IMPROVEMENTS OF THERMAL RESPONSE TESTS FOR GEOTHERMAL HEAT PUMPS

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Abstract: At present, the ground thermal conductivity at borehole heat exchanger (BHE) array locations is usually derived from thermal response test (TRT) data. Thermal response tests record the temperature variation at the outlet of a BHE due to fluid circulation. The fluid outlet temperature is directly related to the rock thermal conductivity around the well. The TRT method only provides the average value of thermal conductivity over the entire length of the borehole. If environmental and experimental conditions satisfy the usual experimental standards, a TRT can predict effective ground thermal conductivity within an error of approximately ±10%. However, the line source approach (on which the analysis of the TRT experiment is based) is restricted to ideal conditions such as homogeneous ground temperature and homogeneous rock thermal properties. GEOWATT developed a new TRT concept in order to overcome many of the TRT constraints and to improve the accuracy of the results. The new concept is based on temperature measurement over the entire length of the BHE using NIMO-T, a wireless temperature probe, which was developed at GEOWATT. The temperature data is evaluated by numerical simulation, using a detailed finite element mesh, which maps the BHE and ground geometry as detailed as possible. This concept allows to calculate the vertical variation of ground thermal properties and groundwater flow and thus provides a better estimate of BHE power.

Key Words: ***geothermal energy, thermal response test, ground thermal conductivity***

1 INTRODUCTION

The thermal power of a borehole heat exchanger (BHE) depends mainly on thermal conductivity λ. It is a common practice to perform thermal response tests (TRT) prior to installing large BHE systems in order to calculate the effective thermal conductivity at the geothermal site (van Gelder, 2001). In most instances, a TRT experiment records increase of the outlet temperature of a duplex BHE due to constant heating of the BHE fluid (Gehlin and Spitler, 2002). The temporal increase of the outlet fluid temperature is directly related to the rock thermal conductivity around the well. The temperature time series is usually analyzed using the line source theory. The analysis is straightforward, but involves many assumptions. As a result, only an integral value of the ground thermal conductivity over the entire length of the BHE can be achieved.

In order to gain additional information about the vertical variation of ground thermal conductivity, the new eTRT-method requires temperature measurements over the entire length of the BHE. For this purpose, the small and wireless borehole probe NIMO-T is used. This probe (235 mm long, 23 mm dia, 99.8 g) sinks through its own weight to the bottom of the BHE U-tube and records pressure (=depth) and temperature at pre-selected time intervals during descent. Further details like construction, calibration, field deployment, and data evalution are given in Rohner et al. (2005).

The temperature in the BHE is measured (1) before the response test and (2) after approximately one and/or two more days, when the temperature field in the ground recovers and approaches to its undisturbed state. The temporal behavior of the three temperature-depth-profiles (temperature-logs, t-logs) reproduces the vertical variation of the ground thermal conductivity in the vicinity of the BHE.

The eTRT is interpreted quantitatively by numerical simulation using a highly resolved FE mesh. The model reproduces the BHE tubes, the BHE fluid, the backfilling material, and the surrounding ground with sufficient accuracy. The thermal properties of the ground may vary with depth.

The temporal cycle of the response test is simulated. The numerical simulated temperature in the BHE tubes are compared to the measured t-logs. The ground thermal properties are changed gradually, until a satisfying correlation between measurement and simulation is reached.

In this paper, we first study the capabilities of the new concept by means of generic data. Subsequent to this general analysis, we present some real eTRT-measurements and evaluations.

2 GENERIC TEST

2.1 Generic reference model

Recently, progress has been made analyzing TRT more precisely by means of numerical simulations, based on the finite-element code FRACTure (Kohl and Hopkirk, 1995, Signorelli, 2005). In principle, numerical simulation can overcome all restrictions of the line source approach (e.g. sensor noise, variation of surface temperature and BHE fluid circulation rate, …).

In order to test the potentials and limits of the new concept, we create generic TRT data set using the Finite Element code FRACTure. Figure 1 shows the FE mesh of the BHE tubes and in the vicinity of the borehole. The mesh represents the BHE tubes accurately. The BHE (double U type BHE) has a total length of 100 m. The four BHE tubes have an inner radius of 1.57 cm, the borehole radius is 7.4 cm. Table 1 summarizes the different material properties of the BHE.

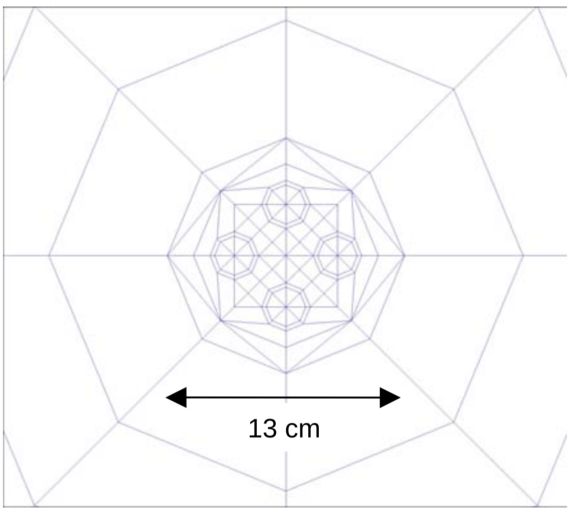

Figure 1: FE mesh in the vicinity of the BHE.

Corresponding to the new concept and in contrast to common TRT analysis, the duration of fluid circulation in this numerical experiment is set to 48 hours only. Fluid temperature is monitored in one of the upward tubes at depth intervals of 10 m before and after fluid circulation. Subsequently, temperature is extracted from the model 24 h and 48 h after circulation was stopped and recovery of the BHE temperature occurred. This numerical experiment is performed using a ground model with four layers with different ground thermal properties (Table 2). This model represents a “real” test site, the temperature data calculated with this model is called reference model.

Table 1: BHE material properties

Material	Thermal conductivity [W/m/K]	Heat capacity [MJ/m³/K]
BHE tubes	0.4	2.0
Backfilling	2.0	2.0
BHE fluid	0.6	2.0

Table 2: Thermal rock properties of the reference model.

Material	Thermal conductivity [W/m/K]	Heat capacity [MJ/m³/K]
0 m – 25 m	1.5	2.2
25 m – 50 m	2.0	2.2
50 m – 75 m	3.5	2.2
75 m – 100 m	2.0	2.2
100 m – 125 m	2.5	2.2
125 m – 1000 m	3.0	2.2

The result of the numerical TRT simulation is shown in Figure 2. The red symbols indicate the undisturbed ground temperature in the borehole. The increase of thermal conductivity at 50 m depth results in a decrease of the temperature gradient. After 48 hours of heat injection and circulation the temperatures are generally high, the temperature gradient is very low and almost constant over the entire length of the BHE. The blue lines map the heat recovery of the ground one and two days after the circulation was stopped. The conductivity contrast becomes visible again. The temperature recovery phase demonstrates the main advance of the new concept. During recovery, the different rock thermal properties become significantly evident and distinguishable in the temperature signal.

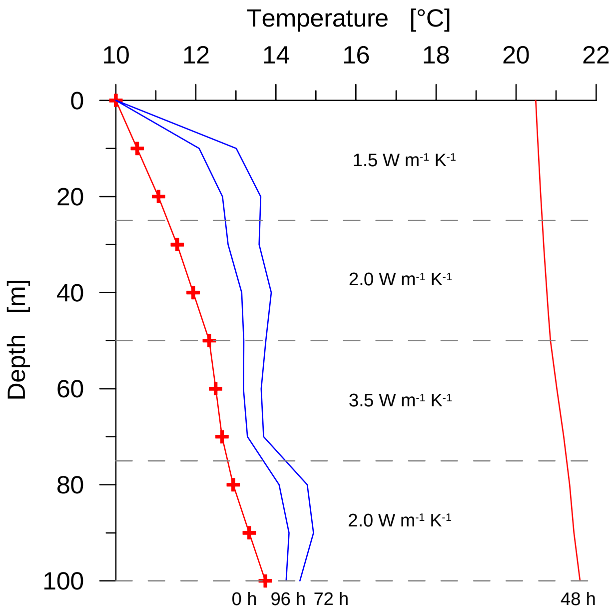

Figure 2: Temperature in the BHE tube during TRT experiment (red crosses: initial temperature profile; red line: temperature at end of injection period; blue lines: temperature while heat recovery)

2.2 Monte Carlo Simulation

The rock thermal properties of the reference model can be evaluated using Monte Carlo (MC) simulation. Therefore, a great number of models with different ground thermal properties are simulated using the reference model boundary conditions and load time functions.

Ground thermal properties of the MC-models are varied statistically. The temperature curves of each model are compared to the reference model. A Gaussian temperature noise signal with a standard deviation of ±0.1°C is added to all temperature data. The four temperature logs consist of 10 temperature measurements each, which yields a total temperature residual of 0.4 K^2. The Monte Carlo-model, which fits best to the reference data, should have at least this threshold residual of 0.4 K^2.

In order to limit the total CPU time, only 2000 Monte Carlo simulations were performed. The temperature residuals with respect to the reference data are calculated for each MC-model. The model with the smallest residual is assumed to be the model, which maps best the original ground thermal properties. The temperature data of the best-fit model is shown in Figure 3. This model has a total residual of 0.98 K2, which is clearly above the noise level of 0.4 K^2. The thermal conductivities of this model are summarized in Table 3.

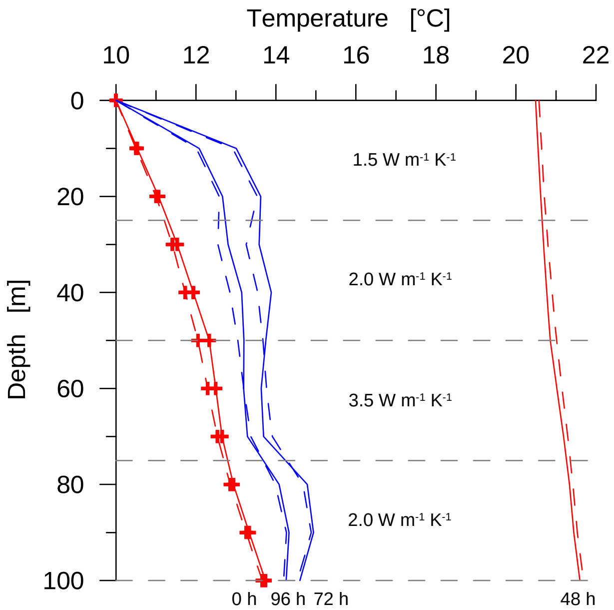

Figure 3: Comparison between reference model (solid lines) and best fit Monte Carlo simulation (dashed lines).

The results demonstrate that the Monte-Carlo technique is suitable to find the original ground thermal properties of the reference model. The only significant difference is visible in the second layer between 25 and 50 m depth, which is also visible in the temperature data in Figure 3. A better fit can be obtained by increasing the total number of Monte Carlo simulations. Here, 2000 simulations correspond to $2000^{1/4} \approx 7$ independent thermal conductivity values for each layer. If the thermal conductivity is assumed to vary between 1 and 4 W/m/K, this yields an average resolution of 0.4 W/m/K for each layer. The resolution can be improved if the total range of probable thermal conductivity values can be constricted by laboratory measurements.

A better resolution can also be achieved by increasing the number of Monte Carlo simulations. As a result, the total simulation time will grow linearly with the number of simulation runs. Here, the simulation time already exceeds 5 days for 2000 simulations.

Table 3: Thermal conductivities of the reference model (λ_{Ref}) and the best fit Monte Carlo model (λ_{MC})

z [m[	λ_{Ref} [W m^{-1} K^{-1}]	λ_{MC} [W m^{-1} K^{-1}]
0 m – 25 m	1.5	1.64
25 m – 50 m	2.0	2.49
50 m – 75 m	3.5	3.28
75 m – 100 m	2.0	2.03

Although the Monte Carlo approach resolves the vertical variation of thermal conductivity reasonably, its routine use is impractical due to the required simulation time. Therefore a simpler, iterative approach has been followed.

3 eTRT EXAMPLE

Figure 4 shows the eTRT measuring device, which was developed by Geowatt AG in 2007. The device is compactly built (0.83 x 0.64 x 0.61 m, 63 kg) and can be transported easily. The data acquisition proceeds automatically; data readout is established via Internet. In this chapter, we demonstrate the eTRT-method by means of a test, which was performed in Zürich in October 2007. The test device was connected to a 220 m deep borehole heat exchanger, which was installed for test purposes.

Figure 4: Geowatt eTRT device. The power is continuously adjustable from 0 to 10 kW. Power and circulation can be regulated independently. The accuracy of electrical and hydraulic power measurement is 1% and 1.5%, respectively.

Table 4 shows the properties of the BHE and the parameters of the TRT. The test was operated for 92 h only, which is much shorter than the typical TRT runtime. Figure 5 shows the TRT power, average inlet/outlet-temperature and the circulation rate as function of time.

Table 4: eTRT parameter and thermal model properties

Model properties	Value
BHE depth	220 m
Average surface temperature	12.9 °C
Thermal conductivity of BHE fluid	0.51 W/m/K
Heat capacity of BHE fluid	4.05 MJ/m^3/K
Thermal conductivity backfilling	2.0 W/m/K
Heat capacity backfilling	2.5 MJ/m^3/K
Thermal conductivity BHE tubes	0.4 W/m/K
Heat capacity BHE tubes	2.0 MJ/m^3/K
TRT heating duration	91.6656 h
TRT recovery duration	69.8103 h
TRT power	4643.4 W
Temperature difference T_{out}-T_{in}	1.999 K

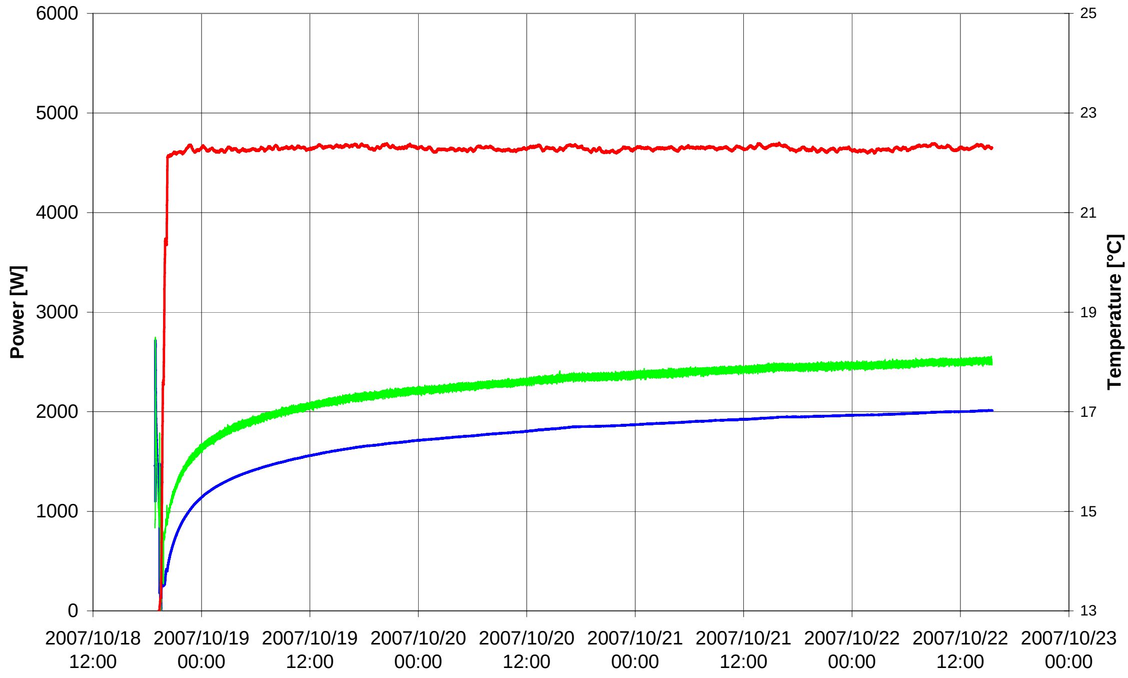

Figure 5: eTRT data (red line: TRT power; green line: average of BHE inlet and outlet temperature ; blue: BHE outlet temperature).

In addition to the general TRT scheme, the temperature within the BHE was measured with the wireless NIMO-T device, immediately before the test was started and two times after the circulation was stopped. The second temperature-log was measured one day after test-stop, the third log was recorded two days after test-stop. The three temperature logs are shown as solid lines in Figure 6a.

The TRT was simulated using the boundary conditions listed in Table 4 and the FE-mesh shown in Figure 1. After each simulation, the temperature-residuals (absolute difference between simulated and measured temperature in the BHE) were calculated as function of BHE length. If the residual at a designed depth exceeded a threshold value (e.g. 0.05 K), the thermal conductivity at this depth was changed systematically. This optimization was repeated until a good correlation between measurement and simulation was achieved.

The best-fit thermal conductivity-model is shown in Figure 5c. The residuals of this model with respect to the measured temperature-logs are shown in Figure 5b. The residuals vanish almost over the entire length of the BHE other than the uppermost layer between the surface and the second model layer at 22 m depth. These residuals (>0.3K) are due to the coarse vertical resolution of the FE mesh. The FE mesh is not able to reproduce the seasonal temperature effects in shallow depths with sufficient accuracy.

The thermal conductivity model shows a remarkable high value of approx. 5.5 W/m/K between 88 m and 110 m. This value is most probably caused by horizontal ground water flow. In the presence of groundwater flow, the heat transfer from the BHE to the ground is enhanced. Thus, the high thermal conductivity does not represent the true rock thermal conductivity but mirrors the heat advection in this layer between 88 m and 110 m.

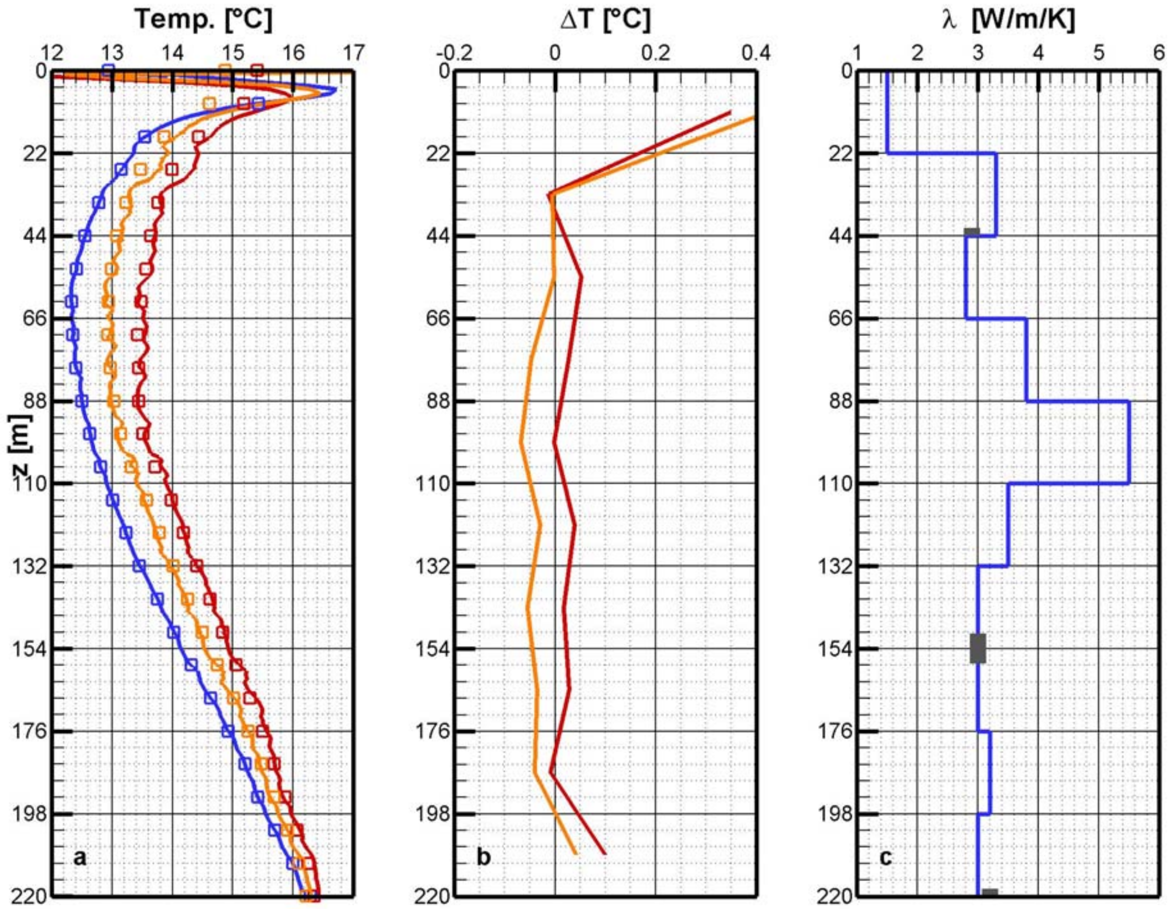

Figure 5: a) Comparison of measured (solid lines) and simulated (symbols) temperatures in the BHE. The blue line denotes the undisturbed ground temperature, the red line denotes the temperature one day and the orange line the temperature two days after TRT stop. b): Temperature difference between measured and simulated temperatures; c) Thermal conductivity of the definitive model which fits best the measured temperatures. The dark symbols represent measurements on rock samples.

4 CONCLUSION

The new eTRT method provides improvements in the determination of ground thermal properties. In contrast to common methods, where only the inlet and outlet temperature of TRT are evaluated and the result yields a uniform thermal profile, the new method provides information about the vertical variation of ground thermal properties and thus better estimate of BHE power.

A Monte Carlo test based on generic data, which was presented in Chapter 2, showed that the method resolves at least four equally spaced layers. In practice, the Monte Carlo method is not suited due to available computer time. In practice, trial and error, that means variation of ground thermal properties systematically by manual mode, provides sufficient accuracy.

The new method is also suitable to detect influence of ground water flow.

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