Multi injection rate – Thermal response test

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ABSTRACT

A groundwater-filled borehole heat exchanger (BHE) is influenced by the convective heat flow induced in the water. This effect is changing the heat transfer during the year and thereby the efficiency of the BHE. When thermal response test (TRT) is used for evaluating the heat transfer properties of the borehole and bedrock this influence ought to be investigated. By using multi-injection rate test with different injection rate periods groundwater influences may be detected. Multi-injection rate TRT measurements have been performed in two boreholes in Luleå, Sweden using heat injection. One borehole is located in solid bedrock while the other is situated in fractured bedrock. Both boreholes show a clear influence of the convective heat transfer, decreasing the borehole resistance for both boreholes. The fractured bedrock also shows that the convective flow influence the bedrock thermal conductivity with higher conductivity for higher injection rate.

1. INTRODUCTION

Thermal response test (TRT) is an in-situ test method to determine heat transport parameters for borehole heat exchangers (BHE). It has been described in several paper and thesis; see e.g. Gehlin (2002) and Austin (1998). Most TRTs are performed in backfilled BHEs using one constant injection rate through the whole test. At some areas groundwater affects the heat transport in and around the BHE. Witte and VanGelder (2006) introduced a procedure of multi-power level heating and cooling pulses to detect groundwater affects.

Regional groundwater is a natural occurring flow which is a result of the hydrogeological conditions at the site. It has been shown by e.g. Claesson and Hellström (2000) and Chiasson et al. (2000) that regional groundwater only influence a BHE under certain conditions such as porous ground or fractured bedrock. However, where it influence it has been shown by Sanner et al. (2000) to affect TRT measurements resulting in problems in test evaluation. Gehlin and Hellström (2003) showed that the modeling approach concerning groundwater influenced the result.

Convective flow may also be thermally induced in the groundwater during heat injection in the BHE. The achieved temperature gradient results in density differences in the water with the outcome of convective flow. In groundwater filled BHEs convective heat flow have been shown, by Kjellson and Hellström (1997, 1999) and Gustafsson and Gehlin (2008), to decrease the borehole thermal resistance (R_b) compared to stagnant water. Gustafsson and Gehlin (2006) used the BHE design program EED to calculate the difference in required total borehole length for a BHE system with R_b=0.1 m,K/W and 0.07m,K/W. The required length changed from 2890 m (0.1 m,K/W) to 2660 m for the fictive 15 borehole system

The thermosiphon effect was described by Gehlin et al. (2003) for fractured ground. It is a thermally induced convective flow through the groundwater filled BHE and out in connecting water filled fractures. They used a small-scaled laboratory experiment and a numerical model to investigate the phenomena. The thermosiphon effect was seen to increase the bedrock effective thermal conductivity (k_{br}). The result depended on the injection rate and the flow resistance in the connecting fractures.

Multi-injection rate TRT (MIR TRT) is here used to investigate the influence of thermally induced convective flow in groundwater filled BHEs. The measurements have been performed in two boreholes, one located in solid bedrock and one in fractured bedrock. Each measurement consists of four different measurement periods with altering heat injection rate.

2. MULTI-INJECTION RATE THERMAL RESPONSE TEST

A multi-injection rate thermal response test (MIR TRT) is performed by using several injection rates in one measurement. The test is preferable started with a first period with only the circulation pump running. This period is used to determine the heat loss from the equipment and connection pipe and to ensure that the beforehand measured undisturbed ground temperature is accurate. For the measurement presented here, the undisturbed ground temperature was logged along the borehole using a thermocouple that was lowered down into the hole before the first measurement. Between two measurements were the BHE aloud to rest for at least 3 weeks. This might have been to short time since the undisturbed ground temperature had to be given different values in the numerical analysis for the different measurements.

After the first period with only the circulation pump running, the first injection rate period (IRP) is started without any resting period between. It is run for approximately 72 hours before next IRP is started directly with another injection rate. In these measurements four different IRP have been used with a heat injection of 3, 6, 9 or 12 kW, each IRP having a different power. As for common TRT, the temperature of in- and outgoing fluid flow, temperature inside the equipment, outside air temperature as well as fluid flow rat and total electricity consumption are measured and logged every 10 min.

In the analysis of the measurement result is parameter estimation used to determine the bedrock thermal conductivity (k_{br}) and the borehole thermal resistance (R_b). A numerical axisymmetric heat conduction model (Hellström , 2001) is used. The parameter estimation minimize the value of the residual squared 2-norm for all time steps, Eq (1). The fluid temperature T_f for the measurement is calculated as a mean value of the in- and outgoing fluid flow temperatures. Each IRP is evaluated with a separate set of k_{br} and R_b for the special IRP time period, given 4 different set of values for each measurement.

$$\min \sum \left(T_f(measured) - T_f(calculated)\right) \quad (1)$$

3. RESULT AND DISCUSSION

Two boreholes located at different sites are used in this investigation. One is located in solid (S) ground with no larger connecting fractures and the other is located in fractured (F) ground. The length of the boreholes differs, where the S-borehole (located in solid ground) is 146 m deep and the F-borehole is 66 m deep. The two boreholes are first checked for regional groundwater flow. This is done by calculating the k_{br} with increasing analysing time, as described by Witte (2001). Both boreholes are shown to be free of regional groundwater influence. All influences of convective flow shown here in the results are therefore thermally induced.

Two MIR TRTs have been performed on each borehole, with 4 IRP in each measurement. Table 1 shows the heat injection rate used in each IRP for the four measurements. Since the F-borehole length is less than half of the S-borehole length, it will have more than twice as high heat injection rates. As may be seen the order of the injection rates have been altered between the different measurement. Of interest is to see whether the order of the injection rate affects the result of the test.

Table 1: Used injection rates [W/m borehole]

Measurement	IRP1 [W/m]	IRP2 [W/m]	IRP3 [W/m]	IRP4 [W/m]
S1:75-21-40-59	75.0	21.0	40.4	58.7
S2:21-75-59-40	21.0	75.0	58.7	40.4
F1:51-91-132-170	50.6	91.1	132.3	170.1
F2:170-51-132-91	170.1	50.6	132.3	91.1

Figure 1 shows the achieved effective bedrock thermal conductivities for the four measurements. It may bee seen that the result from the S-borehole is scattered randomly between 3.0-3.5 W/m,K. The error is slightly larger than normally described for TRT, i.e. ±10% (Spitler et al, 2000 and Witte et al. 2002). This may be a result of the resting period between each measurement being too short. If instead calculating the error within each measurement, the error becomes less than 10%.

The effective bedrock thermal conductivity for the F-borehole increase with increased heat injection rate, except for F2:51. During this IRP there were problems with the electricity whereby the period became hard to evaluate. This value may therefore be disregarded. The IRP F2:170 also experienced some smaller problems during the measurement. The F-borehole shows clear influence of the thermosiphon effect. Convective heat flow is achieved in the groundwater in connecting fractures and in the borehole which increase the heat transfer. An increase in heat injection rate creates larger density differences in the water whereby a higher flow rate is the result.

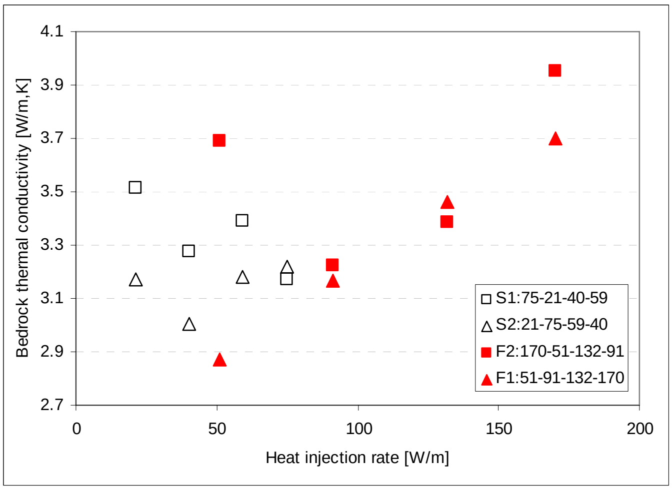

Figure 1: Effective bedrock thermal conductivity

Figure 2 shows the achieved borehole thermal resistance for the four measurements. An increase in heat injection rate results in a decrease in resistance for the S-borehole. Here the convective flow only occurs inside the borehole since there are no connecting fractures. The achieved heat transport in the water results in a 35% lower resistance using a heat injection rate of 75 W/m than using 21 W/m. The F-borehole shows a rather constant value for the borehole thermal resistance except for F2:51, which may be disregarded as mention before. With fractures connecting to the borehole is the achieved convective heat flow even larger than for the S-borehole. The achieved value is close to the thermal resistance for the U-pipe and the circulating fluid flow.

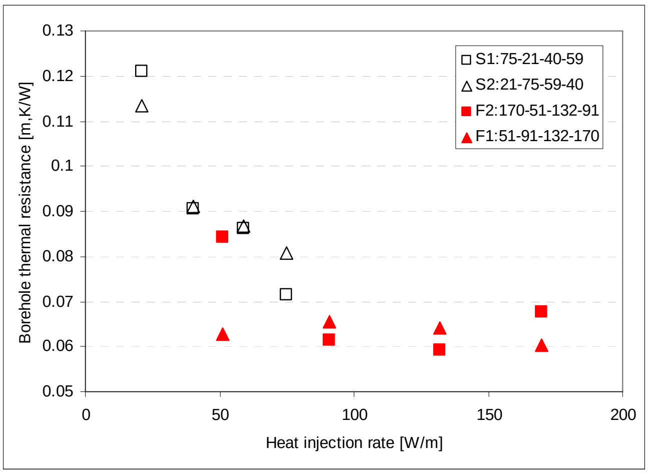

Figure 2: Borehole thermal resistance

To investigate if the order of the heat injection rates influences the result, calculations have been performed for a fictive S-borehole. The bedrock thermal conductivity is set to 3 W/m,K while the borehole thermal resistance is 0.06 m,K/W when the heat injection rate is 82 W/m and 0.1 m,K/W when using 21 W/m,K. Figure 3 shows the temperature gradient in and around the borehole for two fictive measurements (C1 and C2) using 2 IRPs each (82 and 21 W/m). Measurement C1 starts with 82 W/m for 72 h and then is the heat injection rate decreased to 21

W/m, measurement C2 is performed in the opposite way. Using 82 W/m before 21 W/m increases the temperatures inside the borehole (radius of the borehole is 0.07 m) with approximately 1.5ºC. This increase in temperature will affect the achieved convective heat flow.

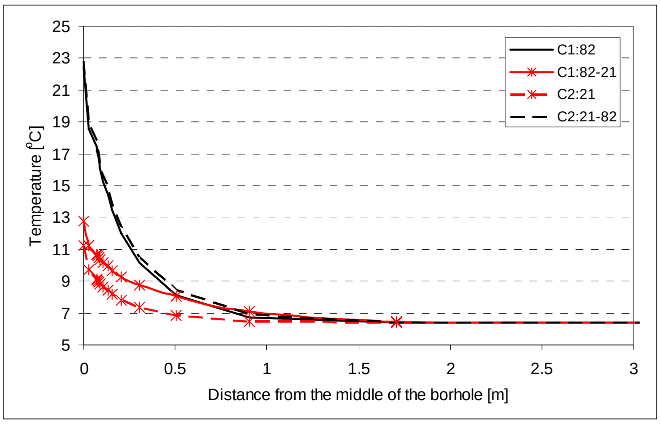

Figure 3: Temperature gradients in and around a fictive borehole.

Using 21 W/m before using 82 W/m hardly influences the achieved temperature gradient at all. The change in temperatures inside the borehole is 0.4ºC between the two measurements after 72 h with 82 W/m heat injection rate. If the result of a MIR TRT measurement is related to the used heat injection rates it is preferable to use lower rates first and then increase. In this way the affect of earlier IRPs are minimized.

Figures 4a and b shows the evaluated result (k_{br}, R_b) plotted against mean fluid temperature of the circulating fluid. The effect of a higher temperature for one measurement when comparing the result for one heat injection rate is seen in the bedrock thermal resistance values for the F-borehole. More heat has been injected into the borehole before F2:91 than before F1:91, this result in a mean fluid temperature of 31.2 instead of 28.7ºC. The higher achieved temperature results in a larger value for the bedrock thermal conductivity. The same may be seen for the 132 W/m heat injection rate. For the S-borehole, temperature dependence may be seen for the borehole thermal resistance where a higher temperature results in a lower R_b-value. Observe that even though S2:75 first have experienced a 21 W/m IRP the temperature in the borehole is still lower (20.6ºC) than the temperature achieved for S1:75 (22.6ºC). This explains why S2:75 receive a higher R_b-value than S1:75.

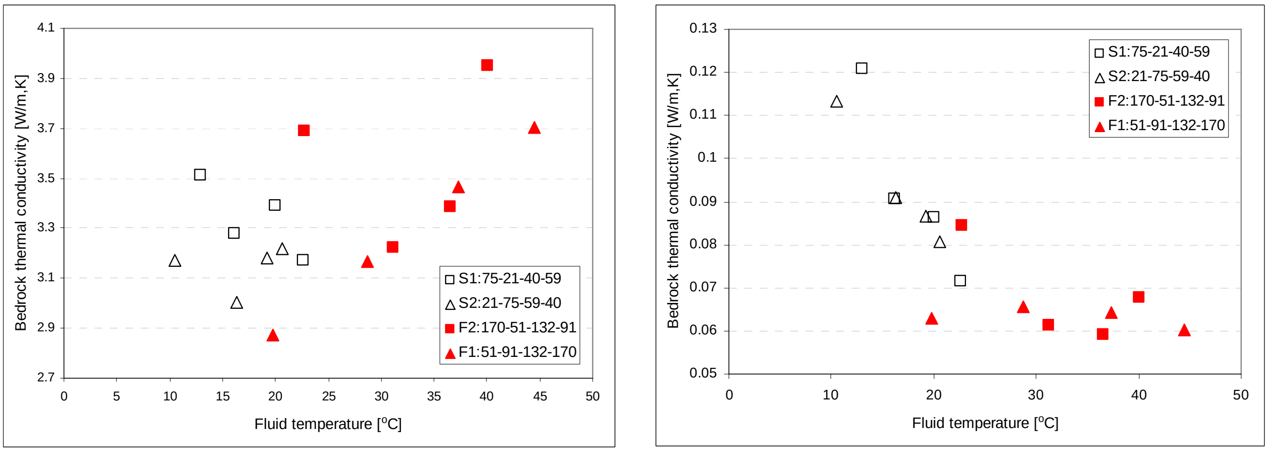

Figure 4a. Bedrock thermal resistance versus mean fluid temperature. *b. Borehole thermal resistance versus mean fluid temperature.*

5. CONCLUSION

Convective heat flow in the groundwater affects the heat transport for a borehole heat exchanger. The BHE will experience different heat transfer situations depending on the density differences in the water. An increase in injection rate increases the convective heat flow. For a borehole situated in solid bedrock, the convective flow will only influence the heat transfer inside the borehole. A higher heat injection rate decreases the achieved borehole thermal resistance.

For a borehole located in fractured bedrock with fractures connecting to the borehole, the convective heat flow is spread out in the fractures. This increases the heat transfer in the borehole water and decreases the borehole thermal resistance even more than for a borehole situated in solid bedrock. The effective bedrock thermal conductivity is also affected of the convective heat flow when fractures connect to a borehole. An increase in effective bedrock thermal conductivity is seen when the heat injection rate is increased.

Multi-injection rate thermal response test (MIR TRT) is a test method to detect thermally induced convective heat transfer. The test is performed using several injection rate periods (IRP) with each having different heat injection rate. The test is then evaluated with one set of heat transfer parameters (k_{br}, R_b) for every IRP. The test method was shown to be useful in detecting convective heat flow influences and determine the change for different heat injection rates.

MIR TRT measurements are preferably performed with increasing heat injection rate for increasing IRP. This is for minimize the effect of achieving a higher water temperature due to the beforehand injected heat. Another way is to relate the evaluated heat transfer parameters to the mean fluid temperature.

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REFERENCES

Austin, W. A. (1998). Development of an in-situ system for measuring ground thermal properties. Master's thesis. Oklahoma State University, USA.

Chiasson, A., Rees, S.J. & Spitler, J.D. (2000). A preliminary assessment of the effects of ground-water flow on closed-loop ground-source heat pump systems. ASHRAE Transactions, 106(1):380-393.

Claesson, J. & Hellström, G. (2000). Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers. Terrastock, 8th Int conf on thermal energy storage, 28 aug-1 sept., Stuttgart, Germany, pp. 195-200.

Gehlin S. (2002). Thermal response test – method development and evaluation. Doctoral Thesis 2002:39. Luleå University of Technology, Sweden

Gehlin, S.E.A. & Hellström, G. (2003). Influence on thermal response test by groundwater flow in vertical fracture in hard rock. Renewable Energy 28, pp. 2221-2238.

Gehlin, S.E.A., Hellström, G. & Nordell, B. (2003). The influence of the thermosiphon effect on thermal response test. Renewable energy 28, pp. 2239-2254.

Gustafsson, A.-M. & Gehlin, S. (2006) Thermal response test – power injection dependence. Ecostock 2006, 10th int. conf. on thermal energy storage, The Richard Stockton college of New Jersey, USA.

Gustafsson, A.-M. & Gehlin, S. (2008) Influence of Natural Convection in Water-Filled Boreholes for GCHP, ASHRAE Transactions, vol. 114, pt. 1, New York, pp. 416-423.

Kjellson, E. & Hellström, G. (1997). Laboratory study of the heat transfer in a water-filled borehole with a single U-pipe. Megastock '97, 7th International Conference on Thermal Energy Storage, Sapporo , Japan , June 1997.

Kjellson, E. & Hellström, G. (1999). Laboratory study of the heat transfer in a water-filled borehole with a c-pipe. Preliminary report. Lund University, Lund, Sweden.

Sanner, B., Reuss, M., Mands, E. & Müller, J. (2000). Thermal Response Test - experiences in Germany. Proceedings of Terrastock 2000, Vol 1, Stuttgart, Aug 28-Sept 1, pp 177-182.

Spitler, J.D., Yavuzturk, C. & Rees S.J. (2000). In situ measurement of ground thermal properties. Proceedings of Terrastock 2000, Vol 1, Stuttgart, Aug 28-Sept 1, pp 165-170.

Witte, H.J.L. (2001). Geothermal response test with heat extraction and heat injection: Examples of application in research and design of geothermal ground heat exchangers. Workshop: Geothermische response tests, EPFL, 25-26 oct, Lausanne.

Witte, H.J.L., van Gelder G.J. & Spitler J.D. (2002) In situ measurement of ground thermal conductivity: the dutch perspective. ASHRAE Transaction, Vol 108, No 1.

Witte, H.J.L. & van Gelder, A.J. (2006). Geothermal response test using controlled multi-power level heating and cooling pulses (MPL-HCP): quantifying ground water effects on heat transport around a borehole heat exchanger. Ecostock 2006, 10th int. conf. on thermal energy storage, The Richard Stockton college of New Jersey, USA.