DISTRIBUTED THERMAL RESPONSE TEST ON A U-PIPE BOREHOLE HEAT EXCHANGER

J. Acuña
Royal Institute of Technology
Brinellvägen 68, 100 44 Stockholm, Sweden
jose.acuna@energy.kth.se

P. Mogensen
Palne Mogensen AB
Emblavägen 29, 182 67 Djursholm, Sweden
palne.mogensen@pmab.se

B. Palm
Royal Institute of Technology
Brinellvägen 68, 100 44 Stockholm, Sweden
bpalm@energy.kth.se

ABSTRACT

In a Distributed Thermal Response Test (DTRT) the ground thermal conductivity and borehole thermal resistance are determined at many instances along the borehole. Here, such a test is carried out at a 260 m deep water filled energy well, equipped with a U-pipe borehole heat exchanger, containing an aqueous solution of ethanol as working fluid. Distributed temperature measurements are carried out using fiber optic cables placed inside the U-pipe, during four test phases: undisturbed ground conditions, fluid pre-circulation, constant heat injection, and borehole recovery. A line source model is used for simulating the borehole thermal response. Fluid temperature profiles during the test are presented. The results show local variations of the ground thermal conductivity and borehole thermal resistance along the borehole depth, as well as a deviation of the latter as compared to the one resulting from a standard thermal response test.

1. INTRODUCTION

The heat transfer between the secondary working fluid and the surrounding rock in ground source heat pump installations depends on the arrangement of and the heat transfer in the Borehole Heat Exchanger (BHE) flow channels, possible convection in the borehole, the thermal properties of the BHEs as well as of the borehole filling material. The thermal resistances associated with these different parts are normally added together and called borehole thermal resistance, defined as \( R_b \) by (Hellström, 1991).

A common method for evaluating the heat transfer performance of BHEs and ground properties is a Thermal Response Test (TRT), dating from 1983, when Palne Mogensen, together with two students from The Royal Institute of Technology (KTH), Sweden, suggested and built the first borehole thermal response tester arrangement. A 2,7 kW constant cooling power was applied to the working fluid in a BHE, while logging the fluid temperature as well as the cooling power. (Mogensen, 1983) found that it was possible to calculate \( R_b \) in addition to the ground thermal conductivity. Later, at the end of the nineties, TRT methods were studied further and several papers were published by Gehlin and others (e.g. Gehlin, 2002). Nowadays, the most common TRT equipment consists of a mobile rig containing an electric heater, a
pump, and temperature and flow sensors. Usually, the heat injection is kept constant. Numerous response testers have been built around the world and they are being used as a standard procedure for measuring the ground thermal conductivity in energy wells and for testing BHE performance. The result of conventional TRTs is very useful and allows a more accurate sizing of BHE installations. However, it presents merely an average thermal conductivity of the surrounding ground and an average borehole thermal resistance.

The impact of TRT results can be enhanced by carrying out a Distributed Thermal Response Test (DTRT), i.e. measuring temperatures at different depths in the borehole while running a TRT. A way to do this is by measuring the fluid temperature using an optical fiber, through which laser pulses are sent. Some of the backscattered light is frequency shifted with the intensity ratio between up- and down-shift being a function of the temperature (Raman scattering). This ratio and the delay time are converted to temperatures and positions by the readout equipment. The accuracy is depending on integration time and measuring length interval among other factors.

A pioneering work has been done by (Fujii, et al., 2006), with an optical fiber cable located on the external wall of the pipe, thereby losing the possibility to evaluate $R_b$, since it relates to the fluid temperature. This is in our case possible thanks to a fiber optic cable located inside the BHE pipe.

2. THE DISTRIBUTED THERMAL RESPONSE TEST (DTRT)

A DTRT was carried out in a 260 m deep water filled borehole, where the groundwater level was 5,5 m below surface before the BHE installation. The borehole diameter is 140 mm and it has been previously characterized in detail (Acuña, et al., 2008), regarding groundwater flow as well as deviation from the vertical position. No significant groundwater flow (about 0,4 l/min after decreasing the ground water level by 35 meters) was the result, but a fracture zone or diameter increase in the range 190 to 200 m depth was indicated.

A 257 meter long U-pipe collector PE 80 40x2,4 mm (plus extra weight) is installed into the well. An aqueous solution of 16 % weight concentration ethanol is used as working fluid and the thermophysical properties for the calculations are obtained from (Melinder, 2007). The flow rate was constant during the test (1,87 m$^3$/h).

The test was carried out during approximately 160 hours with a new TRT apparatus built at the Royal Institute of Technology (KTH), consisting of a circulation pump of the type Magna 25-100 from Grundfos, an inductive flow and energy meter of the type HGS9-R6 from Brunata, a STAD flow regulation valve, and an electric heater with adjustable heating power between 3 and 12 kW.

The borehole was divided into 12 sections of 20 meters each (Figure 1), in which the thermal conductivities and borehole thermal resistances were determined. The first section starts at 10 meters depth and the last section ends at 250 m depth, measured from the ground surface. The
first ten meters were neglected, since there is a portion of the optical fiber cable exposed to ambient air. Neglecting the last ten meters eliminates influence of hemispherical heat transfer around the borehole bottom, which would cause deviation from the line source theory.

An optical fiber cable of type 50/125 – having two graded index multimode fibers, protected with a thin stainless tube – measures the fluid temperature every 10 m along the whole collector length, i.e. there are a total of six measurement points in each section (three in each pipe). The temperature readout equipment is of type HALO-DTS (Sensornet), cable and instrument supplied by Hydroresearch AB. Thermocouples inserted at different depths into the BHE pipes have also been used in this study as an extra tool to confirm the fiber measurements.

The optical fiber temperature measurements were taken with an integrating time of 5 minutes and a measurement length interval of 10 m during the four continuous test phases. In the first phase, the undisturbed ground temperature was measured with no fluid circulation during 3 days. Subsequently, during phase two, the fluid was circulated through the BHE for 24 hours without heating, followed by phase three, in which constant heating power (9 kW) during 48 hours of was applied. In phase four, the measurements continued for one more day without any heating or fluid circulation in order to observe the borehole recovery.

The lateral position of the fiber optic cable inside the U-pipe is not known, since there are no spacers or similar on the cable. The question naturally arises how the temperature readings are affected by the position of the cable. The flow pattern in the pipe is turbulent with a Reynolds number between 6500 and 8900 (fluid temperature varies between 9 and 18 °C). It is well known that there is a laminar sub-layer at the pipe wall, in this case with a thickness between 0,3 and 0,4 mm (Schlichting, 1979). In that layer heat transfer can only occur by thermal conduction. The heat transfer coefficient at the wall can be calculated to 1130 - 1380 W/(m² K). With a heat flux of 180 W/m², we find that the temperature difference between the pipe wall and the fluid (bulk temperature) is close to 0,15 K. According to (Melinder, 2007) the thermal conductivity of the fluid is 0,49 W/(m K). Within the laminar sub-layer the temperature drop is then circa 0,14 K, thus practically the whole temperature drop occurs in this thin layer and the temperature profile in the rest of the fluid is very flat. This statement is also supported by turbulence theory. The diameter of the fiber optic cable is 3,8 mm and it thus measures the bulk temperature of the fluid with sufficient accuracy for our purpose.

3. THE CALCULATIONS

The determination of the rock thermal conductivity ($\lambda_{\text{rock}}$) and borehole thermal resistance ($R_b$) is carried out by calculating the temperature difference between the fluid and the undisturbed ground as a function of time. A computer program subsequently minimizes the squared error between calculated and measured values by adjusting $\lambda_{\text{rock}}$ and $R_b$. The program uses the line source model (Equation 1) presented by (L.R. Ingersoll, 1948) that evaluates the temperature response after time $t$ of a step change in supplied heat power ($q$). The temperature response of many such steps at different times may be superposed.

$$T_f - T_g = \frac{q}{L} \left[ R_b + \frac{1}{2\pi \lambda_{\text{rock}}} \int_{r_h}^{\infty} \frac{e^{-\beta^2}}{\beta^2} d\beta \right]$$

The equation above is used to calculate the temperature difference between the fluid and the ground. The integral term represents the heat transfer from the borehole to the ground.

$$q = \rho \cdot V \cdot Cp \cdot \Delta T_s$$

Equation 2
The integral in Equation 1 (the exponential integral) is evaluated by a series expansion. $R_b$ is an extra term added to Ingersoll’s equation in order to account for the temperature difference between the working fluid and the borehole wall. Equation 1 is applied to each 20 m section of the borehole, and for each section the heating power ($q$) is calculated with Equation 2 – the fluid temperature difference $\Delta T_s$, taken in each pipe at the section entrance and exit, respectively. These points also delimit consecutive sections and are enumerated F1 to F26 following the flow direction, as illustrated in Figure 1.

All six measurement points were used for the estimation of the fluid temperature ($T_f$) in each section. Regarding the undisturbed ground temperature ($T_g$), (Gehlin, et al., 2003) point out that different $T_g$ values are obtained depending on measurement circumstances. In our case, we have used the truly undisturbed ground temperature for each section, in order to later, during the pre-circulation period, account for the heat flow between sections and the friction heat caused by pumping the fluid. $T_g$ is therefore not the same for each section. The undisturbed ground temperature profile, illustrated in Figure 2, is used.

We used a two step method for the determination of $\lambda_{\text{rock}}$ and $R_b$; $\lambda_{\text{rock}}$ was evaluated during the recovery phase, neglecting the first 15 hours. This phase gives the best information about the rock thermal conductivity, since the radial temperature gradients in the borehole are low, thus virtually eliminating the uncertainty caused by the unknown positions of the BHE pipes at different depths. The results for $\lambda_{\text{rock}}$ were then used as an input to calculate $R_b$ during the heating phase, again neglecting the first 15 hours. Moreover, in order to account for previous heat extraction in the borehole, the undisturbed ground temperature was adjusted by adding an experimental slope factor to the measured values.

4. RESULTS AND DISCUSSION

![Figure 2. Average temperatures during the first three phases of the DTRT](image-url)
Figure 2 presents average temperature profiles during the first three phases of the DTRT. It can be observed that the undisturbed temperature gradient is negative between 10 and about 90 meters depth, while positive along the rest of the borehole. An average temperature from this profile is 9.10 °C. From the temperatures during the fluid pre-circulation phase of the test, it can be seen that the fluid adopts quite a constant temperature along the whole depth with an average of 9.19 °C. Most of this temperature increase can be attributed to the circulation pump work. Figure 2 also shows the average temperatures during the heating phase, illustrating that the true average temperature in the borehole is far away from the mean of in- and outlet temperature as assumed during a conventional TRT. Temperature measurement in at least a few points at different depths in the BHE would allow a better estimate of the average temperature. The latter would of course depend on which volumetric flow rate is used during the test as well as on the borehole depth.

Figure 3 presents the supplied power to the sections during the heat injection phase. It is observed that power is neither the same nor constant in each borehole section during the whole DTRT. Different borehole thermal resistances between sections and differences in rock thermal conductivity will show up here. Several disturbing factors are present such as variations in the applied heating power and uncertainties in temperature measurements. The fluid temperature difference over a section is only about 0.15 K getting smaller for deeper sections, thus increasing sensitivity to temperature measurement deviations. A local disturbance in the common temperature measurement point at 170 m is probably the reason for the deviation in temperature observed in Figure 2 and power (between section 8 and 9) in Figure 3.

Figure 4 shows the temperature in each section during part of the heat injection phase ($R_b$ is evaluated from 106 to 138 hours). The differences in temperature level between subsequent sections decreases with depth, showing good accordance with Figure 2. The irregular pattern of the curves is attributed to input power variations. It is observed that the slope of the curves is fairly similar, giving an indication that the surrounding rock is reasonably homogeneous.
Variations in $R_b$ would move the curves either up or down, without a change of the slope, as would be the case with a change in $\lambda_{\text{rock}}$.

Figure 4. Average temperatures in each section during the heat injection phase

Figure 5 presents the average fluid temperatures in each section during the last 20 hours of the test, showing part of the borehole recovery period. Some of the section curves intersect others, while approaching the original undisturbed ground temperatures. Slight slope differences between certain sections are observed. The last 10 hours of this period (155 to 165 hours) were used for optimizing the $\lambda_{\text{rock}}$ for each section.

Figure 5. Average temperatures in each section during the borehole recovery phase
The borehole thermal resistance and rock thermal conductivity in each borehole section are presented in Figure 6 (a) and (b), respectively. The former varies within the range 0,054 to 0,078 Km/W, indicating changes of the pipes position in the borehole along the borehole depth. By averaging all the $R_b$ values we obtain a mean equal to 0,062 Km/W.

The rock thermal conductivity values range between 2,60 and 3,62 W/Km, and the result of averaging all the sections is equal to 3,10 W/Km.

Section 8 and section 9 show extreme values in opposite directions, partially explained once again by the deviation of the temperature measurement at 170 m.

The average $\lambda_{\text{rock}}$ and $R_b$ obtained in the DTRT were compared with those from a conventional TRT analysis. The latter would use the fluid mean temperature at the borehole in- and outlet for the evaluation of the thermal response. In this case, this would correspond to the average between F1 and F26 (see Figure 1 and Figure 2). Both $\lambda_{\text{rock}}$ and $R_b$ were evaluated based on this temperature during the heat injection phase and omitting the first 15 hours. The result was 3,08 W/Km and 0,079 Km/W for $\lambda_{\text{rock}}$ and $R_b$, respectively.

Almost no deviation from the DTRT regarding $\lambda_{\text{rock}}$ was found. However, the $R_b$ value corresponding to the conventional TRT test deviates from the DTRT average result by circa +28 %. The deviation is caused by the overestimation of $T_f$ in using the mean of in- and outlet temperatures instead of an average over the whole borehole (Figure 2). Using this average will yield an $R_b$ equal to 0,063 Km/W and the same value for $\lambda_{\text{rock}}$ as before. This suggests that adjustments should be made to conventional TRT evaluations in order not to overestimate the borehole thermal resistance.

5. CONCLUSIONS

The mean ground temperature was measured during zero flow conditions and pre-circulation of the working fluid. The result validates previous studies regarding the influence of pumping power on the assessment of undisturbed ground temperature during TRTs.
The rock thermal conductivity and borehole thermal resistance were determined in 12 different sections along the borehole depth. The surrounding rock appears to be relatively homogeneous with an average value of 3.10 W/Km, showing good agreement with the result from a conventional TRT analysis.

The variations in borehole thermal resistance indicated variations in the pipe positions with respect to each other and to the borehole wall along the borehole depth, having an average value of 0.062 Km/W and remarkably disagreeing with the result from conventional TRT analysis (0.079 Km/W). This is mainly attributed to the use of a less accurate fluid mean temperature during standard TRTs.

Further studies should be done regarding this in order to point out the necessary adjustments that should be done to the measured mean fluid temperature during standard thermal response tests.

6. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_f$</td>
<td>fluid temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>$T_g$</td>
<td>undisturbed ground temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>$q$</td>
<td>heat injection rate in section</td>
<td>[W]</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>[s]</td>
</tr>
<tr>
<td>$a$</td>
<td>rock thermal diffusivity</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>$r_{bh}$</td>
<td>borehole wall radius</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>section length</td>
<td>[m]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>integration variable</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>fluid density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat capacity</td>
<td>[J/kgK]</td>
</tr>
<tr>
<td>$\Delta T_s$</td>
<td>temperature difference</td>
<td>[K]</td>
</tr>
<tr>
<td>$\lambda_{rock}$</td>
<td>rock thermal conductivity</td>
<td>[W/Km]</td>
</tr>
<tr>
<td>$R_b$</td>
<td>borehole thermal resistance</td>
<td>[Km/W]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>fluid density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat capacity</td>
<td>[J/kgK]</td>
</tr>
<tr>
<td>$\Delta T_s$</td>
<td>temperature difference</td>
<td>[K]</td>
</tr>
<tr>
<td>$\lambda_{rock}$</td>
<td>rock thermal conductivity</td>
<td>[W/Km]</td>
</tr>
<tr>
<td>$R_b$</td>
<td>borehole thermal resistance</td>
<td>[Km/W]</td>
</tr>
<tr>
<td>$V$</td>
<td>volumetric flow rate</td>
<td>[m³/s]</td>
</tr>
</tbody>
</table>

7. ACKNOWLEDGEMENTS

The Swedish Energy Agency, EFFSYS2, and all our industry partners, are greatly acknowledged for financing this project. Special thanks to Brage Broberg who kindly helped to construct KTH’s second Thermal Response Test apparatus.

8. REFERENCES


