Analysis of the influence of the heat power rate variations in different phases of a Distributed Thermal Response Test

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1. Introduction

The Thermal Response Test (TRT) has been used up to now in Borehole Heat Exchangers (BHE) in order to estimate the mean value of the thermal design parameters, such as the thermal conductivity (λ) and the borehole thermal resistance (Rb). The improvements in GSHPs are currently focused on the optimization of the system and the reduction of costs installations. The determination of accurate values for the thermal conductivity and the borehole thermal resistance is crucial for an optimal design and probably lower installation cost. The accuracy in the estimation of these thermal parameters influences the total length of the Borehole heat exchanger at a design stage. It is also known that other factors as groundwater, convective heat and different materials of rock along the depth may influence in the heat transfer to /from the surrounding ground. Currently, some authors as Fujii et al. (2006), Fujii et al. (2009), Acuña et al. (2009) and Acuña et al. (2011) take into account the response of the ground along borehole depth and thereby identify the vertical profile of λ and Rb.

An important issue to consider during heat injection TRTs is variations in heat rejected to the ground due to power fluctuations in the electric generator. The difficulty to maintain a constant heat flux injection has been illustrated by Gehlin and Eklöf (1996). In order to consider the effect of variable heat flux injection, the mean temperature in borehole can be described as a sum of heat input steps from past intervals of time (Eskilson (1987) and Hellström (1991)) according to the temporal superposition principle.

Beier (2003) developed a preprocessing algorithm, in which the variable heat rates effects are removed. This method allows calculate the temperature curve corresponding to one if the heat rate had been constant during the in-situ test. As regards to interruptions in the power during the TRT, Beier (2008) also develops an equivalent time model, based on line source model and the above mentioned principle of superposition, to eliminate their effects in results. Thus, the thermal properties are estimated as a function of an equivalent time expression.

Raymond et al. (2011), following the pumping test concepts, approximate the line source model solution as a Taylor series approximation of the well function, in which the heat injection is accounted as a contribution of heat steps. The uncertainties in the heat injection rate (±3%) taking into account the accuracy of temperature and flow measurements provided by manufacturers’ equipment are also determined. A sensitivity analysis of the mean water temperature increment is carried out for two levels of thermal properties variance during the heat injection and recovery phases. Therefore, the analysis shows the uncertainties decrease when thermal properties are estimated using temperature data of recovery phase. Thus borehole thermal resistance can be estimated with the heat injection data and the thermal conductivity estimates in recovery phase.

This paper is focused on studying how the amount of heat steps considered in a DTRT influence the estimation of the thermal conductivity and the borehole thermal resistance along the borehole depth during the heating phase. The response of the ground is considered during not only the heating injection but also taking into account the influence of a previous pre-circulation phase. The effect of the pre-circulation phase is studied on DTRT results with different pulse
In order to analyze the uncertainties due to the heat pulse variations, the thermal conductivity is also evaluated during the thermal recovery-phase (after heat injection), in which the temperature inside the borehole is measured without heating or circulation. The borehole resistance is also calculated using the thermal conductivity value found during the thermal recovery phase. Finally, the estimated thermal parameters in each DTRT phase for a short heat step analysis are compared with each other, including the profile of both parameters obtained in Acuña et al. (2009) where a polynomial expression using the series solution of the line source model was used superposing all heat steps in time. In this comparison, the results from assuming a constant heat flux during the heating phase are also considered. All this study presented in this paper is a continuation of the work by Monzó et al. (2011).

The estimation of the aforementioned thermal parameters along the borehole depth is carried out using an approach of the Line Source Model (Ingersoll and Plass (1948) including the insertion of a thermal resistance suggested by Mogensen (1983)), as well as considering the heat injection as a superposition of temporal heat steps with different heat injection step approaches. The heat injection rate is studied as different widely-temporal heat steps, as explained in part 2 of this paper.

2. Materials and Methods

The temperature measurements are carried out in an installation located at the south of Stockholm, Sweden. The characteristics of the borehole are: 140 mm in diameter and 260 m in depth. Fiber optical cables are set up inside and along a U-pipe BHE length. To analyze the thermal properties along the depth, the borehole is divided into 12 sections of 20 meters. In order to avoid the influence of the ambient air and the hemispherical heat transfer around the borehole bottom, the first and last ten meters depth are neglected in calculations. The temperature is registered at the inlet and outlet of each borehole section in intervals of time of 25 minutes. Then, the profile temperature is acquired during the four test-phases of the DTRT presented in page 52 (Acuña (2010)). The injection rate \( q \) is calculated as a difference between the temperature at the inlet and at the outlet in each borehole section for every 25 minutes, as follows in equation 1.

\[
q(t) = \rho \cdot V \cdot C_p \cdot \Delta T(t) \quad (1)
\]

The temperature and the heat power rate profiles are analyzed using an analytical approach based on the line source model (Ingersoll and Plass (1948), including the insertion of a thermal resistance suggested by Mogensen (1983)). Assuming a constant heat rate, an undisturbed ground temperature \( T_o \) as well as BHE surroundings are homogeneous and isotropic, the fluid temperature \( T_f \) can be written as expressed in equation 2.

\[
T_f(t) = \frac{q}{4\pi\lambda} \cdot \int_0^\infty \frac{e^{-u}}{\tau^2} du + q \cdot R_b + T_o \quad (2)
\]

A good approximation of the solution of the exponential integral in equation 1 can be expressed as shown in equation 3, resulting a liner relation between \( T_f \) and the natural logarithm of time (Eklöf and Gehlin (1996)). The thermal conductivity can be related to the slope of the curve \( T_f \) over natural logarithm of time.

\[
T_f(t) = \frac{q}{4\pi\lambda} \cdot \left( \ln \left( \frac{4\alpha t}{\tau^2} \right) - \gamma \right) + q \cdot R_b + T_o \quad (3)
\]

In this study, the analytical procedure is implemented in MATLAB considering the fluid temperature as a function of an addition of multiple heat power steps in accordance with the superposition principle, as it is shown in following scheme (equation 4):
Therefore, the temperature in the bedrock can be written as a sum of the input of each heat step, as expressed in the equation 5:

$$T_r(t) = \sum_{n=1}^{N} \left( \frac{q_n - q_{n-1}}{4\pi \alpha} \cdot \ln(t - t_n) + \left[ q_N \cdot \left( \frac{1}{\sqrt{\alpha t_N}} \ln \left( \frac{4\alpha t_N^2}{\tau_0^2} \right) - \gamma \right) + R_b \right] + T_0 \right)$$

A tau parameter can be defined from equation 5, when $t_n + 5\alpha < t < t_{N+1}$, as presented in equation 6.

$$\tau_n(t) = \sum_{n=1}^{N} \frac{q_n - q_{n-1}}{q_{ref}} \cdot \ln(t - t_n)$$

Finally, the line source solution can be written as presented in equation 7:

$$T_r(t) = \frac{q_{ref}}{4\pi \alpha} \tau_n(t) + \left[ \frac{1}{\sqrt{\alpha t_N}} \ln \left( \frac{4\alpha t_N^2}{\tau_0^2} \right) - \gamma \right] + R_b + T_0$$

A linear relation between the temperature and $\tau_N$ parameter is now observed. Thus the thermal conductivity will be related to the slope of the curve $T_r(t)$ over $\tau_N$, now accounting for n power variations during the DTRT.

The input data to the calculations is the profile of the undisturbed temperature in each borehole section, the profile of arithmetic mean fluid temperatures during the all four DTRT-phases every 25 minutes along every borehole section as well as the heat injection rate in intervals of 25 minutes, previously calculated with equation 1.

As mentioned above, the response of the ground at each borehole section is studied in the following cases:

- 3rd DTRT-phase (heat injection), in which only the heat injection supplied during 45 hours is considered.
- 2nd & 3rd DTRT-phases (heat injection including pre-circulation), all power steps during the first 70 hours are considered
- 2nd & 3rd & 4th DTRT-phases, heat steps during pre-circulation and heat injection phases are taken into account to analyze the temperature measurements during the recovery phase. The response is evaluated during 96 hours.

In these three study cases, the change in temperature in the ground is analyzed according to the temporal superposition principle as shown in equation 7. Thus, the flux injection is considered as a sum of injection steps from past interval of time. It is studied according to different temporal duration of the heat steps:

- Long step: about 3 hours constant pulse,
- Medium step: about 1.5 hours constant pulse,
- Short step: 25 minutes constant pulse.

The case with one single constant heat step during phase 3 is also presented for comparison purposes.

In the first case, the long step, the injection input data, which is logged every 25 minutes, has been grouped and averaged in measurements of about three hours; thus the injection data is
In the medium temporal step length, the injection is the average in the injection data every 1.5 hours. And in the low temporal width step, the injection is evaluated every 25 minutes, using the original input data from the field test. The difference between these three temporal injection steps is just the time in which the heat pulse is assumed to be constant.

In the first case of study, in which only data for the heating phase is considered, the thermal conductivity results from the slope of the curve of the experimental temperature measurements over its corresponding value of the tau parameter, in each borehole section and for different temporal step analyses. The thermal conductivity is also estimated considering the heat injection as the average of the injection rate considering it as one constant heat step.

During the 2nd DTRT-phase; the fluid is circulating without heating, but some heat is rejected to the ground due to the circulation pump. It should be pointed out that in case in which the 2nd DTRT-phase is considered, only temperature measurements in the heating interval are plotted against to its corresponding tau, but these tau values reflect the influence of previous pre-circulation phase in thermal estimates.

After the thermal conductivity is estimated in the 3rd phase and during the 2nd & 3rd DTRT-phases for all the cases of different temporal injection steps, the borehole thermal resistance is estimated with equation 7. When considering a constant heat flux, then equation 3 is used. For all these analyses, the borehole thermal resistance is calculated during the last 30 hours of the 3rd-DTRT phase for each studied time step. Then, the mean value is used as the estimated value of the borehole thermal resistance for all cases of study and in each borehole section.

Taking into account the recovery phase, in which no heating and no fluid circulation take place; the thermal conductivity is evaluated by two different methods. Figure 1 shows a scheme of the methodology carried out in this phase.

![Figure 1. Scheme of calculations carried out in the recovery phase.](image-url)
last 20 hours of the recovery phase and the thermal conductivity is estimated considering the absolute value of the slope. Therefore the thermal conductivity, \( \lambda_1 \), is estimated for the three cases of pulse studied. Using the thermal conductivity estimated in the case of short step, the thermal borehole resistance is calculated considering heat injection as a constant heat flux and a sum of short flux steps during the 3\(^{rd}\) DTRT-phase and 2\(^{nd}\) & 3\(^{rd}\) DTRT-phases.

In method 2, the thermal conductivity is estimated as the slope of the curve (temperature over time) in the last 20 hours of 4\(^{th}\) phase and the mean value of the heat injected during the 3\(^{rd}\) phase. Then the borehole thermal resistance is calculated using \( \lambda_2 \) and considering the flux injection during the heating phase as a constant heat flux.

All results from this study are compared with the estimates calculated in Acuña (2010), where the thermal conductivity is estimated during the recovery phase and used as an input for obtaining \( R_b \), using a polynomial expression from the series solution of the line source model presented in Ingersoll&Plass (1948).

3. Results and Discussion

3.1. Analysis of the duration of the pulse in the heating phase.

The profile of \( \lambda \) and \( R_b \) resulting from different heat step duration during the 3rd DTRT-phase is shown in Figure 2. The results from the different temporal heat step analyses are described in the figure in terms of long, medium and short constant step. The constant heat injection case is denoted with a no-filled circle symbol.

As regards to the thermal conductivity, the values estimated by assuming a constant heat power differ significantly from the values resulting from the analysis of heat pulses. Considering the analysis of different heat steps, there is a relation between the temporal width of the step and the

![Figure 2](image-url)
value of the parameter. The shorter the heat pulse is considered, the higher estimated value is obtained. Although the differences are small, this correlation may indicate the effect of the heat variation in the thermal conductivity. When a short heat pulse is considered, the relative variations between subsequent pulses are higher, possibly indicating a higher variation in the value of the tau parameter. Therefore, the slope of the curve may be lower and a higher value of the thermal parameter is obtained.

The constant heat rate analysis seems to overestimate the borehole resistance in the upper part of the borehole and to underestimate it in the lower part.

Considering the result of the borehole thermal resistance profile, a significant difference is observed between the constant heat power and the heat step cases. In the same way as for the thermal conductivity, with lower duration of the heat pulse, a higher estimated borehole thermal resistance is obtained.

3.2. Study of the effect of the pre-circulation period on the DTRT results evaluated during the heat injection phase with different pulse durations.

This subchapter shows the thermal parameters values when the influence of the pre-circulation phase is considered together with the heating phase. These are also studied accounting the injection as pulses of different duration. The results are shown in Figure 3.

(a) 2nd&3rd phases DTRT- $\lambda$

(b) 2nd&3rd phases DTRT - $R_b$

In this case, there is not a clear tendency between the duration of the step considered and the value of the thermal conductivity. However, comparing with the previous results obtained from heat step analysis during the heating phase, there are significant differences between the range of variation of the thermal conductivity. For example, considering the estimation of the thermal conductivity in section 4 for a medium heat pulse analysis, the value of the thermal conductivity estimated is 2.55 [W/Km] in this case, while in the previous one it is 3.03 [W/Km]. This significant difference can also be observed in the estimation of the borehole thermal resistance.
It is estimated in 0.070 [Km/W] in the 3rd DTRT-phase analysis and 0.046 [Km/W] in this case. This fact reflects the importance to delimit the value of the thermal conductivity and its variation.

3.3. Analysis of the DTRT results evaluated during the thermal recovery phase with different pulse duration.

The thermal conductivity is evaluated during the 4th DTRT-phase, as explained in the previous section. These results are shown in Figure 4. Since the thermal conductivity is evaluated in two different ways, it is denoted in the figure as $\lambda_1$ and $\lambda_2$ in accordance with the explanation of method 1 and 2 illustrated in Figure 1, respectively. These results are also compared with the results from Acuña et al. (2009), in which the response of the ground during the thermal recovery phase was evaluated using a polynomial approximation of the solution of the exponential integral.

The borehole thermal resistance is calculated using $\lambda_1$ and $\lambda_2$. In case of considering $\lambda_1$, the borehole thermal resistance is calculated assuming a constant heat power and short heat steps during the heating phase, these results are denoted in Figure 4.b as $\lambda_1/Q$ mean 3rd DTRT and $\lambda_1$/Short step in 3rd DTRT-phase, respectively. Considering the pre-circulation phase the results are described as $\lambda_1$/Short step in 3rd & 2nd DTRT-phases. The results taking into account $\lambda_2$ are expressed as $\lambda_2$/ $Q$ mean 3rd DTRT. All these results are also compared with the results from Acuña et al. (2009).

Figure 4. (a) Thermal Conductivity and (b) Borehole Thermal Resistance profiles considering the response of the ground in the Recovery phase.
In most of the sections, it can be appreciated that the estimates of the thermal conductivity resulting from the heat step analysis present a lower deviation compared to Acuña et al. (2009) solution while the estimates of $\lambda_2$ deviate slightly more. The estimates resulting from the short heat step analyses present almost the same result with variations in the third decimal place. Comparing the values of $\lambda_1$ and $\lambda_2$, in which the difference in methodology is how the heat injection is considered, the differences in the estimates reflect this fact showing a smoother profile along the borehole depth.

Regarding the thermal borehole resistance, there are significant differences that seem not to just be related to the value of the thermal conductivity, $\lambda_1$ or $\lambda_2$ in most of the sections. The heat step methods present the same approximate results whereas the constant power approach and Acuña et al. (2009) solution seem to result in lower Rb values in the lower part of the borehole. The difference with the Acuña et al. (2009) solution may be explained by the fact the values presented in Acuña et al. (2009) were optimized with the by minimizing the squared error between a calculated temperature response and the measured temperatures. In general, a tendency cannot establish as regards to the influence of the 2nd DTRT-phase in the Rb estimates. However, the estimates in this case do not present a variation higher than 0.003 [Km/W] in the worst cases.

### 3.4. Comparison of DTRT results based on different test phases.

Finally, a comparison of the short step results considering each DTRT-phase is carried out. The result from assuming a constant power during the heating injection is also included together with the estimates from Acuña et al. (2009). It has been decided to consider the estimates from the short step analysis in order to be consistent in the comparison with the Acuña et al. (2009) solution, where the data is also analyzed in intervals of 25 minutes.

![Figure 5](image-url)
As regards to the thermal conductivity profile, it can be observed that there is a tendency in accordance with the DTRT-phase considered in this analysis in most borehole sections. The estimates evaluated only during the 3rd DTRT-phase present higher values than in the other cases studied. The thermal conductivities obtained in the recovery phase present the lowest values in comparison with the estimates when the heating and pre-circulation phased considered. Additionally, simultaneously accounting for the pre-circulation and heating DTRT-phases, results in values between the cases for only heating phase and the recovery phase. This is valid in most of the borehole sections. It should be noted that the differences in estimation between the values of 2nd & 3rd DTRT-phases and 2nd & 3rd & 4th DTRT-phases are lower than the ones between 3rd DTRT-phase and 2nd & 3rd & 4th DTRT-phases. The difference in the results during the heating (3rd DTRT-phase) and considering the thermal response in the recovery phase (2nd & 3rd & 4th DTRT –phase) is about 12.9% on average whereas it is about 3.13 % comparing the results accounting the pre-circulation phase and the ones from the recovery phase. Besides, it can be observed that there is a significant difference in the estimates when a constant heat power is assumed to occur during the whole period of the heat injection.

Concerning the borehole thermal resistance, the filled triangle represents the value of Rb calculated considering the thermal conductivity from the recovery phase and considering 25 minute pulses. The value assuming a constant heat power during the heating phase is also included together with the results from Acuña et al. (2009). The results that only consider the heat injection phase also tend to overestimate the borehole thermal resistance. The values considering the pre-circulation phase diverge less than for the former case and, in general, a good agreement in thermal conductivity and borehole resistance is observed between the case when all phases are considered and results by Acuña et al. (2009), being this logical since both approaches follow almost the same methodology.

All tendencies discussed about in this chapter 3 have not considered the borehole section 9 due to possible anomalies found in this borehole section, as explained in Acuña (2010).

4. Conclusion

According to the analysis of the duration of the pulse during the heating phase, the values of the thermal parameters become higher when a shorter heat pulse is considered. When these are compared with the case of a single pulse assuming a constant heat power, the results present significant differences. Also, the assumption of a constant heat power may imply an overestimation of the thermal parameters in the upper part of the borehole and their underestimation in the lower part.

In the DTRT-phase analysis for a short heat step, there is a clear tendency. Significant differences are observed between the results from the heating phase and the ones from the recovery phase as well as in results when the pre-circulation is considered. The highest values are obtained when only accounting for the data during the heating phase and the lowest values result from the analyses of the recovery phase. Moreover, in the recovery phase, the duration of heat steps considered in the DTRT analysis does not seem to have any effect on the thermal conductivity result as long as the superposition principle is applied.

5. References


6. Acknowledgements

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