ZURICH, SWITZERLAND
6 – 10 OCTOBER 2025

EUROPEAN
GEOTHERMAL
CONGRESS
2025

Thermal response testing in deeper geothermal wells – is it better to inject or extract heat?

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ABSTRACT

Thermal Response Tests (TRT) conducted in medium-deep Borehole Heat Exchangers (BHEs), typically ranging from 500 to 1,000 meters in length, require more critical evaluation compared to those performed in shallow BHEs. The accuracy of the analytical interpretation depends on the applied heating power, the duration of the test, and the length of the BHE. In this paper, we investigate the suitability of the TRT in groundwater-filled geothermal wells with lengths ranging from 100 metres to one kilometre, as these are relevant to deeper U-pipe collector lengths.

Our investigation aims to increase the understanding of the careful planning of TRTs in deeper BHEs. The correct identification of the thermal resistance of deeper BHEs depend on whether the test is conducted by heating or cooling the bedrock.

1. INTRODUCTION

Replacing combustion-based energy with geothermal energy helps reduce emissions and dependence on fossil fuels. It supports a cleaner, more sustainable energy system for heating and cooling needs. Finland is experiencing a breakthrough in geothermal drilling, with efforts to reach deeper geothermal reservoirs. While 300-meter wells are drilled routinely, several projects have strived to exceed one-kilometre depths and more (Arola et al., 2024).

Thermal response testing is critical in designing and optimising borehole heat exchanger (BHE) systems (Gehlin, 2002). As drilling depths increase, questions have emerged regarding the validity of conventional thermal response tests for deeper geothermal wells. Due to the geothermal gradient, the temperature at the bottom of the borehole can be so high that fluid temperature may remain lower than the initial bedrock temperature during a conventional TRT. This results in difficulties in calculating a reliable value for the bedrock effective thermal conductivity and borehole properties, especially when considering medium-deep geothermal wells.

There is little information in the literature about TRTs conducted in medium-deep geothermal wells. In addition, TRTs involving heat extraction even from shallow boreholes have been performed relatively rarely. Our interest in applying cooling TRT arose after performing a conventional TRT via heating mode in a 600-meter-deep geothermal well drilled into crystalline bedrock in Pirkkala, Finland, and observing the challenges described above. The HDPE U-pipe in the borehole was equipped with fibre-optical cables, allowing continuous monitoring of the heat transfer fluid's temperature throughout the TRT. With a lower heating power of 8 kilowatts, the heat-carrying fluid temperature at the bottom of the borehole remained below the initial bedrock temperature. At a higher power of 15 kilowatts, it took 21 hours from the start of the test for the heat-carrying fluid temperature at the bottom section of the borehole to slightly exceed the initial bedrock temperature. Thus, based on our simulations, a TRT involving cooling, i.e., extracting heat from a BHE, appears to be a better option for the experimental determination of bedrock properties in medium-deep boreholes than a TRT involving heating, i.e. injecting heat into a BHE.

Observations made during the TRT conducted in Pirkkala prompted a more detailed investigation of the phenomenon through numerical modelling. In this paper, we want to highlight the suitability of TRT in groundwater-filled medium-deep geothermal wells and answer questions about whether it is better to inject or extract heat via TRT. Detailed *in situ*-measurements can significantly reduce the required drilling meters (Marcotte et al., 2008; Sass et al., 2016) and thus affect system costs.

2. MATERIALS AND METHODS

We used COMSOL Multiphysics® – a finite element solver – to simulate conventional TRTs in groundwater-filled BHEs expected to be embedded in crystalline bedrock. The lengths of the BHEs were varied from 100 meters to 1 kilometre at 100-meter

steps. The collector loop comprised a single U-tube of high-density polyethene (HDPE) pipe. The TRTs were simulated either by injecting or extracting heat from the bedrock. For the heating tests, heat was injected into the ground at either 8 or 15 kilowatts for 1,000 hours. Similarly, for the cooling tests, heat was extracted from the ground at either 8 or 20 kilowatts for the same duration. Each synthetic TRT was interpreted using the standard infinite line source model (ILS), as recommended by the IEA Annex 21.

The COMSOL model used to generate synthetic TRT data was a full 3-D model including domains to represent the bedrock, grouting, HDPE pipe and heat-carrying fluid. The material parameters were chosen to represent typical Finnish BHEs and geology. The thermal conductivity of bedrock was chosen to be 3.25 W/m·K. In the Finnish crystalline bedrock, grouting of boreholes is not used as there is no risk of collapse and the boreholes are naturally filled with groundwater. The groundwater filling will feature natural convection, which increases heat transfer in the BHE (e.g., Spitler et al., 2016; Johnsson and Adl-Zarrabi, 2019). This issue was considered in the numerical model as an elevated thermal conductivity value (or effective thermal conductivity), which was three times that of stagnant water, i.e., 1.8 W/m·K. This way, the heat transfer in the model could be assumed to occur solely by conduction.

The inlet temperature of the fluid for the 3-D model was calculated as

$$T_{inlet} = T_{outlet} + \frac{Q}{\rho_{fluid} c_{p,fluid} \dot{V}}, \qquad (1)$$

where T_{outlet} is the fluid temperature in the ascending pipe branch at ground level, Q is the heat rate (W) and $\dot{V}$ the volumetric flow rate (m³/s). The temperature at the bottom of the borehole was set to be the same in both pipe branches.

Synthetic TRTs from simulations with the numerical model were interpreted using the ILS method. Observed fluid temperature from the synthetic data T_{obs} was calculated as an average from the inlet and outlet temperatures, and ILS was used to calculate the average fluid temperature that is dependent on the bedrock effective thermal conductivity k_r (W/m·K) and borehole thermal resistance R_b (m·K/W) as

$$T_{calc}(t, k_r, R_b) = \frac{Q}{4\pi k_r L} E_1 \left(\frac{r_b^2}{4\alpha t} \right) + \frac{Q}{L} R_b + T_0, \qquad (2)$$

where T_0 is the initial temperature and α is the thermal diffusivity of bedrock. The ILS model shown in Eq. (2) was fitted to synthetic TRT data calculated using COMSOL by solving the minimization problem

$$\underset{k_r, R_b}{\operatorname{argmin}} \sum_i \left[T_{calc}(t_i, k_r, R_b) - T_{obs,i} \right]^2. \qquad (3)$$

Both k_r and R_b are influenced by the duration of the fitting interval. The temperature evolution was simulated for 1,000 hours using the numerical model.

If the ILS fitting is conducted over a brief initial period of the measurement, the reliability of the resulting data is more uncertain.

TRT performed in deeper boreholes may under- or over estimate both the bedrock effective thermal conductivity and borehole thermal resistance if the duration of the TRT is too short. The duration of TRT should be as long as possible, particularly in medium-deep boreholes, to allow heat transfer effects within the bedrock to develop fully and to be accurately reflected in the measurement results. If groundwater movement occurs within fracture zones in the bedrock, its effect on the measured TRT temperature becomes more pronounced over time, as convective heat transfer gradually develops (Simon et al., 2021).

3. RESULTS AND DISCUSSIONS

The result in Fig.1 demonstrates the applicability of the analytical ILS method for interpreting the thermal conductivity of the bedrock through BHEs at various lengths. The accuracy of the interpretation improves with the duration of the TRT. The ILS method is not nearly as suitable for determining the effective thermal conductivity of the bedrock in deeper BHEs as it is in shallow ones.

The light grey shaded area in Fig. 1 represents a 10 % confidence interval relative to the true thermal conductivity, 3.25 W/(m·K), set in the numerical model. When heating the bedrock with a power of 15 kilowatts, the analytical interpretation result starts to deviate significantly from the true value once the BHE depth exceeds 750 meters. At a lower heating power of 8 kilowatts, the 10 % error margin is exceeded when the BHE length is greater than 650 meters. The corresponding lengths for cooling TRT at heat rates of -20 kilowatts and -8 kilowatts are approx. 1,000 meters and 700 meters. The discrepancy between the thermal conductivity value defined in the COMSOL model, 3.25 W/(m·K), and the value derived through the ILS method diminishes as longer time intervals are used in the ILS interpretation.

With a low cooling power of 8 kilowatts, reliable measurements can still be conducted in boreholes up to approximately 650 meters without exceeding a 10% margin of error. Under equivalent heating conditions, the maximum borehole depth is approximately 550 meters.
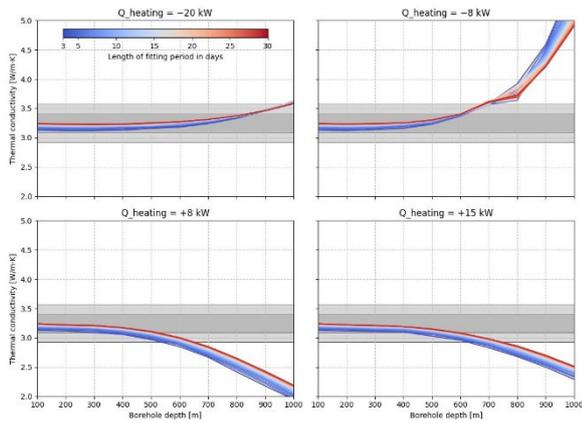
Figure 1. Thermal conductivity determination from the COMSOL simulated synthetic data.

Figure 2. Borehole thermal resistance determination from the COMSOL simulated data.

The thermal resistance of the BHE depends on its length, as shown in Figure 2. In the definition of the synthetic data, the bedrock thermal conductivity is constant, but the borehole thermal resistance depends on the heating/cooling power and thus also on the fluid temperature

$$R_b = \frac{(T_f - T_b)}{Q} L \, . \qquad (3)$$

The ILS method assumes uniform heat transfer along the depth of the BHE, thereby treating the borehole thermal resistance as depth independent. In practice, however, heat transfer during a heat injection TRT is not uniform, with the upper layers of the bedrock typically experiencing greater temperature increases.

Figure 2 shows that the thermal resistance interpreted from the cooling TRT data using the ILS closely aligns with the resistance given by the numerical model, even in deeper BHEs.

If the measurement is carried out using a cooling TRT, the groundwater temperature in the BHE reflects more accurately the actual operating temperature of the borehole, resulting in a higher value for the borehole thermal resistance. In Finland, BHEs are primarily used for heat extraction, which causes the bedrock to cool down, and as a result, the groundwater temperature in the borehole is lower than during a heating TRT. Therefore, a more accurate value for the borehole thermal resistance—one that better represents actual operating conditions—is obtained by cooling the bedrock.
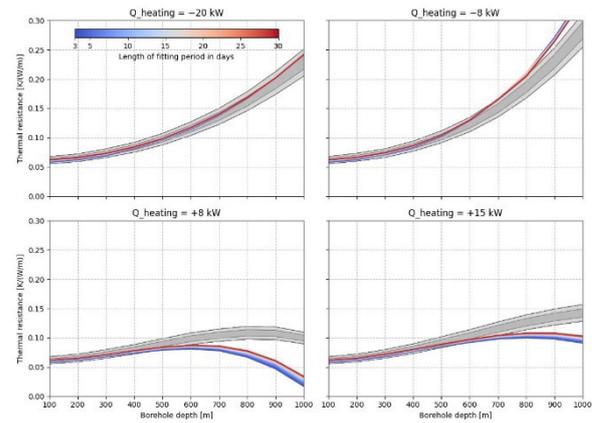
The results of this theoretical analysis provide several important insights. With deeper wells, the temperature gradient raises the bottom well temperature so high that in the heating TRT, the circulation fluid only heats the upper portion of the well, while the lower section gets cooled. Increasing the heating power can somewhat mitigate this issue, but even doubling the heating power was not enough to completely solve it. An alternative solution is to attempt to cool the bedrock instead of heating it. Cooling tests were simulated with promising results. The cooling TRT generally outperformed the heating TRT.

For well lengths between 100 and 1,000 meters, the effective borehole thermal resistance ranged from 0.06 to 0.23 K/(W/m) when using 8 kilowatts of heat extraction, and from 0.06 to 0.28 K/(W/m) when using 20 kilowatts of heat extraction for the cooling TRT. This suggests that effective borehole thermal resistance is influenced not only by borehole length but also by the cooling power used during the TRT.

A significant reason why the interpretation of heating TRT data using the ILS model deviates from the numerical model in deeper BHEs is that, during the measurement, the bedrock may not heat uniformly along its entire length. The bottom section cools down, while the upper sections heat up significantly.

Figures 3 and 4 illustrate, with examples, how the length of a BHE affects the temperature of the heat-carrying fluid at different heating and cooling outputs. When the duration of the heating TRT is limited to three days (72 hours), the fluid temperature in a 500-meter-deep borehole increases only marginally above the initial bedrock temperature at a thermal load of 8 kilowatts (Fig. 3). In a 1,000-meter-deep borehole subjected to the same test conditions, the upper section of the bedrock experiences notable heating, whereas the lower section exhibits cooling, indicating uneven thermal interaction along the borehole depth. This is highly problematic for the analytical interpretation of the effective thermal conductivity of the bedrock because at the bottom of the BHE, heat is transferred

from the bedrock to the fluid, while in the upper part, heat flows from the fluid into the bedrock. A high heating power is required to ensure that the lower part of the bedrock also heats up in a 1,000-meter-deep borehole.
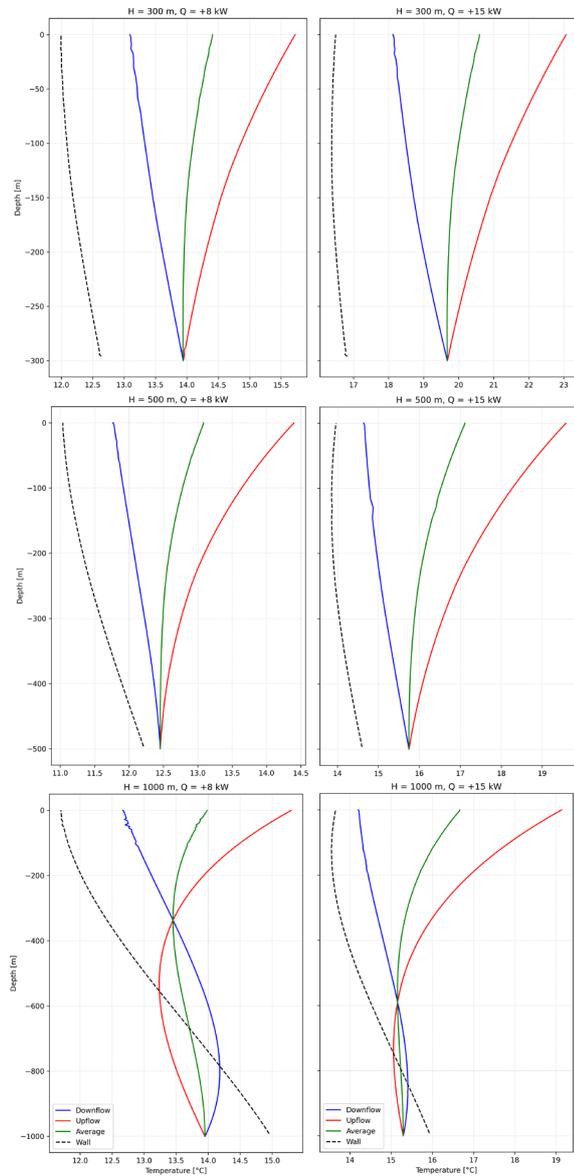

Figure 3. Temperature development in 300 m, 500 m, and 1,000 m deep boreholes after a 3-day TRT. Heating powers: 8 and 15 kilowatts.
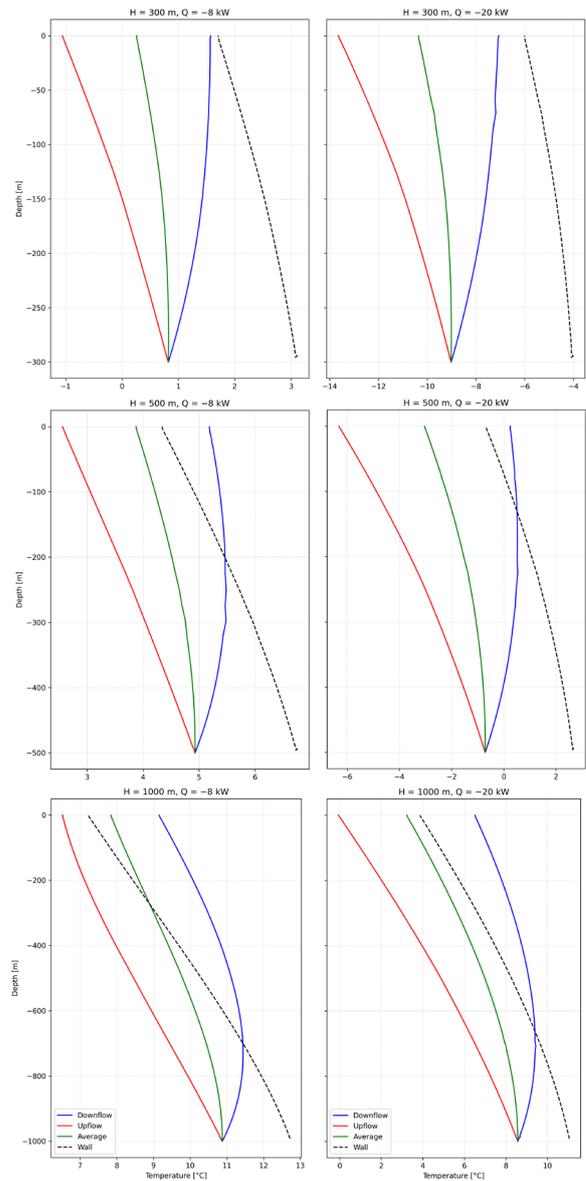

Figure 4. Temperature development in 300 m, 500 m, and 1,000 m deep boreholes after a 3-day TRT. Cooling powers: 8 and 20 kilowatts.

In contrast, during a cooling TRT measurement (Fig. 4), the temperatures between the pipe branches do not intersect at any point, and heat transfer occurs from the bedrock toward the heat-carrying fluid at every depth. For that reason, there are no issues in the analytical interpretation of the effective thermal conductivity of the bedrock during cooling TRTs. Furthermore, it is possible to interpret the thermal conductivity as a function of depth if fibre optic cables are installed inside the U-pipes for the duration of the measurement.

4. CONCLUSIONS

Conducting a TRT in a medium-deep BHE (500–1,000 meters) requires greater attention compared to a corresponding measurement in a shallow BHE. Therefore, it is important to consider in advance whether the measurement will be carried out in heating or cooling mode.

In the context of the heating TRT, the effective thermal conductivity and effective borehole thermal resistance could be determined within a 10% margin of error only up to depths of 500 to 600 metres. However, using the cooling TRT with 8 kilowatts, accurate results (within a 10% margin of error) were obtained for wells up to 700 meters deep. Moreover, cooling at 20 kilowatts produced results within a 10% margin of error even for wells as deep as 1 kilometre. These findings imply that the cooling TRT is the most viable option in deep groundwater-filled wells. It's important to note that this study did not account for natural convection in groundwater-filled boreholes, which likely impacts TRT outcomes.

TRTs utilising cooling have been considerably less common than those employing heating. Nevertheless, the results demonstrate that the cooling option is a highly viable alternative, especially for medium-deep geothermal wells. From a practical standpoint, the heating option is somewhat simpler to implement, which may partially account for the relatively lower adoption of the cooling approach.

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