials. These temperatures are obtained after one year of constant heat extraction.

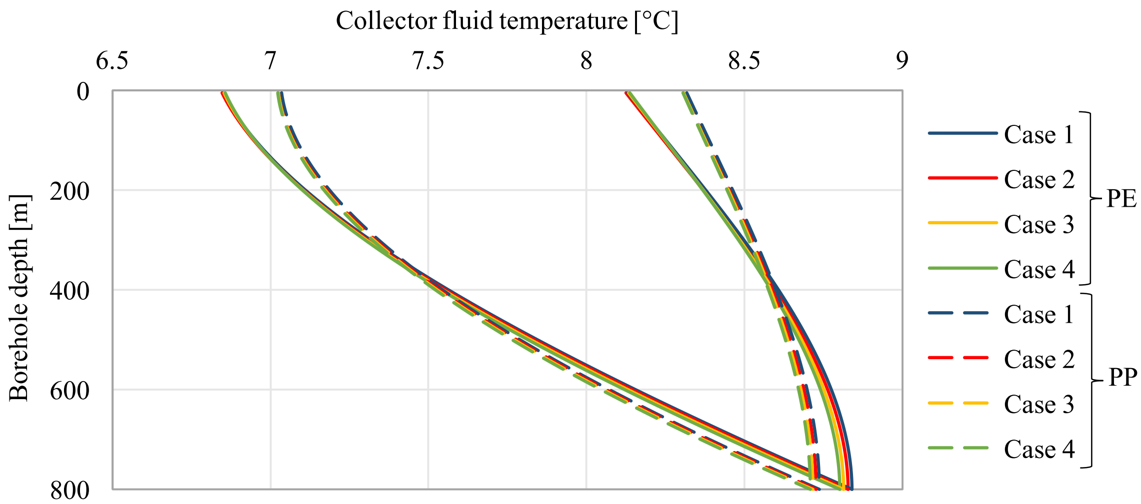

Figure 33. Temperature profile in the collector pipes after 1 year of operation

The differences when varying the dimensions are almost unnoticeable, but the tendency is a reduction in the heat loss from the upward flow as the diameter of the center pipe is reduced. This is due to the increase in velocity when the flow area is reduced, since the mass flow is maintained constant. The benefit of increased velocity seems to outweigh the effect of a thinner pipe wall when the diameter is reduced. The type of material, however, has a larger influence on the heat loss. Using polypropylene, which has almost twice thermal resistance of polyethylene, gives a higher temperature level on the circulation fluid and will therefore result in a higher COP for the heat pump. The heat loss for PE in the upward flow is 36 % of the heat gained in the downward flow, and this heat loss is reduced to 25 % when using PP. The resulting difference in outlet temperature for these two materials is about 0.2 degrees. This temperature difference would increase if the mass flow were to be reduced. Considering only technical aspects, PP would therefore clearly be a better choice for center pipe material. However, PE is a cheaper material, and since the temperature differences are relatively small, the increase in thermal performance might not justify the additional investment cost.

Since the pipe dimensions and thickness only had a small influence on the thermal performance of the BHE, the determining factor in this case will be the pressure drop, together with practical and economical considerations. Figure 34 shows the result of the pressure drop calculations for each of the four cases. For a fixed pressure drop, a reduction of the center pipe thickness would allow for a higher mass flow. Based on the evaluation of the thermal performance, this is likely to be the most beneficial configuration, both in terms of performance and cost.

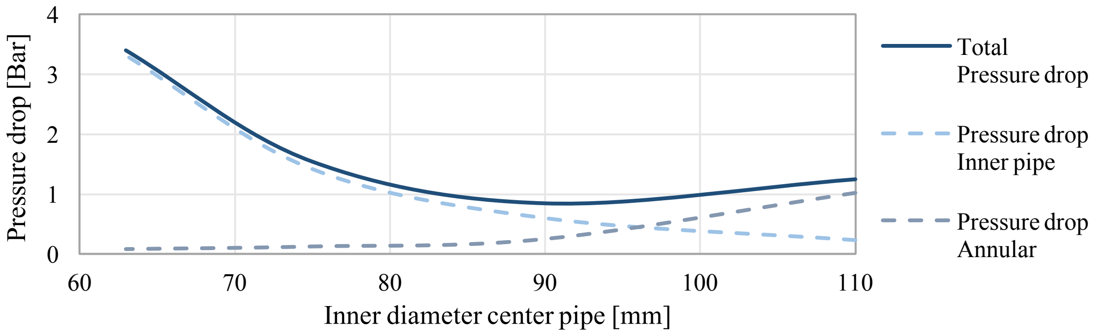

Figure 34. Pressure drop for different pipe dimensions

Based on the pressure drops in Figure 34, case 2 with an center pipe diameter of 90 mm would give the best hydraulic performance for this particular case. For lower mass flows, a smaller center pipe diameter could be beneficial, since the investment cost would be reduced and the pipe would also be easier to install. This would limit the boreholes ability to handle peak loads with larger mass flows, but if the system is only intended to cover a base load, as in the pilot project, this would not be a problem. Ultimately, the choice of pipe dimensions and material will be a sum of many factors, depending on both technical and economical aspects.

7. Thermal response testing of boreholes

The project work that was conducted previous to this thesis concluded that in a field test there are several sources of error that can cause inaccuracy in the estimation of the ground thermal properties [24]. In deep boreholes the energy outtake is larger, so an error in the estimation of the thermal properties will cause a larger discrepancy between the expected and the actual borehole performance. In this chapter Holmberg´s numerical model is used to evaluate the accuracy of the traditional TRT, both for shallow and deep boreholes. New possible methods for response testing of deep boreholes are also tested and evaluated using the model. All the simulated tests are for the coaxial collector described in the previous chapter. The tests are analyzed both by using the simulated circulation fluid temperature and in some cases the borehole wall temperature.

7.1. Traditional thermal response test

In a traditional TRT heat is injected at a constant rate, and the line source solution is used to determine the effective thermal conductivity based on the measured thermal response of the ground. The methodology is extensively used to evaluate the properties of shallow boreholes, and it has also been applied to boreholes with a depth up to 500 m. However, little research has been done regarding the testing of deeper boreholes, and the accuracy of this method when applied to deep boreholes is therefore uncertain. Another challenge related to deep boreholes is that the required power input has to be larger in order to maintain the same heat rate per borehole meter as for shallow boreholes.

In the present work response tests are simulated with the numerical model developed by Holmberg [18], using both heat injection and extraction with different heat rates. The resulting inlet and outlet temperatures over time are used to determine the ground thermal conductivity with the line source solution. The influence of the borehole depth is studied to evaluate the accuracy of the traditional TRT for deep boreholes. For the test analysis a linear expansion of the exponential integral in the line source is used, resulting in the following equation, where $\bar{T}_f$ is the average circulation fluid temperature.

$$\bar{T}_f(t) = \frac{\dot{q}}{4\pi k_g}\ln(t) + \frac{\dot{q}}{4\pi k_g}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - 0.5776\right) + \dot{q}R_b^* + T_g \qquad (12)$$

The error in this approximation is small for large values of the factor $\alpha t/r^2$. In boreholes the minimum time to achieve good accuracy is usually about 10 to 20 hours.

7.1.1. Results

Simulations of thermal response tests, followed by an analysis using the line source solution, reveal that this type of testing gives a good estimation of the ground thermal conductivity when a large heat injection or extraction rate is used. The duration of the simulated tests is 72 hours. For specific heat rates smaller than 30 W/m the error increases rapidly, and heat injection generally gives a better estimation of the thermal conductivity than heat extraction, especially for shallow boreholes. A ground thermal conductivity of 3 W/m·K is used in all the numerical simulations. Figure 35 shows how the error in the thermal conductivity estimation changes depending on the borehole depth and the heat rate used in the test.

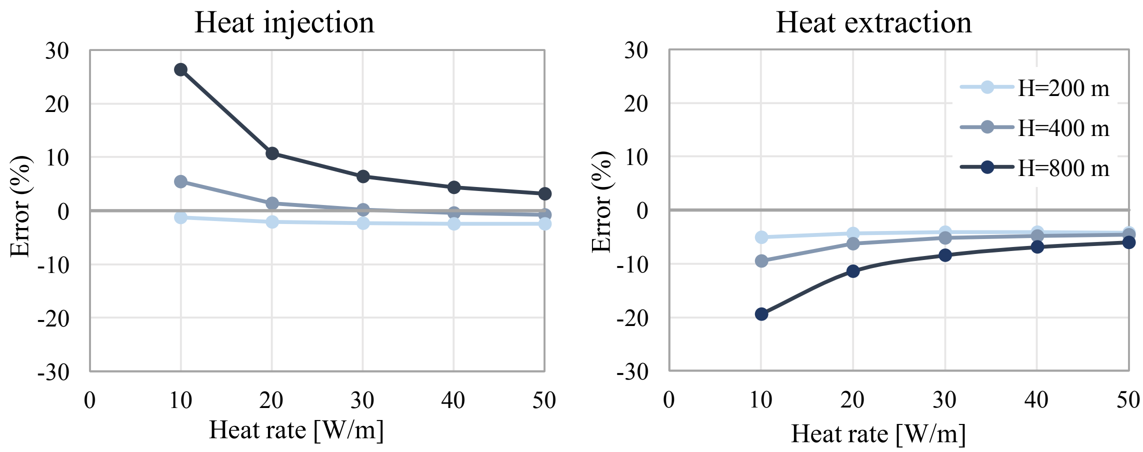

Figure 35. Error in the estimation of the ground thermal conductivity

For deep boreholes heat injection tends to overestimate the ground thermal conductivity, while heat extraction underestimates the thermal conductivity. It is clear that the thermal conductivity estimation is less accurate for the 800 m deep borehole, and for deep boreholes the accuracy is also more dependent on the specific heat rate used in the test for.

7.1.2. Thermal conductivity variations with depth

A real BHE is likely to have a thermal conductivity that changes with the borehole depth. To evaluate how these variations will affect the result of a TRT, tests are simulated with different thermal conductivities at different depths. In this case a conductivity of 2 W/m·K is assumed for the upper half of the borehole, and 3 W/m·K for the lower half. In general, the value obtained with the line source analysis using the average fluid temperature at the outlet and inlet is close to the arithmetic mean thermal conductivity. The results also show that for heat injection, the estimated thermal conductivity is closer to the actual value of the upper part of the borehole. For heat extraction the opposite occurs, and the estimated value depends more on the conductivity of the lower part of the borehole. However, in this case the general underestimation of the thermal conductivity when using heat extraction has a larger influence on the results than the axial variations in conductivity.

A standard analysis of a TRT only determines an average value for the ground thermal conductivity for the entire BHE, and will therefore not provide any information on the variations along the axis. However, if the temperature is measured at different depths during the TRT, as in a distributed thermal response test (DTRT), it is possible to determine the local conductivity for each section of the borehole. This requires knowing both the temperature on the borehole wall, as well as the heat transferred within each section. The heat rate can be calculated with the mass flow and the circulation fluid temperatures at the entrance and exit of each section. Since the coaxial collectors in the pilot project will be equipped with an optical fiber cable between the external pipe and the borehole wall providing local temperature measurements [22], the wall temperature is assumed to be a known parameter. In the local conductivity estimation, it was seen that the use of the heat load aggregation algorithm and a numerical evaluation of the exponential integral in the line source calculations gives the best results. This method is therefore used in the local analysis instead of the simpler method using the linear expansion and the slope of the temperature curve. In the global analysis, however, there is little difference between the two methods.

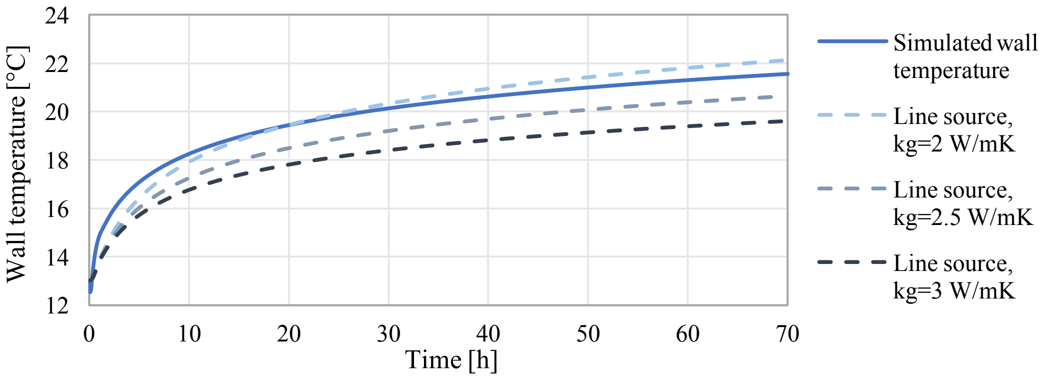

Figure 36. Average conductivity from TRT with an average heat injection of 50W/m

Figure 36 shows the result of a simulated TRT analysis, using mean values for the borehole wall temperature and heat rate and thereby obtaining an average value for the thermal conductivity in the entire BHE. The line source calculation which provides the best fit to the wall temperature development over time is for a thermal conductivity between 2 and 2.5 W/m·K. The actual arithmetic mean thermal conductivity for this BHE would be 2.5 W/m·K.

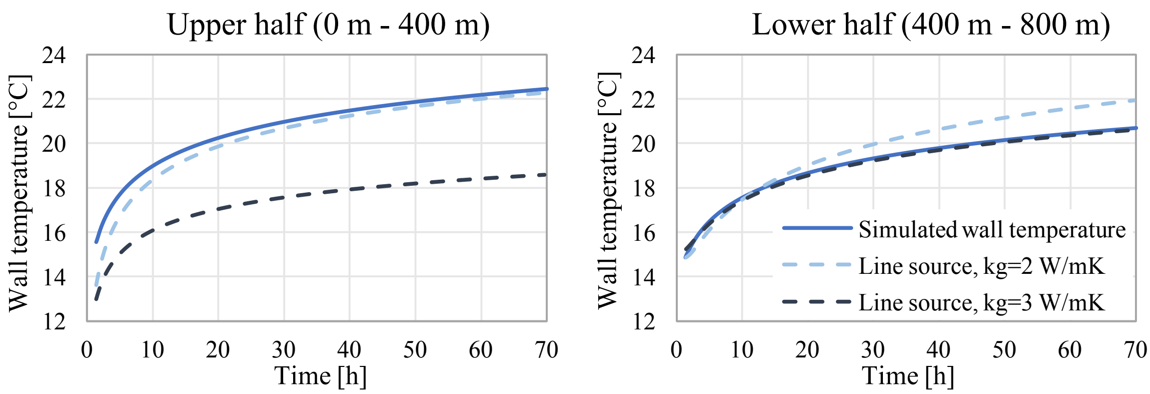

Figure 37. Analysis of local thermal conductivity with an average heat injection of 50 W/m

Figure 37 shows the result of analyzing the upper and lower part of the borehole separately. In the figure to the left, which is for the upper half of the borehole, the temperature development on the borehole wall agrees well with the line source calculation for a conductivity of 2 W/m·K. Likewise, in the lower half of the borehole shown in the figure to the right, a conductivity of 3 W/m·K gives a result very close to the simulated temperature.

These results coincide very well with the actual thermal conductivity of each section. This also shows that the accuracy of the conductivity estimations will increase as the size of the analyzed sections decreases. Additionally, it can be observed that the difference between the two line source calculations in the figures is much larger for the upper half of the borehole. This is due to the heat rate distribution along the borehole, since the average heat rate is larger in the upper half of the borehole than in the lower half. This confirms why a larger heat rate during the test will give a more accurate estimation of the thermal conductivity.

7.1.3. Discussion

Based on the results from the simulations, it can be concluded that a traditional TRT with only two fluid temperature measurements is not an ideal method for testing of deep boreholes. One of the reasons for this could be the temperature profile in the borehole, which causes variations in the heat rate along the depth of the borehole. In shallow boreholes the heat rate variations along the borehole axis are much smaller than in a deep borehole, and therefore also closer to the average value that is used in the test analysis. In deeper boreholes the specific heat rate differs significantly from the average value, as shown in Figure 38. These profiles are obtained after 72 hours of heat injection, with an average specific heat rate of 50 W/m.

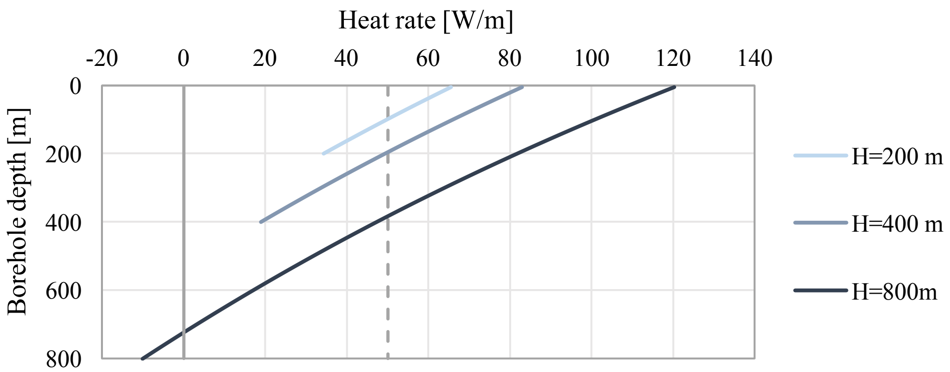

Figure 38. Heat rate distribution along the borehole with average heat rate=50 W/m

In the 800 m deep borehole most of the injected heat is transferred in the upper part of the borehole, and heat is actually being extracted from borehole in bottom 100 m. This could explain why the thermal conductivity obtained from temperature analysis corresponds to the actual properties of the upper part of the borehole.

The power requirements would also represent a challenge in terms of the practical execution of the response test. This type of test is usually performed with an average heat injection rate between 30 and 40 W/m, so an 800 m deep borehole would require a power source between 24 and 32 kW to achieve this specific heat rate.

The fact that almost all the heat is injected in the upper part of the borehole due to the temperature increase with depth, favors the use of heat extraction instead of injection in deep boreholes. If heat was extracted at an average rate of 50 W/m the heat transfer would be more equally distributed along the axis compared to using heat injection. The difference between top and bottom would be 73 W/m, compared to 130 W/m which was the case for heat injection in Figure 38. Since the temperature level in a deep borehole is higher than in a shallow one, the circulation fluid temperature required to cool the borehole is also lower, which opens up for other options for response testing using cold inlet water. This possibility is evaluated in the following chapters.

7.2. Constant inlet temperature

A method that has been suggested for response testing of deep boreholes is to use a constant inlet temperature on the circulation fluid. This can be achieved by using cold tap water directly, thereby no large power source or equipment is required to heat or cool the circulation fluid. Naturally the heat rate during the test will not be constant, but decrease as the temperature in the borehole decreases.

Similar to the previous chapters several tests are simulated using the numerical model. The inlet temperature on the circulation fluid is set to 4 °C, the borehole depth 800 m, and the mass flow rate 3 kg/s. The average circulation fluid temperature is used in the analysis, defined as the average between the inlet and outlet fluid temperatures. This temperature development during the TRT is shown in the figure below for different ground thermal conductivities, with the corresponding trend lines for each case.

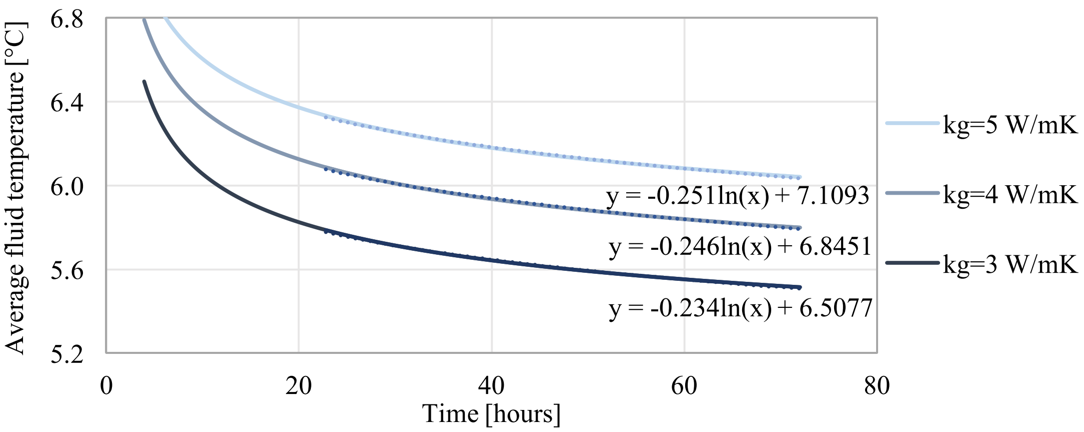

Figure 39. Temperature development during a 72 hour test with constant inlet temperature

A higher thermal conductivity gives a higher temperature in the BHE during heat extraction, since heat is transported more efficiently from the surrounding ground, and the resulting temperature determines the heat rate in the BHE. The fact that the heat rate adapts to the thermal conductivity actually causes the temperature gradient of the circulation fluid to stabilize and become almost independent of the conductivity. Due to the very small differences in the gradient, it is not possible to accurately determine the conductivity using the conventional method of analysis. Different inlet temperatures have been tried to see if this could provoke a larger temperature gradient, unfortunately similar results were obtained.

7.3. Constant heat rate and inlet temperature

Since the use of a constant inlet temperature did not provide satisfactory results, other options must be explored. By continuously adjusting the mass flow rate, it would be possible to maintain both a constant heat rate and a constant inlet temperature during the test. The constant heat rate makes the line source analysis simpler, since the existing method can be applied directly without considering a load aggregation algorithm. The amount of heat extracted from the borehole is given by the following equation, where T_{in} is cold tap water at a constant temperature.

$$Q = \dot{m} c_{p,water} (T_{out} - T_{in}) \quad (13)$$

As the temperature in the borehole decreases, the mass flow rate would be increased to maintain the same heat extraction rate. The use of tap water requires a relatively high temperature in the borehole in order to achieve a temperature difference between the circulation fluid and the ground, meaning that this method is not suitable for shallow boreholes.

7.3.1. Analysis of 800 m deep BHE

The first analysis with this test method using the average value of the inlet and outlet temperatures did not show a good agreement with the line source solution. Similar to the previous chapter using only constant inlet temperature, this method obtains small differences in the temperature gradient over time for different conductivities. By maintaining the circulation fluid temperature constant at the inlet, it seems that the relationship between the heat extracted and the resulting fluid temperature is weakened, which complicates the analysis. However, the development of the wall temperature during the test showed very good agreement with the analytical line source solution, and this parameter is therefore used in the analysis. Varying the mass flow during the test also changes the borehole thermal resistance, making the BHE more or less efficient. Therefore, another benefit to using the wall temperature instead of the circulation fluid temperature is that possible variations in the borehole thermal resistance are eliminated from the analysis. Numerical simulations of this test method show that the accuracy in the estimation of the conductivity depends both on the inlet temperature and on the heat extraction rate, as shown in Figure 40.

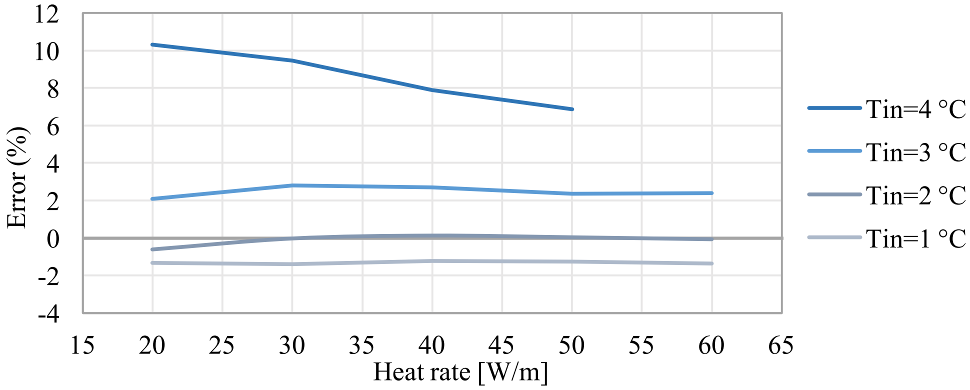

Figure 40. Error in the estimation of conductivity for H=800 m and T_g=13 °C

A lower inlet temperature, and thereby a larger temperature difference between the circulation fluid and the ground, will reduce the error. Increased heat rate, which is achieved by increasing the mass flow rate, will also contribute to reducing the error. The average undisturbed temperature in this case was 13 °C and the conductivity was set to 3 W/m·K. For inlet temperatures from 1 to 3 °C, giving a temperature difference from 10 to 12 degrees between the inlet and the undisturbed temperature, the estimation of the thermal conductivity is very good, with an error of less than 3 %. For an inlet temperature of 4 °C the error increases to between 7 and 10 %, depending on the heat rate. An even higher inlet temperature either leads to very large mass flows or very large errors.

Figure 41 shows the mass flow at the end of each test, for at test duration of 72 hours. The change in mass flow from the beginning until the end of the test is about 10 % for the lowest heat rates, but increases to more than 50 % change for the largest heat rates.

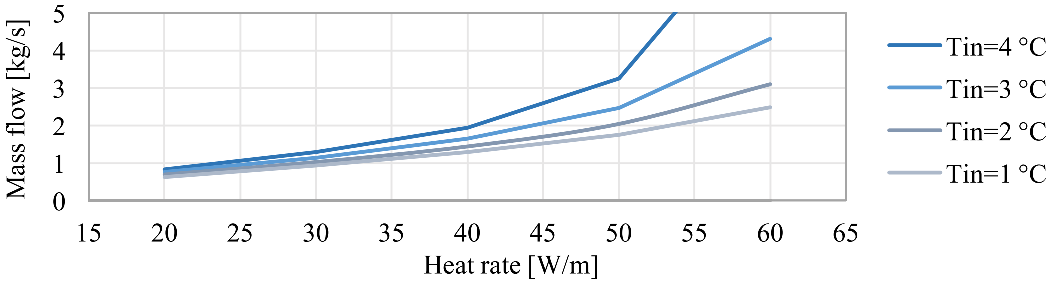

Figure 41. Mass flow after 72 hours for given heat rates and temperatures

The error obtained when using a higher inlet temperature could in theory be reduced by further increasing the heat rate. However, for T_{in}=4 °C the mass flow required to maintain a specific heat rate of 60 W/m is already more than 8 kg/s. Since very large mass flow rates lead to high velocities and large pressure drops in the collector, the maximum heat rate is limited for high inlet temperatures.

To evaluate the influence of the temperature difference between the inlet fluid and the undisturbed ground temperature the analysis is repeated for an 800 m deep borehole with the same temperature gradient, but an average ground temperature of 16 °C. The increased borehole temperature means that a larger range of inlet temperatures can be used. Figure 42 shows that the most important factor in the analysis is indeed the difference between the ground temperature and the inlet temperature. The same trends as in the previous case are observed; a low inlet temperature underestimates the conductivity, and for a temperature difference of less than 10 degrees the error increases rapidly.

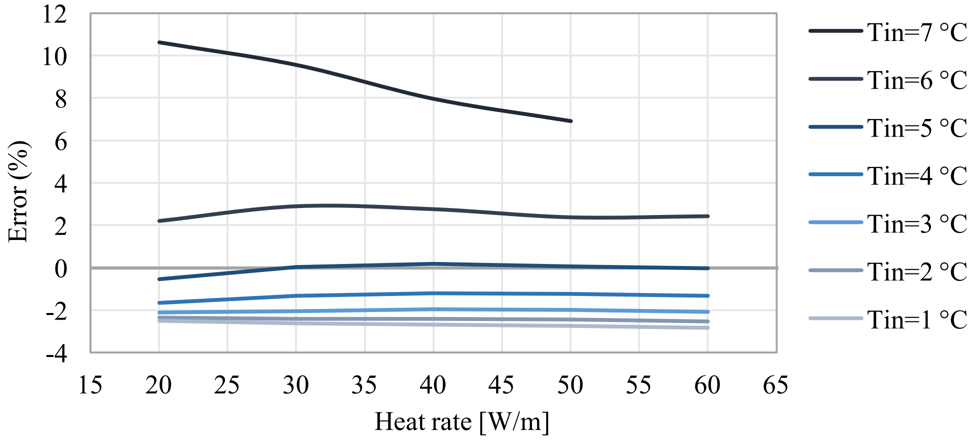

Figure 42. Error in the estimation of conductivity for H=800 m and T_g=16 ℃

For the same inlet temperature and heat rate, the required mass flow was reduced with between 20 and 50 %. This means that for a warmer borehole, a high heat rate can be used without this leading to very large mass flows.

7.3.2. Analysis of 1600 m deep BHE

Increasing the borehole depth to 1600 m while maintaining the geothermal gradient of 0.02 K/m will give an average ground temperature of 21 °C. The results of thermal response tests with the proposed method for this depth are shown below.

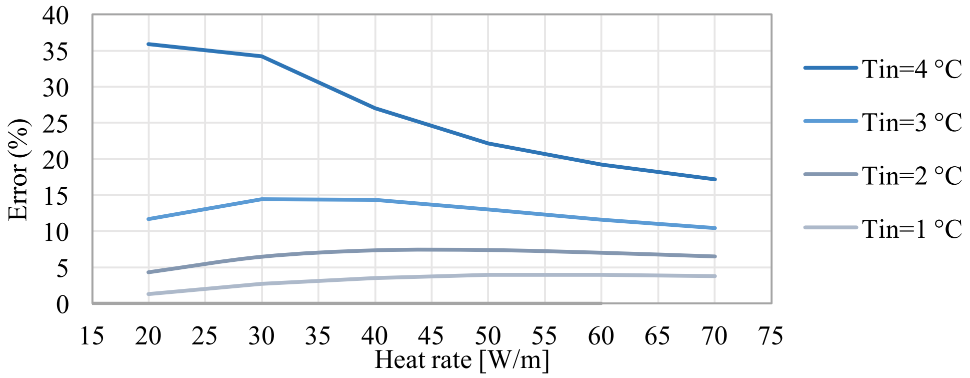

Figure 43. Error in the estimation of conductivity for H=1600 m and T_g=21 ℃

Even though the average temperature in this borehole is higher, which increases the temperature difference between the inlet fluid and the undisturbed temperature, the error in the thermal conductivity estimation is much larger than for the 800 m borehole. A possible explanation for this is that the differences in temperature and heat rate between top and bottom are larger in the 1600 m BHE. An increase in temperature difference gives a reduction of the mass flow. On the other hand, the total power extraction will also increase as the borehole depth increases, which again increases the mass flow rate. The sum of these effects results in a higher mass flow in the 1600 m deep BHE for low heat rates, but a lower mass flow for heat rates larger than 50 W/m. With an inlet temperature of 4 °C and a specific heat rate of 60 W/m, the mass flow in the 1600 m deep BHE is still less than 3 kg/s, compared to the 8 kg/s required in a 800 m BHE. Based on these results, it can be concluded that the accuracy of these test depends on the mass flow rather than the specific heat rate, and a large mass flow should therefore be used.

7.3.3. Discussion

Although the theoretical analysis of a response test with constant heat rate and inlet temperature showed promising results, a field test will contain many possible sources of error. The most important factor will probably be the temperature measurements, since the accuracy of the analysis will depend directly the quality of the input data. Even though the optical fiber cable will be pressed against the borehole wall, there will be some thermal resistance between the two. Additionally, the borehole wall is not completely smooth, which might also affect the accuracy of the temperature measurements.

The error in the estimation of the conductivity was shown to be very sensitive to the difference between the inlet temperature and the undisturbed ground temperature. For temperature differences smaller than 10 degrees the error increases rapidly, and the mass flow rate also becomes large. Low inlet temperatures lead to a small underestimation of the conductivity. These finding comply with the evaluation of the traditional TRT, which also showed that heat extraction underestimates the conductivity. Based on these results, it is recommended to conduct this type of test with a low inlet temperature and a rather high mass flow. A high mass flow will also reduce the influence of possible variations in the flow regulation, thereby making it easier to achieve a constant heat rate. The required temperature difference between the borehole and the inlet also leads to some limitations regarding the boreholes in which this type of test can be performed. If the temperature level in the borehole is too low, the inlet water would have to be cooled down, creating additional practical challenges.

The results of the tests using constant inlet temperature and constant heat rate were somewhat improved when using the evaluation method described for the local conductivity estimation, with a graphical comparison of the temperature development. The heat load aggregation algorithm and the numerical evaluation of the exponential integral increases the complexity of the analysis, but this method is still recommended to improve the accuracy of the test. This evaluation method also showed a higher tolerance regarding maximum inlet temperature, which improves the applicability of this new TRT method. For the boreholes in the pilot project, a measurement of the temperature profile along the axis is recommended. Given that the average temperature is sufficiently high, the testing method with constant inlet temperature and constant heat extraction is considered to be a better option than the traditional TRT.

8. Conclusions and suggestions for further work

8.1. Conclusions

Thermal interaction between boreholes was shown to have a significant influence on the operating conditions of the system when evaluating the long term operation. Two 800 m deep boreholes with the properties assumed in this study should be separated by a minimum distance of about 30 m to avoid excessive thermal interaction. However, the heat extraction rate has a larger effect on the temperature level in the borehole than the separation distance between the boreholes. For the boreholes in the case study, a maximum amount of energy extraction of about 350 MWh per year is recommended, which equals an average heat extraction rate per borehole length of 25 W/m. If a larger amount of energy is extracted the temperature in the borehole becomes very low, and the upper part could freeze. Since the pilot project will use a BHE with water as circulation fluid, this means that the system would stop working.

The temperature increase with depth due to the geothermal gradient allows for a larger energy extraction in deep boreholes. In an 800 m deep borehole with a temperature gradient of 0.02 K/m it was shown that 75 % of the total energy was extracted from the bottom half of the borehole. This means that a deep borehole can provide more energy than a group of shallow boreholes when the total borehole length is the same. However, since the heat rate is larger towards the bottom of the borehole, the amount of thermal interaction will also increase with depth. Therefore, including the influence of thermal interaction in the performance simulation becomes increasingly important as the borehole depth increases.

The evaluation of the thermal performance of the coaxial collector showed that both using PP and PE will give a significant heat loss from the center pipe to the downward flow. The thermal resistance of PP is almost twice as large as for PE, which leads to a reduction in heat loss of about 11 %. The choice of center pipe diameter should be based on minimizing the total pressure loss in the collector. Since the improvement in thermal performance when increasing the center pipe thickness was rather small, the additional cost as well as the reduction in flow area will probably outweigh the benefits of using a thicker center pipe. The optimal mass flow rate will also depend on the heat pump. A larger mass flow gives a better thermal performance and a higher outlet temperature from the collector, which increases the COP of the heat pump. However, this has to be weighed against the increased pressure drop and power consumption of the circulation pump.

The evaluation of the thermal response testing indicates that the traditional method is not suitable for deep boreholes. The temperature difference between top and bottom of a deep borehole lead to large variations in the heat rate along the borehole axis, which reduces the accuracy of the test analysis. The simulations of response tests using a constant inlet temperature and variable heat rate did not provide satisfactory results. However, combining a constant inlet temperature with a variable mass flow to obtain a constant heat rate during the test was shown to provide fairly accurate conductivity estimations. With a minimum temperature difference of 10 degrees between the inlet and the average undisturbed ground temperature, the conductivity was estimated with an error of less than 3 %. Based on the results of the simulations, using a constant inlet temperature and a variable mass flow could be a viable option for response testing of deep boreholes if accurate temperature measurements are available.

8.2. Suggestions for further work

The results from the numerical simulations should be validated with data from field thermal response tests. Since the method proposed in this thesis showed some limitations regarding the minimum temperature of the borehole, other possible methods to test deep boreholes should also be evaluated. Methods that are considered to be viable options in the future are for example response testing by using a heating cable to heat sections of the borehole [25]. This method only requires a low power source, making the testing both more economical and easier to conduct. The method can also be combined with distributed temperature measurements to perform local measurements of the ground thermal conductivity along the depth of the borehole.

In this thesis the main focus has been on determining the ground thermal conductivity through response tests. However, the effective borehole thermal resistance is also an important parameter when evaluating the borehole performance, therefore methods to determine this value in deep boreholes should also be studied.

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