INNO-U-27

Thermal Response Test: Practical experience and extended range of application

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1. Introduction

The Thermal Response Test (TRT) is a tool to investigate ground thermal parameters required for design of borehole heat exchangers (BHE), as used in Borehole Thermal Energy Storage (BTES). While the theory and the use of the basic principles date back to the 1970s, the first mobile application of TRT is reported in Eklöf & Gehlin (1996), and the first TRT in Germany was done in 1999 (Sanner et al., 1999). Since then, a wealth of practical experience could be sampled both in the practical setup of the test (accuracy, reliability, site accessibility, insulation, etc.) as in the understanding of the different evaluation methods.

The paper shares some practical experiences on test operation gained during more than a dozen years of TRT tests throughout many European countries. Experience has also clearly shown that it is crucial to have a verification of the final results by using methods of sequential (step-wise) evaluation. Through this method a sufficient length of test time and the prevalence of conductive heat transport can be checked. Beside this verification, an awareness of the overall accuracy of the results as depending on accuracy of data collection is required. For the validity of temperature logs, the bottom heat dissipation can be used as an indicator.

A lot of additional information can be obtained from the test data, in particular if a temperature log inside the borehole is combined with the test. Examples of such information comprise layers with groundwater flow, distinction of layers of different thermal conductivity, quality of grouting, geothermal gradient, etc. It is also possible to use the TRT for investigating the actual depth of the borehole heat exchanger by use of the Thermo-Impulse Method (Sauer et al., 2010)

2. Measurement principle: heat injection versus heat extraction

The measurement signal of a TRT is a temperature change due to heat injection or extraction. Concerning the basic physics, it does not matter if heat is injected (temperature increase, solid line in fig. 1) or extracted (temperature decrease, dotted line in fig. 1). The parameter to be determined, thermal conductivity is not dependent from the direction of heat flow. There might be some anisotropy in thermal conductivity in sediments; however, a 180° change of direction of heat flow will have no influence, the maximum anisotropic effect would be found at 90°. Reversing heat injection to heat extraction could only result in such 180° change (any other degree of change would require inclining of the BHE, which is clearly impossible after installation).

The most important impact is given by the uniformity of the thermal load. This must be as constant as possible, in order to achieve an undisturbed signal. An evaluation of the possible sources for the thermal load shows the following results:

- any heating from combustion is dependant upon many factors like fuel supply, fuel quality, air supply, etc. and thus not sufficiently uniform, and it also cannot be controlled quickly and easily.
- heating/cooling using electricity relies on a steady electric power supply, be it from the grid or from a generator. This is much easier to achieve than steady combustion.
- for electric heating/cooling, the two alternatives available are resistive heating and heating/cooling using a heat pump.

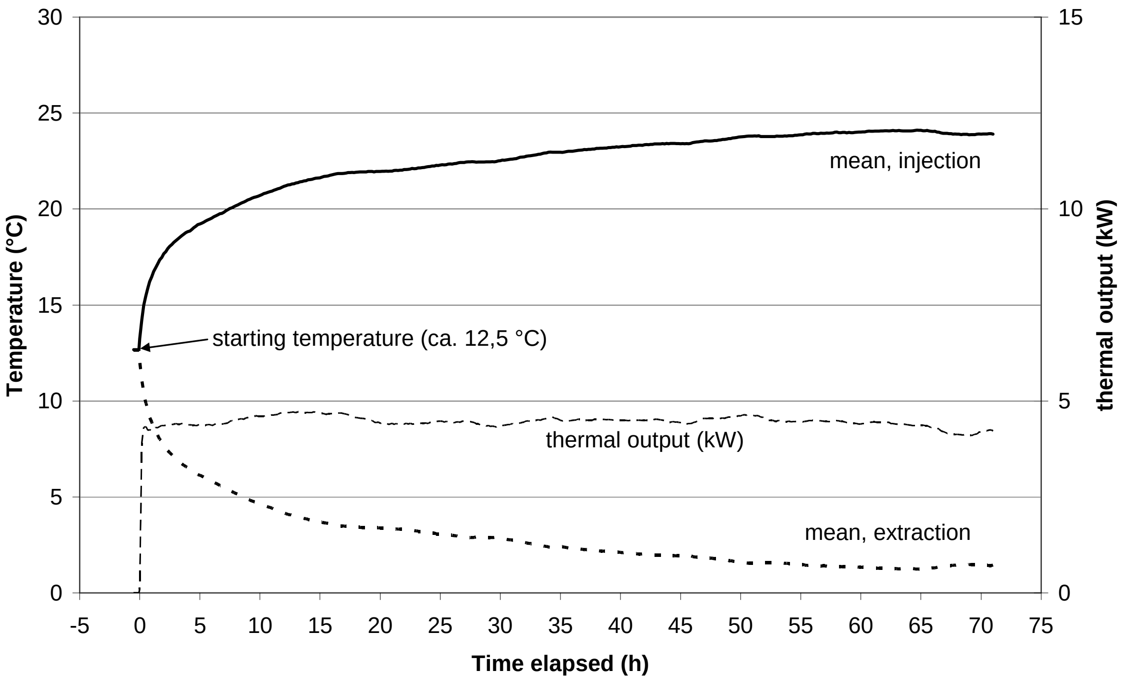

Fig. 1: Measurement principle of TRT (injection example from real field data UBeG); ideal cooling curve (dotted line) would look exactly reciprocal to the heating curve (solid line)

The **electric resistive heating** is rather simple in control. It is based on Joule's first law, which states that the heat produced is proportional to the square of the current multiplied by the resistance of the heater: $Q \propto I^2 \cdot R$. As the current is determined by voltage and resistance, an electric resistive heater can easily be controlled through control of the voltage. Within the temperature changes occurring during a TRT (10-20 K), the dependence of electric resistance from temperature of the heater can be neglected completely.

The electric power sent to the heater is always transformed fully into heat (1 KW_{el} = 1 KW_{th}), independent of the temperature of the water in the BHE circuit or the ambient air. Changes in thermal output as visible in fig. 1 can have two reasons:

- voltage variations in the grid
- thermal influence from outside (ambient temperature, solar irradiation, rain, etc.)

Thermal influence from outside will be the same for TRT units with electric heater as with heat pump; the only way to cope with it is thorough insulation of the test rig and pipes on the surface (cf. chapter 3). Voltage fluctuations should be as low as possible; typically they cancel themselves out statistically over time (white noise).

Providing the thermal load for a TRT by a **heat pump**, be it for heat injection or for heat extraction, creates major challenges and obstacles. A heat pump uses a thermodynamic process that is determined by several input characteristics. They comprise mainly:

- temperature level and temperature development at evaporator and condenser

- compressor efficiency (dependent upon pressure, speed/rpm, refrigerant, etc.)
- compressor motor power (e.g. with voltage variations in the grid)

Figure 2 elucidates the temperature dependence of heat pump output both at evaporator and condenser side. The basic curves are taken from publications of a recognized German heat pump manufacturer. The left graph shows how the heating output (condenser output) of a heat pump at constant condenser temperature drops with decreasing evaporator temperature, and the right graph shows the variations of cooling output (evaporator output) with increasing condenser temperature for two different values of constant evaporator temperature (18 °C and 7 °C).

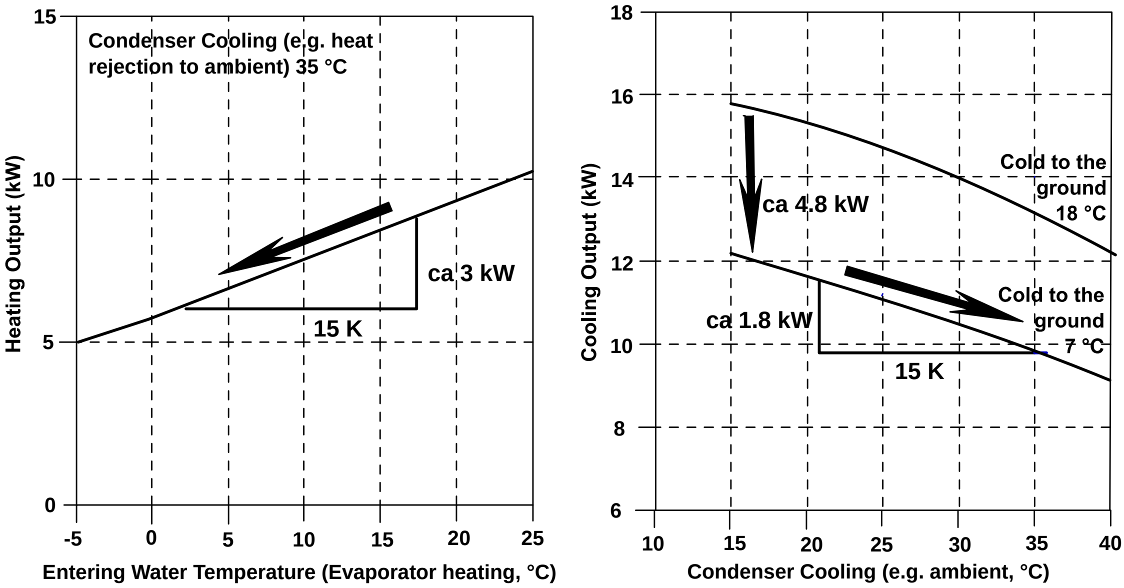

Fig. 2: Substantial drop in heat output with decreasing entering water temperature (left) and drop in cooling output with increasing ambient temperature and decreasing cooling temperature (right); example using heat pump performance data by Alpha-Innotec

In practical application for a TRT with heat extraction, the following fluctuations will result:

- decrease of evaporator temperature (this cannot be avoided, as it actually is the result of the measurement signal)
- variations in the condenser temperature due to the climatic impact on the re-cooling (ambient air)
- in consequence, a highly volatile and uncontrollable cooling output

A direct coupling of the heat pump to the BHE for a TRT thus is not feasible, as the fluctuating cooling output directly would be the heat extraction load. Hence an external control system must be put in between. To cope with the fluctuating cooling load, a large buffer storage (water tank) need to be installed and be kept always somewhat colder than the required input temperature to the BHE for heat extraction. This temperature need to be decreased over the course of the TRT. From the buffer storage, a certain amount of cold water needs to be added to the fluid circulating in the BHE circuit. This amount has to be controlled as to achieve a steady heat extraction rate.

A main problem is that a fast-reacting control is almost impossible here. The signal for controlling the extraction load would be given by the temperature difference between the fluid injected into the BHE and returning from the BHE. Alas, the travel time through a BHE always is several minutes (chapter 5). The signal from the return line thus will be much delayed compared to the actuation of load increase or decrease. This kind of delayed-signal control circuits tend to overcompensate and will result in a wave-form thermal output curve, and in the worst case may escalate completely out of control. The sensitivity of the weak signal in a system with relatively small temperature differences (3-4 K between inflow and return) will aggravate this behaviour.

As a result, a TRT with thermal load provided by the heat pump can never achieve a sufficiently constant heat load, not by control of the heat pump nor by using buffer storage and controlling the heat extraction at the BHE. Contrary to grid voltage variations, which typically cancel out over time (and affect both electric resistive heaters and heat pumps), the thermodynamics of the heat pump are on an increasing or decreasing path and thus will jeopardize a reliable test evaluation many times more. Of course it is possible to evaluate a TRT with fluctuating thermal load. In this case a parameter estimation method (analytical or numerical) has to be applied instead of the line-source approximation, and the load curve has to be measured accurately. However, as in this case a quasi-intransient state of heat transport will not be achieved, the general significance of the results is poorer as with almost constant thermal load.

It should also be mentioned that in a TRT with heat extraction, the signal strength is limited. While heating up can be done to temperatures of 30-40 °C (or even higher in tests for thermal storage), cooling down cannot be done lower than about 2-3 °C in BHE filled with water (as is the case in almost all BHE destined for a TRT) and about -5 °C in a BHE with water/antifreeze. As figure 1 shows, a TRT with signal strength of about 15 K and starting temperature of ca 12.5 °C will result in end temperatures of 26 °C (mean of inflow/return) in heat injection mode and -1.0 °C in heat extraction mode. The signal strength for a TRT in heat extraction thus would need to be reduced, decreasing overall accuracy of the results.

From the facts explained above, we deduct the following recommendations:

- from the physical background, there is no difference in heat transport and test results for both methods, heat injection and heat extraction; therefore a real need to use a heat pump for heat extraction is not given.
- the test rig for heat extraction with heat pumps will be much more complicated than for heat injection with electric resistive heater, increasing cost, size, weight and operational risk – the smaller, simpler and more reliable device is preferable.
- keeping the thermal load constant with the heat pump is almost impossible; heat pump control can be sufficiently accurate for heating and cooling a building, but not for providing a quasi-constant heat extraction from a test BHE. A heat pump thus should be avoided as thermal load for a TRT rig.

Experiences with several hundred TRT done by UBeG alone, and many others in the international geothermal community, have proven the reliability and accuracy of the heat-injection concept. Individual attempts to try heat extraction have been done with high expense (mainly for R&D-reasons), but heat extraction has been abandoned for commercial application almost everywhere.

3. Practical experience

Based upon our experience, we have developed some mandatory routine procedures to be performed before the start of the response test. In order to help others in avoiding unpleasant incidents, the main items are reported here:

- Power supply check. The test can of course not be performed without electric power, be it from the grid or from a generator. Considering the required power levels, typically 3-phase AC is the source. Wrong phasing of this power supply can result in shunt fault, controller failure, overheating of the device and even smouldering of the test rig. Power breakdown or instable power supply may lead to inconsistent development of the temperatures, and thus makes it difficult or impossible to evaluate the test.
- Sufficient de-aeration. Without proper de-aeration, the flow inside the borehole can collapse after an unknown amount of time, and the test will come to an unexpected early end.

- Insulation of the test rig and connections. The ambient influence (heat or cold) should be kept as low as possible, as it cannot be controlled and heavily affects the test in a similar way as fluctuating power supply.

The so-called “Stepwise Evaluation” (sequential data analysis) allows for cross-checking if any of the effects mentioned above have had an influence on the test operation. An evaluation of the recorded data is performed here with a fixed start time and increasing length of the data set, until the full duration to the end time. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a perfect test (figure 3, top). This procedure is a useful tool to check the quality of the data collected and the validity of the results.

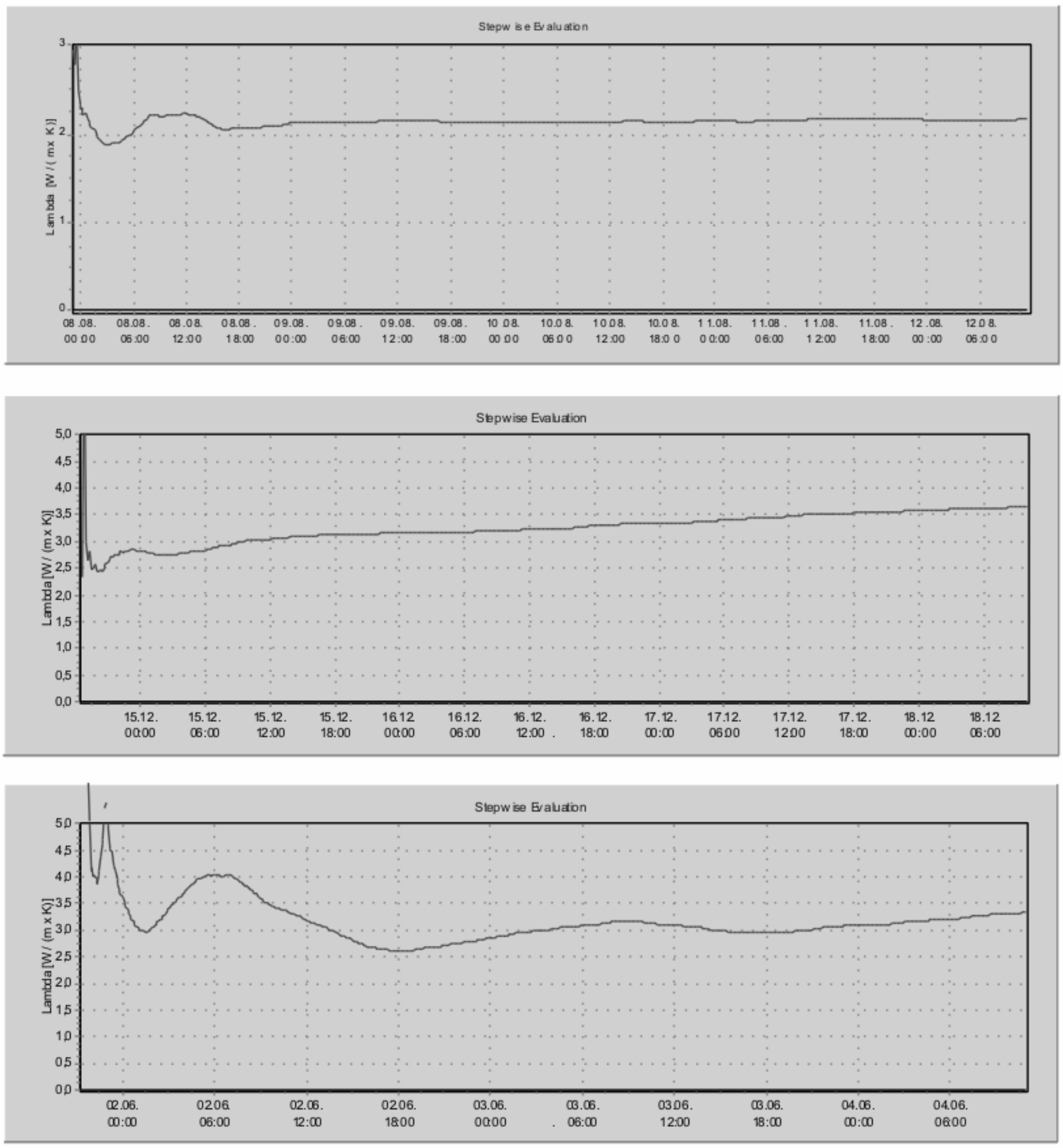

Fig. 3: Examples of stepwise evaluation of TRT: Dominated by conductivity, good reliability (top), dominated by advection and not usable (middle), and high fluctuations and low reliability (bottom)

With substantial influence of flowing groundwater, the curve rises upwards steadily after some time (figure 3, middle). Thus the test result value (λ) is determined by the duration of the test, and the longer the testing time is, the higher the λ will be. There is no reliable result for such a test. In case of influence of fluctuating power supply or environmental influences (e.g. solar radiation), the test result is not stable, and testing time must be extended (figure 3, bottom).

4. Extended range of applications

Beside the thermal conductivity of the underground, the undisturbed ground temperature (as average over the BHE length) is of crucial importance when calculating a BHE-field design. This parameter can be drawn from the temperatures recorded with the TRT device before the heating phase started with just the circulation pump running (fig .4). However, due to the (very small) heat input from the circulation pump, a small increase of the value might occur over time. An observation of temperature development without heating over some hours (as in fig. 4) also can help in detecting any residual heat from drilling or solidifying of the grout, given away by a temperature decreasing over time

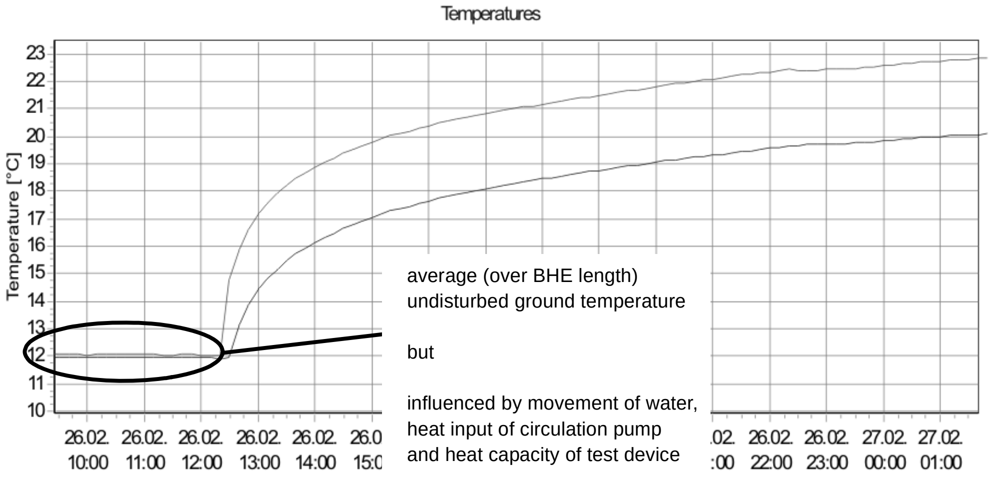

Fig. 4: undisturbed ground temperature from TRT

Another method, which in addition allows for exclusion of the zone of annual variation (cf. figure 5) and which gives much more details that could be used for further information, is the temperature log. There are several tools available for taking a log, even inside a 32-mm-pipe as used for most BHE. Logging requires some patience to allow for full thermal equilibrium at each depth level to be measured, and some handling skills not to get a tool stuck in a well or pipe.

The temperature log before the test as shown in fig. 5 should be complemented with temperature logs after the end of the TRT (a recommendation could be a log directly after, one about 1 hour later, and another one 2-3 hours after the end of the test). These logs will show the gradual cooling of the fluid inside the pipes and allows for various conclusions as shown in figures 6 and 7. It should be taken into account that the exact time of the tem-

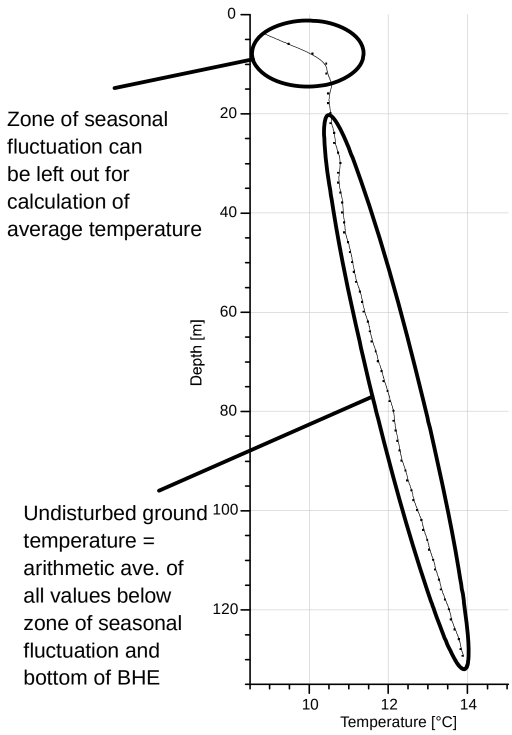

Fig. 5: Temperature profile before performing TRT

perature measurement is not the same over the depth of the BHE, as the logging takes some time (up to 30 minutes for 100 m). So the signals might by slightly different with depth.

Among the features visible (figures 6 and 7) are groundwater flow, missing grout (to cool down so quickly as in figure 6, the BHE must have a direct contact to flowing groundwater, i.e. not being encased by the grouting), or layers with different conductivity. Sometimes it is not clear if the temperature sensor went all the way to the bottom of the BHE, or if the BHE is just blocked (e.g. by a pinch). The "Bottom Heat Dissipation" (figure 7) gives a confirmation for having reached the bottom, as at this point the heat is also transported in vertical direction downwards, and a faster cooling can be seen.

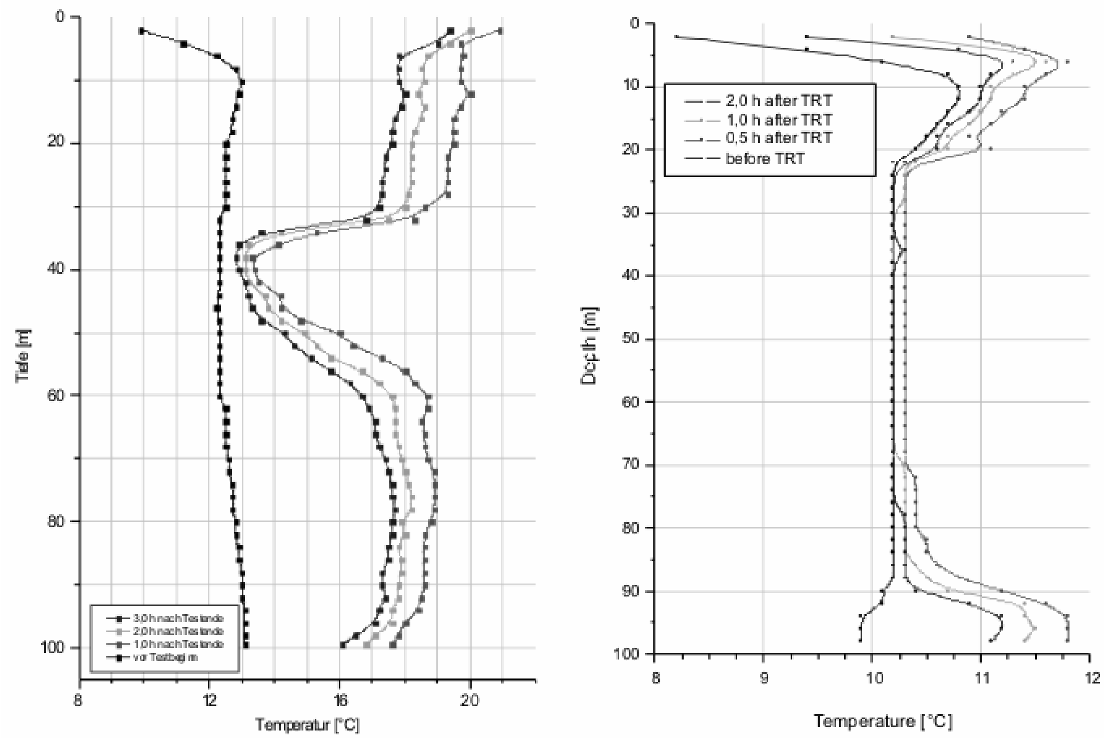

Fig. 6: Features as elucidated by temperature log before and after TRT: Influence of groundwater-flow (left), poor or non-existent grouting (right)

5. Thermo-Impulse Method

Using the Thermo-Impulse Method, a practical issue can be solved in shallow geothermal installations. Sometimes disputes arise on the question if the BHE actually has the full length as contracted. The TRT rig can offer a convenient method of determining the actual BHE-depth within a narrow margin of error. The method was first published in Sauer et al. (2010). It comprises the following steps (fig. 8):

- A strong thermal signal (impulse) is injected into the BHE circuit
- The time the impulse needs to return is measured.
- With the (measured) flow rate and pulse-time-delay the volume of the BHE can be calculated.
- With the known diameter of the BHE tube and the volume the length can be calculated.

Tests with recurring Thermo-Impulse measurement at the same borehole heat exchanger confirmed the reproducibility of the depth measurement (table 1).

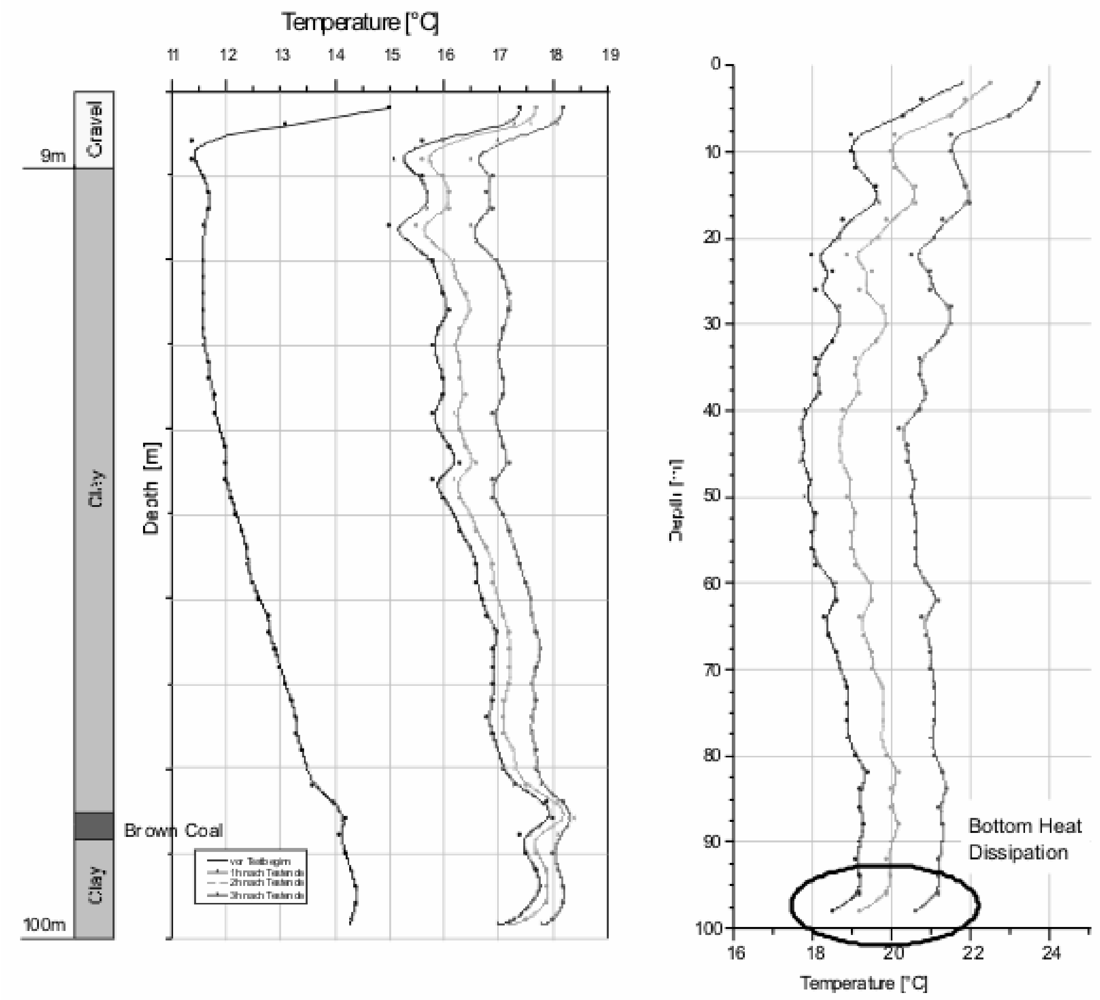

Fig. 7: Features as elucidated by temperature log before and after TRT: presence of a low-conductivity layer (left), prove of final depth (right)

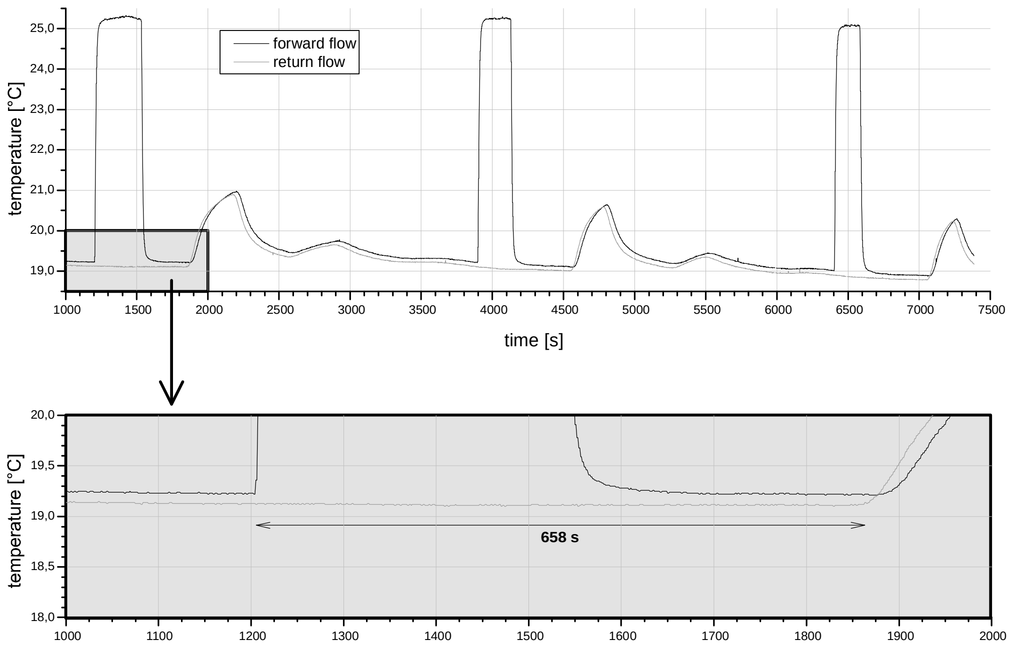

Fig. 8: Principle of Thermo-Impulse method (recurrence of impulse)

Table 1: Reproducibility of Thermo-Impulse measurement

Measurement	Time delay to recurrence	Depth (m)
1st:	658 s	129.0
2nd:	662 s	130.2
3rd:	659 s	129.7
Average		129.6
Maximum deviation		±0.6 m (±0.5 %)

6. Possible use of TRT for investigation of deep geothermal potential

As a side note, some thought are presented here on measurements in TRT that could be of interest for deep geothermal projects. From temperature logs before TRT, the geothermal gradient (temperature increase with depth) and, with knowledge of the thermal conductivity as a result of the TRT, the geothermal heat flux can be determined as:

$$Q_g = k_g * \lambda$$

with: Q_g = Geothermal heat flux (W/m^2)
k_g = geothermal gradient, in K/m
λ = thermal conductivity (W/m/K)

Estimates on the expected lithology under the site allow for extrapolation of these values down to the depth required for geothermal power (cf. project Geoelec at http://www.geoelec.eu/). Naturally, such extrapolation will not sufficiently reflect deep groundwater movements and other factors contributing to geothermal anomalies, but it can be a first hint to the geothermal character of an area where no deep boreholes yet exist.

7. References

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