Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Modelling Thermal Response Tests for Deep Coaxial Borehole Heat Exchangers

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Keywords: Deep Borehole Heat Exchangers, Newcastle Science Central Deep Geothermal Borehole, MATLAB, OpenGeoSys, Thermal Response Test

ABSTRACT

Deep borehole heat exchangers (DBHEs) have been proposed as a method for repurposing hydrocarbon and geothermal exploration wells for further use, yet, typically the in-situ rock properties may be poorly defined or not recorded. Therefore, thermal response tests (TRTs) can provide estimates of the subsurface radial thermal conductivity and borehole thermal resistance. This data can then be utilized to model the resource, determining the thermal capacity and potential for redevelopment. In this study, the capability of numerical modelling tools (a MATLAB model by Brown *et al*. (2021) and OpenGeoSys (OGS)) and an analytical solution (Beier, 2020) were investigated to simulate TRTs and their ability to estimate subsurface parameters.

The Newcastle Science Central Deep Geothermal Borehole was selected as a deep case study as plans are in place to carry out a TRT as a DBHE with coaxial design. The borehole was initially drilled as a geothermal exploration well targeting the Mississippian Fell Sandstone Formation; however, it proved to have low hydraulic conductivity and subsequently would not be suitable for development using conventional methods. The borehole was drilled to a total depth of 1821 m, but we regard only the top 922 m as being available for testing due to a 4.5 inch (~11.4 cm) liner inserted below this depth. This means it is hydraulically unattractive and restrictive of access for pipework to repurpose the well at depths greater than 922 m. Initially, a shallow 188 m case study was modelled, where it was possible to compare the results against real data from a coaxial TRT which has been documented in literature.

In this study, modeled data was compared to develop an understanding of subsurface characteristics. Model results show that the thermal conductivity and thermal resistance estimates vary between different modelling approaches despite identical model inputs. For the shallow example, analysis of data generated from all models using the line-source theory resulted in thermal conductivity accurately being predicted relative to the input after 3 days to within 15 %. In contrast, for the deep case study, data generated from OGS and the analytical solution provided far more internally consistent thermal conductivity estimates than the MATLAB numerical model. For both shallow and deep scenarios, estimates of thermal conductivity from data generated from the analytical solution of Beier provided approximates of the true input value most accurately; however, estimates varied with time for the deeper case. Furthermore, it would appear longer TRTs are required for progressively deeper DBHEs due to the stronger influence of internal counter-flow heat transfer between up-flowing and down-flowing heat transfer fluids, the thermal gradient and the time taken for the heat flow field to reach quasi-steady state.

1. INTRODUCTION

Borehole heat exchangers (BHEs) are commonly used at shallow depths (c. 50-200 m) as a supply of thermal energy to ground source heat pumps, which subsequently are used for spatial heating. Typically, a series of BHEs are used in an array for heating and/or cooling, thus, requiring a large surface footprint. In more populous areas it may be unfeasible for a large surface area to be used for drilling and therefore, a single DBHE may be more suited for development.

In recent years, research focus has increased in single well coaxial DBHEs (e.g., Alimonti *et al*., 2016; Falcone *et al*., 2018; Renaud *et al*., 2020; Brown *et al.*, 2023a,b); these studies tend to highlight that a higher thermal yield per drilled metre is available with increased depth due to the combined effects of greater borehole length for heat exchange and higher temperatures from the Earth's natural thermal gradient (Brown *et al*., 2021; Xia *et al*., 2021). In the UK, and internationally, there is a significant number of deep hydrocarbon wells approaching the end of life, plugged or abandoned, which could be repurposed for geothermal utilisation (Watson *et al*., 2021). Therefore, there is significant scope for the repurposing of existing wells to the coaxial DBHE configuration.

Thermal response tests (TRTs) are used to characterise the ground around a BHE by either injecting or extracting heat from a system at a predefined thermal power (e.g., Gehlin, 2002). This is accomplished by a surface thermal source or sink heating or cooling the heat transfer fluid circulating through the borehole. The response of the subsurface can then be recorded by monitoring the outlet and inlet temperature, which in turn can be used to approximate the thermal properties of the subsurface, such as the thermal conductivity of the surrounding rock and borehole thermal resistance.

Typically, BHEs under 300 m depth utilise the U-tube configuration (Fig. 1a) with literature dominated by shallow studies (e.g., Beier *et al*., 2011, Yang *et al*., 2010). Modelling, experimental and feasibility studies have shown that shallow TRTs are influenced by test duration, groundwater flow, fracture fluid flow, heterogeneity, depth, shank spacing, initial conditions (such as a geothermal gradient), rock thermal conductivity, lithological layering and grout material (Gehlin and Hellström, 2003; Signorelli *et al*., 2007; Esen and Inalli, 2009; Wagner *et al*., 2012; Sliwa and Rosen, 2017; Beier *et al*., 2021).

Some studies have investigated the potential for TRTs to be used for parameter estimation for deep coaxial borehole heat exchangers. Beier (2020) highlighted that different modelling approaches resulted in varying under-estimations of the rock thermal conductivity and borehole thermal resistance, whilst the analytical solution developed for a 2D model with a geothermal gradient showed depth had limited impact on the estimation of the thermal parameters. Further studies modelling different depths of U-tube BHE TRTs also suggest the same (for up to 400 m depth) (Signorelli *et al*., 2007). Different BHE configurations have also been tested to 800 m depth, with coaxial BHEs showing a higher error when estimating thermal parameters than single and double U-tubes (Morchio *et al*., 2022). Few (if any) however, have tested the ability of multiple numerical and analytical solutions to model deep TRTs.

In this study, therefore, our primary aim is to test the impact of depth on a TRT performed on a coaxial BHE by comparing analytical solutions and several numerical models. Numerical and analytical solutions can be used to determine the thermal performance of a system, i.e., the heat extraction rates that can be supported by a BHE for a given change in circulating fluid temperature. Analytical algorithms can produce rapid and acceptably accurate solutions, whilst numerical solutions can provide more detail on the subsurface components, especially in heterogeneous or anisotropic environments. This paper compares two numerical solutions and one analytical approach; including OpenGeoSys (Shao *et al*., 2016; Chen *et al*., 2019), a numerical implementation on MATLAB developed by Brown et al. (2021) and an analytical solution by Beier (2020). Initially, the models were tested against data from a shallow TRT for validation and comparison (for data see Acuña and Palm, 2013). Following this, the codes were applied to a case study of a DBHE to test the respective models' ability to simulate a TRT; the modelled TRT data was subsequently inversely analysed by a line-source approach to provide a back-estimate of the thermal parameters. Thus, three modelling environments were used for forward modelling of the impact of a thermal response test (with an applied constant heat injection rate over the course of several days) on rock and fluid temperatures; in particular, the simulated fluid inlet and outlet temperatures, as it is these that are conventionally monitored in a thermal response test. Conventional line source theory was then applied to inversely model the simulated fluid inlet / outlet temperatures (which is the conventional method of analysing a TRT, but not the only method) to estimate average rock thermal conductivity (λ) and effective global borehole thermal resistance ($R_{b\text{-}global}$).

The Newcastle Science Central Deep Geothermal Borehole (NSCDGB) was chosen as a case study due to (i) high heat flows present in the area (Fig. 1) which are associated with underlying radiogenic granites (Younger *et al*., 2016; Howell *et al*., 2021; Brown, 2022), and (ii) plans to retrofit this as a coaxial DBHE to test the potential for it to contribute heat supply to a nearby building or heat network (GOW, 2020). The NSCDGB was drilled in 2011-2014 in Newcastle upon Tyne, UK, to investigate the potential of the Mississippian Fell Sandstone Formation to be exploited as a conventional resource; unfortunately, the sandstone hydraulic conductivity was too low to sustain sufficient flow rates for development (Younger *et al*., 2016). Therefore, research will focus on repurposing and testing the well as a DBHE. Only the top 922 m was regarded as available for testing due to a 4.5 inch liner inserted below this depth, as it is hydraulically unattractive, requiring excessive pumping power, to circulate fluid in narrow pipe diameters in the lower part of the well (e.g., Liu *et al*., 2019). This study aims to evaluate and provide preliminary modelling results for a TRT, highlighting the most suitable approaches for evaluation of TRTs.

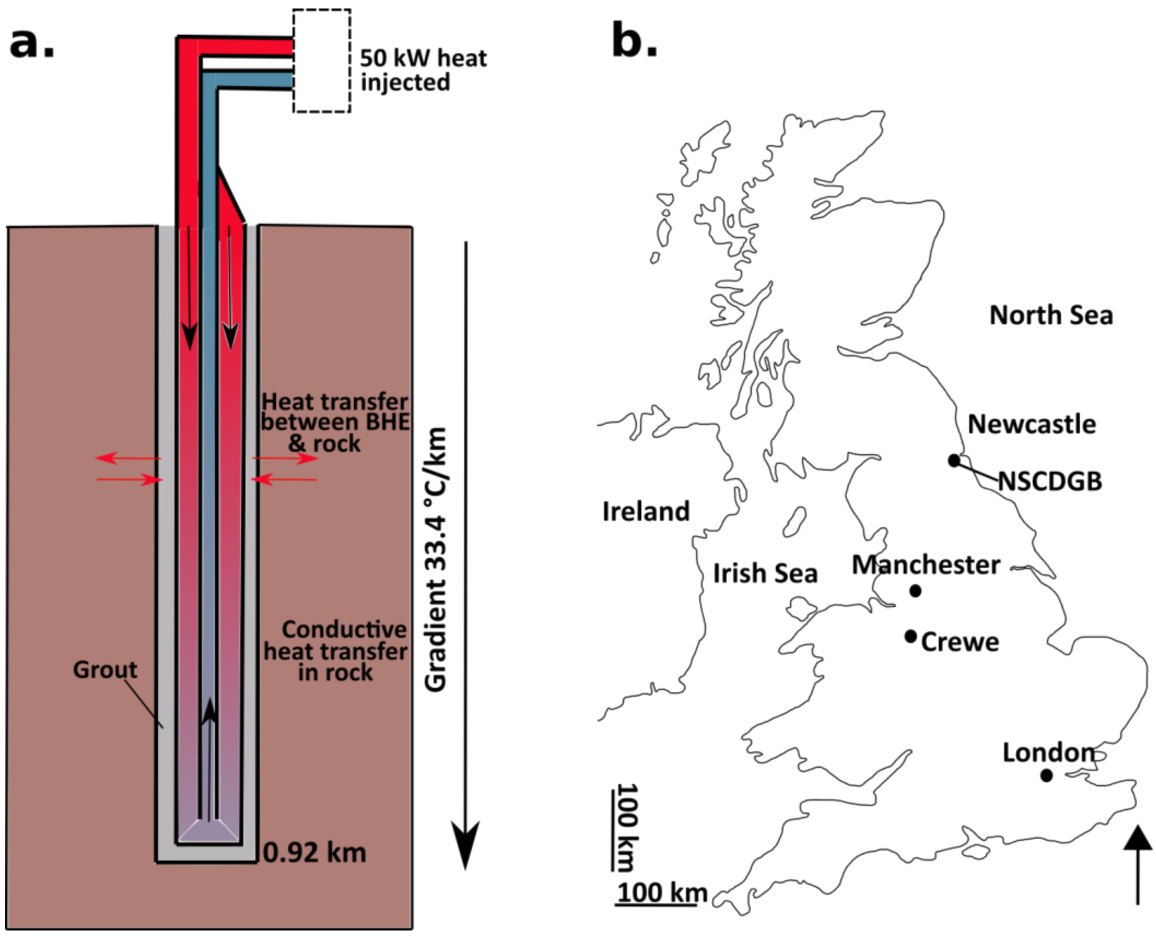

Figure 1: (a) Schematic of the Newcastle Science Central Deep Geothermal Borehole (NSCDGB) as modelled and (b) location of the borehole marked next to Newcastle.

2. METHODOLOGY

Modelling was undertaken using three different approaches to compare their ability to accurately model the NSCDGB: OpenGeoSys (OGS) software (e.g., Chen et al., 2019; Kolo et al., 2022), a numerical solution developed by Brown *et al.* (2021) on MATLAB and Beier's analytical solution (2020). Prior to this, a comparison against data from a shallow well was undertaken, whilst the Line Source Method was used to evaluate the data produced from each simulation to inversely model the fluid inlet/outlet temperatures and estimate thermal conductivity and effective borehole thermal resistance. This section outlines the Line Source Method, modelling approaches and parameters used.

2.1 Line Source Theory

TRTs can be analysed using the logarithmic approximation of the line source heat transfer solution (e.g., see Carslaw and Jaeger, 1959), which is valid beyond a certain critical time t_{crit}, where $t_{crit} > \frac{5{r_b}^2}{\alpha}$, although some authors cite $t_{crit} > \frac{20{r_b}^2}{\alpha}$ (Ingersoll *et al*., 1954, Gehlin, 2002; Banks *et al*., 2013):

$$\bar{T}_{(f,t)} - T_0 \approx qRb_{global} + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right] \quad (1)$$

where $\bar{T}_{(f,t)}$ is the apparent average fluid temperature, as seen at the wellhead, r is the radius of the borehole, t is time since the start of the test, q is the heat injection rate per meter of the borehole length, λ is the average (horizontal) thermal conductivity, α is the thermal diffusivity and T_0 is the average undisturbed rock temperature over the length of the borehole.

$\bar{T}_{(f,t)}$ is simply calculated as $\frac{T_{in}+T_{out}}{2}$, where T_{in} is the temperature of the inlet fluid temperature to the borehole heat exchanger (i.e., into the annular space of a coaxial DBHE), T_{out} is the temperature of the outlet fluid temperature (i.e., exiting through the central pipe).

Equation 1 resembles the equation for a straight line (equation (2)), with time (t) being plotted on a logarithmic axis and the change in average fluid temperature (or temperature displacement ($\bar{T}_{(f,t)} - T_0$)) being plotted on the y-axis (e.g., Beier *et al*., 2021). Conventional line source theory asserts that log-linearity should be approached after the critical time t_{crit}:

$$(\bar{T}_{(f,t)} - T_0) = k\ln(t) + m \quad (2)$$

Thus, the gradient of the log-linear plot (i.e., the change in temperature per ln cycle) $k = \frac{q}{4\pi\lambda}$, and the intercept on the y-axis m is related to the effective (global) borehole thermal resistance $R_{bglobal}$.

This means that, from the evolution of average fluid temperature during a TRT, a thermal conductivity estimate λ_E can be calculated from the gradient (k) by:

$$\lambda_E = \frac{q}{4\pi k} = \frac{q}{4\pi}\frac{[\ln(t_1) - \ln(t_2)]}{\bar{T}_{(t_1)} - \bar{T}_{(t_2)}} \quad (3)$$

where the heat load per meter of borehole length is constant and equal to $q = \frac{\rho_w C_w Q(T_{in} - T_{out})}{L}$. ρ_w is the density of the fluid, C_w is the specific heat capacity of the fluid, Q is the heat load and L is the length of the borehole. The effective (global) borehole thermal resistance is calculated from the intercept *m* by (e.g., Banks, 2012; Lhendup *et al*., 2014):

$$m = qRb_{global} + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right], \text{ thus} \qquad Rb_{global} = \frac{m}{q} - \frac{1}{4\pi\lambda}\left[\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right] \quad (4)$$

It is also worth noting that there are other methods of estimating the thermal parameters, but studies indicate that they provide similar results for coaxial BHEs (Sliwa *et al*., 2022). When evaluating parameters at specific time points (to find the gradient in equation 2 for instance) data within up to 10 h of the selected temporal point where used. As some modelling approaches use dynamic time steps, if no time values were within this range, then the closest values were used (i.e., t^{+1} and t^{-1}).

The above discussion considers the overall (global) effective borehole thermal resistance. One should note that some authors (e.g., Acuña and Palm, 2010) also define a local borehole thermal resistance (Rb_{local}) as:

$$Rb_{local} = \frac{\overline{T^*}_{(f,t)} - T^*_{(r,t)}}{q^*} \quad (5)$$

where $\overline{T^*}_{(f,t)}$ is the average fluid temperature at any depth in the borehole and $T^*_{(r,t)}$ is the temperature of the borehole wall at that depth, while q^* is the rate of heat transfer through the borehole wall at that depth. The asterisk * denotes a local measurement at a specific depth. The local borehole resistance is usually difficult to measure in real scenarios due to the absence of measurements at the borehole wall. We will therefore omit discussion of this local borehole thermal resistance in this study.

Although the line source method is suitable for analysing short- to medium-term behaviour of BHEs, it is limited by several assumptions: 1) it ignores effects from the base of the BHE and interaction with the ground surface (this is reasonable as these end-effects only become significant after long periods). 2) There is no convective heat transfer within the surrounding rocks; the modelled scenarios have the same assumption. 3) It assumes the ground is radially isotropic and homogenous. 4) It assumes that the ground has a constant, uniform initial temperature, neglecting the geothermal gradient. For shallow BHE this is not usually a significant problem and T_0 is set to the average undisturbed ground temperature over the BHE. However, with progressively deeper BHE, the geothermal gradient and non-uniform ground temperature may lead to deviations from conventional line source theory, especially with how Rb_{global} evolves with time (Banks, 2022). 5) It assumes that Rb_{global} can be characterised as a single constant value. In shallow BHEs, this is usually valid for times greater than a few hours. In DBHEs, it may be less valid. Long circulation times and large temperature differences along the BHE mean that fluid temperatures and temperatures at the borehole wall may evolve asymmetrically for some time after a TRT has commenced. Note that Rb_{global} combines the effects of local fluid-ground borehole thermal resistance (due to thermal resistance of grout, pipework) and internal heat transfer between central pipe and annulus along the borehole length. Thus, all the models used in this paper carry assumptions and limitations. If estimates of λ deviate from "true" input data, the discrepancy could be due to limitations with the forward (numerical or analytical) models, or due to violated assumptions of the inverse (line source) model. If estimates of λ or Rb_{global} deviate from each other, then they are due to differences in the forward modelling environments applied.

2.2 Modelling Approaches

Three modelling approaches were used to simulate the problem. Beier's (2020) analytical solution simulates heat flux by applying the Laplace transform method. OpenGeoSys (e.g., Chen *et al.*, 2019) and the MATLAB model developed by Brown *et al.* (2021) and Brown (2020) both apply the dual-continuum method, which simulates heat flux in the wellbore in 1D and the surrounding rock in 3D. The former uses the finite-element method to discretize space and the latter the finite-difference method. The detailed governing equations and model setups can be obtained in the aforementioned references.

The boundary conditions were applied as a constant surface temperature, basal heat flow of 85.17 mW m^{-2} (calculated using the thermal gradient and conductivity) and lateral boundary conditions set to equal the natural geothermal gradient. Under initial conditions, the DBHE components (fluid, grout) were set to equal the natural undisturbed geothermal gradient (33.4 °C/km). Beier's analytical solution, Brown *et al.*'s MATLAB solution and OGS all allow a specified heat extraction rate to be imposed.

2.3 Parameters

Two notional cases are described in this subsection, the former using shallow TRT data from Acuña and Palm (2010, 2013) with further data tabulated in Beier *et al*. (2014), and the latter based on the NSCDGB. The shallow data was used for initial comparison to test the different modelling environments against data obtained from a real case study, before simulating a deep TRT.

2.3.1 Shallow Thermal Response Test Data

The initial modelling study tests data from a shallow 188 m case study by Acuña and Palm (2010, 2013). Models were compared to TRT data from the study where a 6 kW heat load was imposed with a circulating flow rate of 0.58 l/s. Fluid was injected in the central pipe and extracted through the annular space (coaxial pipe with centred inlet - CXC configuration). The active borehole heat exchanger length was unknown in this example and recording of vertical data in the distributed thermal response test (DTRT) began at 17 m depth, therefore, a length of 168 m was chosen to model the BHE. Further parameters are summarized in table 1.

Table 1. Parameters for the shallow case study – see Acuña and Palm (2013) or Beier (2014) for more details. Note the critical time (t_{crit}) for line source to be valid is 3.2 h.

Parameter	Value	Units
Borehole diameter	115	mm
Active heat exchanger length	168	m
Internal pipe outer diameter	40	mm
Internal pipe wall thickness	2.4	mm
External pipe outer diameter	114	mm
External pipe wall thickness	0.4	mm
Pipe wall thermal conductivity	0.40	W/(m.K)
Ground thermal conductivity	3.25	W/(m.K)
Ground volumetric heat capacity	2.24×10^6	J/(K m^3)
Water flow rate	0.58	l/s
Water density	999	kg/m^3
Water volumetric heat capacity	4.19×10^6	J/(K m^3)
Water thermal conductivity	0.59	W/(m.K)
Water viscosity	1.138×10^{-3}	kg/(m s)
Water Prandtl number	8.09	-
Heat input rate	6360	W
Average ground temperature	8.4	°C

2.3.2 Newcastle Science Central Deep Geothermal Borehole

The NSCDGB was modelled as there are plans to use this as a pilot DBHE in the UK, with TRTs planned. This is part of the 'NetZero GeoRDIE project – Net Zero Geothermal Research for District Infrastructure Engineering (Grant number EP/T022825/1)' (GOW, 2020). It will test the potential of the borehole to be repurposed for spatial heating. Although the borehole was drilled to 1821 m, it is likely to be limited if repurposed as a DBHE to 922 m or less as the diameter reduces significantly at depths in excess of this. In this study, a flow rate of 3 l/s with fluid injected down the annulus was imposed with a heat load of 50 kW. Further parameters modelled are summarized in table 2.

Table 2. Parameters for the deep NSCDGB case study. Thermo-physical parameters of the model. Model parameters are either taken from literature, assumed unpublished values (assembled by Westaway (2020) and Banks (2021)), calculated values or given as the most likely value. [1] Younger *et al*. (2016), [2] Kimbell *et al*. (2006), [3] Westaway and Younger (2016), [4] Brown *et al*. (2021), [5] Gebski *et al*. (1987), [6] Bott *et al*. (1972), [7] England *et al*. (1980), [8] Lesniak *et al*. (2013). Note the inner pipe is the coaxial pipe and the outer pipe is the casing. The real nature of the casing situation is notably more complex than that modelled. [9] Thermal parameters calculated by Kolo *et al*. (2022). The critical time (t_{crit}) for line source to be valid is 15 h.

Parameter	Value	Units
Borehole Depth [1]	922	m
Borehole Diameter [1]	0.216	m
Outer Diameter of Inner Pipe	0.1005	m
Thickness of Inner Pipe	0.00688	m
Thickness of Outer Pipe	0.0081	m
Thickness of Grout	0.01905	m
Thermal Conductivity of Polyethylene Inner Pipe	0.45	W/(m.K)
Thermal Conductivity of Steel Outer Pipe	52.7	W/(m.K)
Bulk Density of saturated Rock [2]	2480	kg/m^3
Thermal Conductivity of Saturated Rock [1,5,6,7]	2.55	W/(m.K)
Specific Heat Capacity of Saturated Rock [3,8]	950	J/kgK
Volumetric Heat Capacity of Saturated Rock	2.356	MJ/m^3/K
Density of Grout	995	kg/m^3
Thermal Conductivity of Grout	1.05	W/(m.K)
Specific Heat Capacity of Grout	1200	J/kgK
Density of Fluid [4]	998	kg/m^3
Thermal Conductivity of Fluid	0.59	W/(m.K)
Specific Heat Capacity of Fluid	4179	J/kgK
Water viscosity	0.8×10^{-3}	kg/(m s)
Water Prandtl number	5.6	-
Heat Load Injected	50	kW
Surface Temperature [5]	9	°C
Geothermal Gradient [1,5]	33.4	°C/km
Volumetric Flow Rate	0.003	m^3/s

3. RESULTS

A shallow and deep comparative study was undertaken to give an indication of the modelling solutions' ability to simulate TRTs. The thermal response of the models and subsequent calculations of thermal parameters were then analyzed. Preliminary results are presented in this section.

3.1 Validation and Comparison to Shallow Example

3.1.1 Thermal Analysis

Model results from all approaches provide similar results to each other, with the circulation fluids inlet and outlet temperatures nearly identical after ~1 day (Fig. 2a). There is a minor discrepancy initially; however, late-stage TRT data (i.e., data recorded after 1 day) is usually used to evaluate the thermal properties. Data from the study was taken at 63 h for the central pipe and annular space, corresponding to depth (Fig. 2b). When comparing the models' solutions, vertical profiles from Beier's analytical solution are a near perfect match with the data. This is unsurprising, as some of the data has been used to validate the model previously and had a strong correlation to data (Beier, 2020). The MATLAB (Brown *et al*. 2021) and OGS solutions were also close to the data, with each solution remaining within 0.3 °C and 0.15 °C, respectively. It is worth noting that the data from the publication by Acuña and Palm (2013) may also be subject to error from the tests themselves. Error may occur due to fluctuations in the thermal load (and flow rate), eccentricity of the central pipe (i.e., it was not centralised) and averaging of temperature along the fibre optic cable.

3.1.2 Evaluating Thermal Conductivity and Borehole Resistance

Using equations 1-5 the thermal conductivity and thermal resistance was calculated for the TRTs modelled using each approach (table 3) using conventional line source theory applied to fluid inlet and outlet temperature data after $t_{crit} > \frac{5{r_b}^2}{\alpha}$ (which in this case was 3.2 hrs). Thermal conductivity and resistance generally show similarities between each modelling environment's results. The thermal conductivity and resistance was compared at day 3 of the simulation (table 3); inverse analysis of data generated by Beier's analytical solution yielded the closest estimate in comparison to the model input (3.25 W/(m.K)), whilst the numerical models show similar estimates and are all within 15 % of the modelled input. The global thermal resistance generated from modelling (table 3) was similar to that in the study from Acuña and Palm (2013), which ranged from 0.024 to 0.035 K/(m.W).

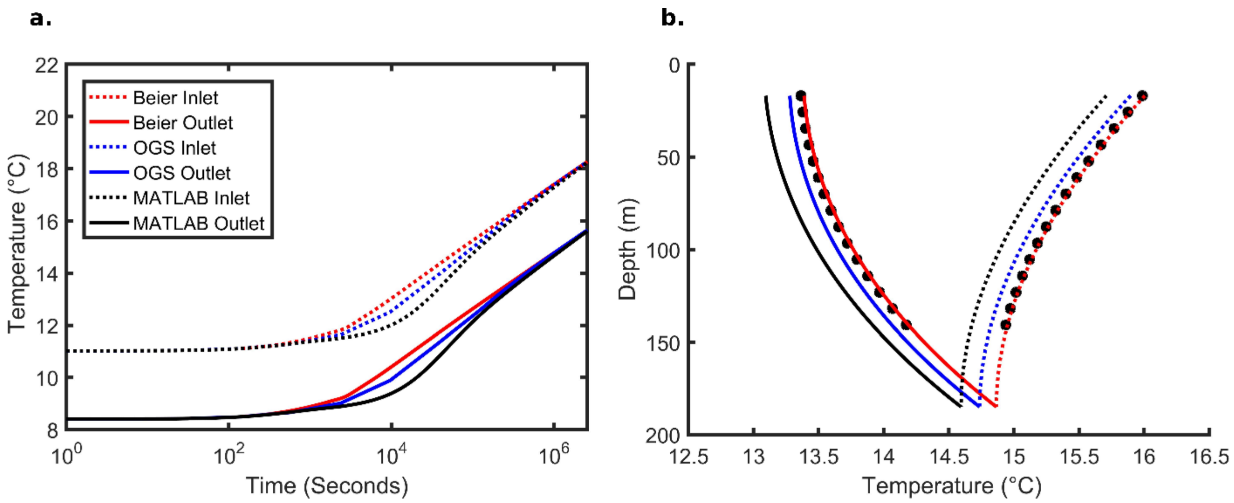

Figure 2: (a) Evolution of inlet and outlet temperatures with time for each modelling approach and (b) a comparison of the vertical profile's temperatures with depth. Real experiemntal data points at 63 h highlighted as black dots in figure b.

Table 3. Estimated thermal parameters calculated at day 3 (shallow example).

Software/Code	Thermal Conductivity Estimate (W/(m.K))	Global Thermal Resistance (K/(m.W))
Beier (2020) – MATLAB	3.21	0.033
Brown et al. (2021) – MATLAB	2.75	0.007
OGS (e.g., Shao *et al*., 2016; Chen *et al*., 2019)	2.83	0.015

3.2 Newcastle Science Central Deep Geothermal Borehole

3.2.1 Thermal Analysis

The thermal evolution of the circulating fluid with time is similar between the different modeling methods; however, there are some differences. The initial spike in average fluid temperature within the first circulation cycle is less pronounced in OGS in contrast to the other solutions (Fig. 3). The rapid increase in temperature across all simulations was due to hot fluid at the base of the DBHE under static conditions being pumped to the surface within the first cycle. In reality, fluid would be circulated without a heat load for several cycles, and this would negate this effect and fluid temperature would be evenly distributed in the DBHE. During the first cycle, the average fluid temperature for the MATLAB and Beier analytical solution are nearly parallel. Following this MATLAB and OGS are similar. At the end of the simulation, the plots of average fluid temperature are nearly parallel between all approaches (Fig. 3b). The maximum discrepancy at the end of the simulation is between Beier and OGS, where the difference in average fluid temperature is 2.3 °C.

When evaluating the vertical profiles of the circulating fluid with increasing depth, the shape of the temperature profiles are similar between different methodologies (Fig. 4). As reflected by inlet and outlet temperatures at the surface (Fig. 3), the vertical temperature profile created from the model by Beier is consistently ~2 °C warmer at both 3 and 5 days than the other solutions which are close to each other (Fig. 4).

3.2.2 Evaluating Thermal Conductivity and Borehole Resistance

The impact of the differences in the models' fluid thermal behavior is reflected when estimating the thermal properties by inverse (line source) modelling (table 4). The delay in the apparent average fluid temperature for MATLAB becoming parallel to the other models' results in poorer thermal conductivity and global borehole resistance estimates. This is more pronounced in the deeper case study in comparison to the shallow one. After ~10 days of simulation, the thermal conductivity is estimated to within 15 % of the model input parameter (Fig. 5). Global borehole thermal resistance estimates are different between all solutions, OGS is an order of magnitude lower than Beier and MATLAB produces a negative value at day 3. With time, the global borehole thermal resistance estimates for data generated by OGS and MATLAB increases. After ~10 days, estimates from MATLAB become positive, whilst OGS estimates are 0.009 K/(m.W) higher than those recorded at 3 days.

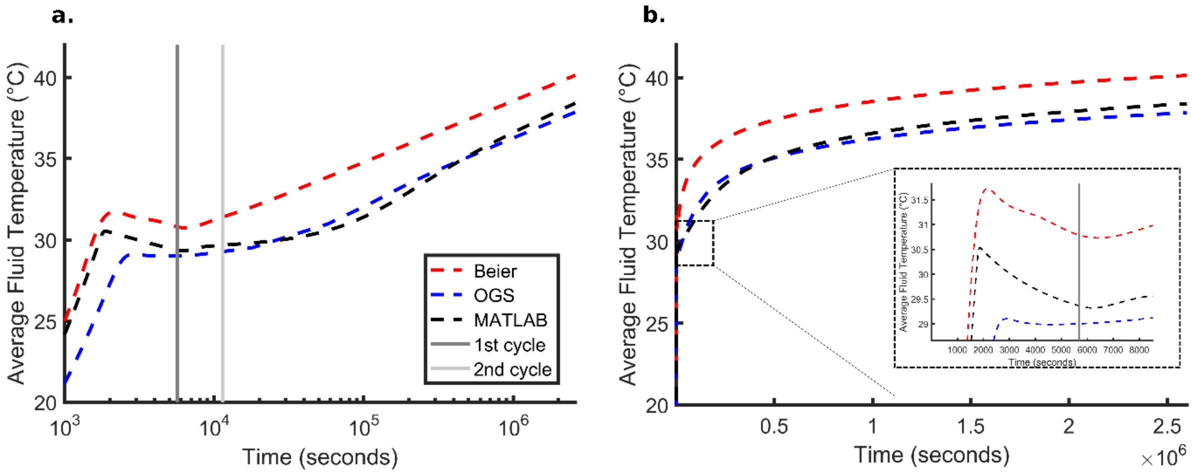

Figure 3: Evolution of apparent average fluid temperatures with time for each modelling approach using a logarithmic x-axis (a) and linear (b).

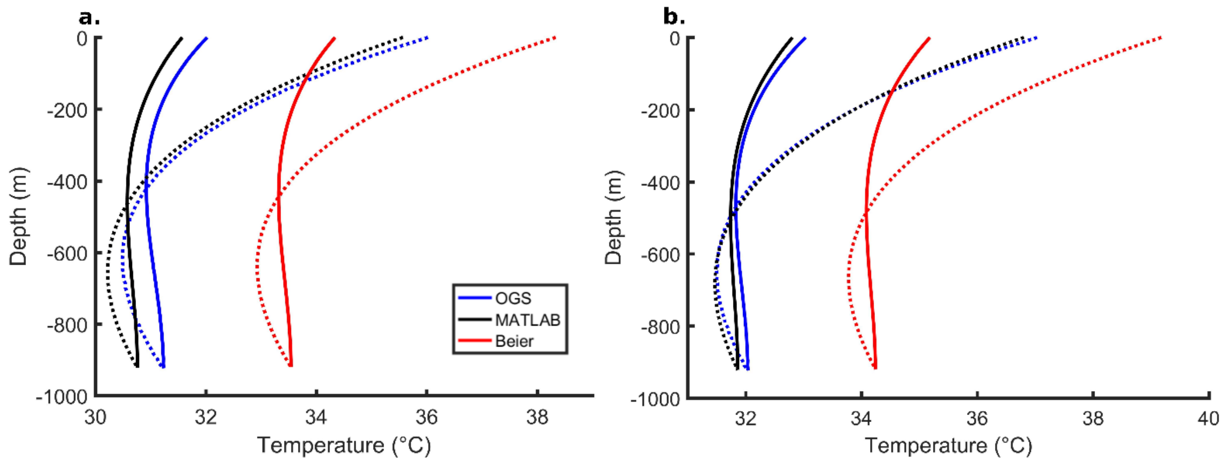

Figure 4: Evolution of inlet and outlet temperatures plotted against depth for each modelling approach for 3 days (a) and 5 days (b). Dashed line is the inlet fluid through the annulus and solid line is outlet through the central pipe.

The temporal variations in thermal conductivity estimates were also considered further. MATLAB estimates using inverse line source theory were less than the input value for thermal conductivity (2.55 W/(m.K)), but estimates improve with time (fig. 5). Similarly, estimates of thermal conductivity from OGS improve with time, slightly exceeding the input value after ~10 days. Beier's data fluctuations with time. The impact of these fluctuations could be mitigated by increasing the sampling points.

4. DISCUSSIONS: IMPLICATIONS OF MODEL RESULTS AND SUITABILITY FOR MODELLING THERMAL RESPONSE TESTS

The different modelling approaches produced similar thermal changes in fluid circulation temperature and similar results for thermal parameter estimates for the shallow TRT; however, there were more discrepancies for the deeper test. When considering the average fluid temperature's evolution with time for the deeper scenario, it was observed that all modelled trends became nearly parallel (at time ~>15 days), leading to similar results when estimating the thermal conductivity, but within the initial 10 days the MATLAB numerical model (Brown *et al.*, 2021) struggled to provide thermal conductivity estimates that matched the input. The MATLAB model is therefore less likely to be suited to modelling TRTs in DBHEs and more suited for longer term simulations. It is also worth noting the discrepancy between model inputs and calculated thermal parameters from data could also be due to imperfections of the line source inverse analysis method too.

When estimating the global borehole thermal resistance, the models provided similar estimates for shallow studies, but in the deep studies global thermal resistance estimates for the MATLAB model provided negative estimates, although this did increase and become positive with time. The low (and negative) estimates of global borehole thermal resistance from OGS and MATLAB at shorter time intervals also suggests more time is required for deeper TRTs to provide realistic estimates of thermal parameters. However, they do begin to level out at day 30 and were recorded as 0.018 and 0.009 K/(m.W), respectively. It could also be hypothesized that effective borehole resistance (which is ultimately, a "constructed" concept) in deep boreholes takes longer to stabilize at a consistent value.

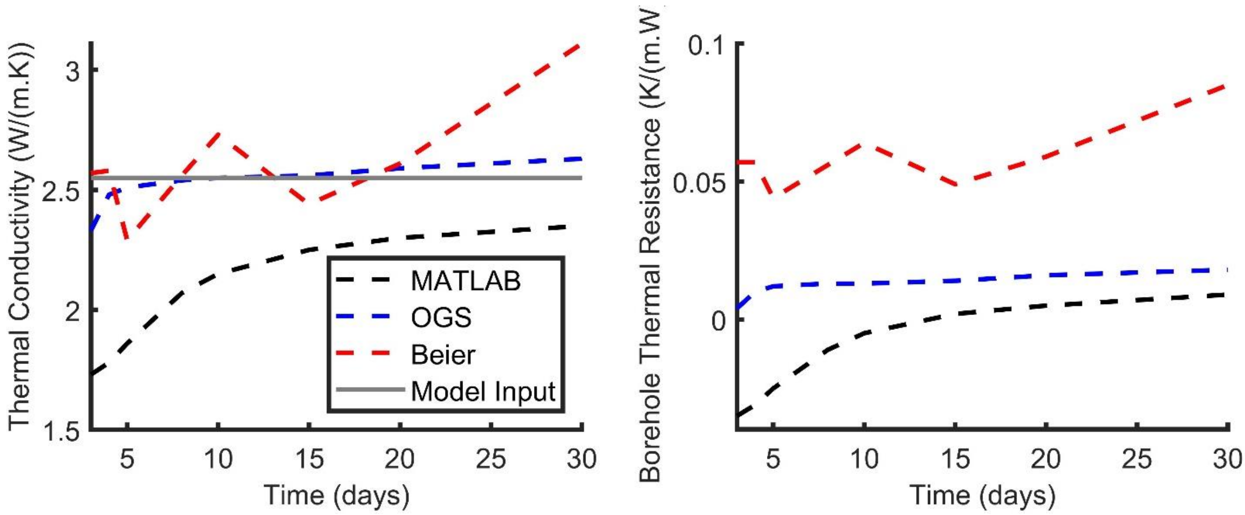

Figure 5: Evolution of (a) thermal conductivity and (b) global effective borehole thermal resistance with time. Input thermal conductivity to the model was 2.55 W/(m.K).

Table 4. Estimated thermal parameters calculated at day 3 (deep example).

Software/Code	Thermal Conductivity Estimate (W/(m.K))	Global Thermal Resistance (K/(m.W))
Beier (2020) – MATLAB	2.62	0.059
Brown et al. (2021) – MATLAB	1.73	-0.035
OGS (e.g., Shao *et al*., 2016; Chen *et al*., 2019)	2.33	0.004

The approach that produces the most similar estimates to the input through inverse modelling is Beier's analytical solution; however, there are further considerations. Beier's solution is limited to homogenous rocks, whilst the numerical simulations can all incorporate heterogeneity to more realistically model the subsurface and can be used for distributed thermal response tests. The local plans for testing at the NSCDGB aim to perform multiple TRTs if funding permits and therefore, some consideration should be given to whether a given modelling technique is capable of simulating a series of TRTs and their rest periods. We should finally point out that, differences in the models documented in this paper do not necessarily reflect upon the underlying approach, but could equally well reflect upon the construction and discretization of the geology and BHE within those software environments, as much as on the underlying computational algorithms.

5. CONCLUSIONS

In conclusion three different modelling approaches were compared for shallow and deep case studies with the aim of comparing software suitability for being used for data analysis and modelling of the future planned deep tests at Newcastle. Several conclusions were made:

- For shallower tests, all data generated through forward modelling provided estimates of thermal conductivity using inverse line source analysis within 15 % of the input value after 3 days. Data from Beier's analytical solution provided the closest estimates to that of the TRT data listed in Acuña. and Palm (2013) for thermal conductivity and borehole resistance.
- For deeper scenarios, the data produced from the MATLAB numerical model by Brown *et al*. (2021) produced lower estimates of thermal conductivity and global borehole thermal resistance in contrast to OGS and Beier's solution. As a result, it appears less suited for thermal response tests. Model response did improve after ~10 days and it is, therefore, more suited for longer term simulations with a sustained heat extraction rate.
- It would appear deeper TRTs require longer circulation periods due to the influence of the thermal gradient and it takes longer time for the heat-flow in the rocks proximal to reach near quasi-steady state.
- When considering the most suited software for deep TRTs data generated from the model by Beier can produce thermal conductivity estimates through inverse modelling most similar to the model input; however, these do fluctuate over time (see figure 5). This could be improved by taking more data points during temporal sampling. Both MATLAB and OGS predict lower fluid temperatures than the analytical solution by Beier, implying lower borehole thermal resistance. This could also be due to discrepancies in modelling of fluid dynamics of heat transfer at the fluid interface.
- Future work should aim to test the models against actual data from a deep TRT for the NSCDGB.

ACKNOWLEDGMENTS

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/T022825/1 and EP/T023112/1. The funding sources are for the NetZero GeoRDIE (Net Zero Geothermal Research for District Infrastructure Engineering) and INTEGRATE (Integrating seasoNal Thermal storagE with multiple enerGy souRces to decArobonise Thermal Energy) projects, respectively.

REFERENCES

Acuña, J. and Palm, B. A novel coaxial borehole heat exchanger: description and first distributed thermal response test measurements. In *Proceedings of the World Geothermal Congress*, 2010 pp. 7.

Acuña, J. and Palm, B. Distributed thermal response tests on pipe-in-pipe borehole heat exchangers. *Applied Energy*, *109*, 2013, pp.312-320.

Alimonti, C., Berardi, D., Bocchetti, D. and Soldo, E. Coupling of energy conversion systems and wellbore heat exchanger in a depleted oil well. *Geothermal Energy*, *4*(1), 2016, pp.1-17.

Banks, D. *An introduction to thermogeology: ground source heating and cooling*. John Wiley & Sons, 2012.

Banks, D., Withers, J.G., Cashmore, G. and Dimelow, C. An overview of the results of 61 in situ thermal response tests in the UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, *46*(3), 2012, pp.281-291.

Banks, D. Thermal properties of well construction materials - Newcastle Science Central borehole. Internal University of Glasgow report for NetZero GeoRDIE project: unpublished, 2021.

Banks, D. Examining issues of circulation asymmetry in closed loop borehole heat exchangers. University of Glasgow report for the EPSRC INTEGRATE and NetZero-GEORDIE projects. Final version F1.2, 2022. doi:10.13140/RG.2.2.15735.29608

Beier, R.A., Smith, M.D. and Spitler, J.D. Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. *Geothermics*, *40*(1), 2011, pp.79-85.

Beier, R.A., Acuña, J., Mogensen, P. and Palm, B. Transient heat transfer in a coaxial borehole heat exchanger. *Geothermics*, *51*, 2014, pp.470-482.

Beier, R.A. Thermal response tests on deep borehole heat exchangers with geothermal gradient. *Applied Thermal Engineering*, *178*, 2020, p.115447.

Beier, R.A., Fossa, M. and Morchio, S. Models of thermal response tests on deep coaxial borehole heat exchangers through multiple ground layers. *Applied Thermal Engineering*, *184*, 2021, p.116241.

Bott, M.H.P., Johnson, G.A.L., Mansfield, J., Wheilden, J. Terrestrial heat flow in north-east England. Geophysical Journal of the Royal Astronomical Society, 27, 1972, 277–288.

Brown, C.S. *Modelling, characterisation and optimisation of deep geothermal energy in the Cheshire basin* (Doctoral dissertation, University of Birmingham), 2020.

Brown, C.S., Cassidy, N.J., Egan, S.S. and Griffiths, D. Numerical modelling of deep coaxial borehole heat exchangers in the Cheshire Basin, UK. *Computers & Geosciences*, *152*, 2021, p.104752.

Brown, C.S. Regional geothermal resource assessment of hot dry rocks in Northern England using 3D geological and thermal models. *Geothermics*, *105*, 2022, p.102503.

Brown, C.S., Kolo, I., Falcone, G. and Banks, D. Repurposing a Deep Geothermal Exploration Well for Borehole Thermal Energy Storage: Implications from Statistical Modelling and Sensitivity Analysis. *Applied Thermal Engineering*, 2023a, p.119701.

Brown, C.S., Kolo, I., Falcone, G. and Banks, D. Investigating scalability of deep borehole heat exchangers: Numerical modelling of arrays with varied modes of operation. *Renewable Energy*, 2023b.

Carslaw, H.S. and Jaeger, J.C. *Conduction of heat in solids* (No. 536.23). Clarendon press, 1959.

Chen, C., Shao, H., Naumov, D., Kong, Y., Tu, K. and Kolditz, O. Numerical investigation on the performance, sustainability, and efficiency of the deep borehole heat exchanger system for building heating. *Geothermal Energy*, *7*(1), 2019, pp.1-26.

England, P.C., Oxburgh, E.R., Richardson, S.W. Heat refraction and heat production in and around granite plutons in north–east England. *Geophysical Journal International*, 62, 1980, 439–455.

Esen, H. and Inalli, M. In-situ thermal response test for ground source heat pump system in Elazığ, Turkey. *Energy and Buildings*, *41*(4), 2009, pp.395-401.

Falcone, G., Liu, X. , Okech, R. R., Seyidov, F. and Teodoriu, C. Assessment of deep geothermal energy exploitation methods: The need for novel single-well solutions. *Energy*, 160, 2018, pp. 54-63. (doi: 10.1016/j.energy.2018.06.144)

Gebski, J.S., Wheildon, J., Thomas-Betts, A. Investigations of the UK heat flow field (1984-1987). Report WJ/GE/87/6, British Geological Survey, Nottingham, 1987, 60 pp.

Gehlin, S. Thermal response test: method development and evaluation (Doctoral dissertation, Luleå tekniska universitet), 2002.

Gehlin, S.E.A. and Hellström, G. Influence on thermal response test by groundwater flow in vertical fractures in hard rock. *Renewable energy*, *28*(14), 2003, pp.2221-2238.

GOW. Grants on the web. EPSRC EP/T022825/1, 2020. Accessed on 11/4/2022: https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T022825/1

Howell, L., Brown, C.S. and Egan, S.S. Deep geothermal energy in northern England: Insights from 3D finite difference temperature modelling. *Computers & Geosciences*, *147*, 2021, p.104661.

Ingersoll, L.R., Zobel, O.J. and Ingersoll, A.C. Heat conduction, with engineering, geological and other applications. University of Wisconsin Press. 1954, 325 pp.

Kimbell, G.S., Carruthers, R.M., Walker, A.S.D., Williamson, J.P. Regional geophysics of southern Scotland and northern England. Version 1.0 on CD-ROM. British Geological Survey, Keyworth, 2006. Available from: https://shop.bgs.ac.uk/Bookshop/product.cfm?p_id=KRGSC

Kolo, I., Brown, C.S., Falcone, G. and Banks, D. Closed-loop Deep Borehole Heat Exchanger: Newcastle Science Central Deep Geothermal Borehole. In *European Geothermal Congress, 2022.*

Lesniak, B., Słupik, Ł., Jakubina, G. The determination of the specific heat capacity of coal based on literature data. *Chemik*, 67, 2013, 560–571.

Liu, J., Wang, F., Cai, W., Wang, Z., Wei, Q. and Deng, J. Numerical study on the effects of design parameters on the heat transfer performance of coaxial deep borehole heat exchanger. *International Journal of Energy Research*, *43*(12), 2019, pp.6337-6352.

Lhendup, T., Aye, L. and Fuller, R.J. In-situ measurement of borehole thermal properties in Melbourne. *Applied thermal engineering*, *73*(1), 2014, pp.287-295.

Morchio, S., Fossa, M. and Beier, R.A. Study on the best heat transfer rate in Thermal Response Test experiments with coaxial and U-pipe Borehole Heat Exchangers. *Applied Thermal Engineering*, *200*, 2022, p.117621.

Renaud, T., Verdin, P. G. and Falcone, G. Conjugated numerical approach for modelling DBHE in high geothermal gradient environments. *Energies*, 13(22), 2020, 6107. (doi: 10.3390/en13226107)

Signorelli, S., Bassetti, S., Pahud, D. and Kohl, T. Numerical evaluation of thermal response tests. *Geothermics*, *36*(2), 2007, pp.141-166.

Shao, Haibing and Hein, Philipp and Sachse, Agnes and Kolditz, Olaf. Geoenergy Modeling II: Shallow Geothermal Systems. ISBN: 978-3-319-45055-1, Springer International Publishing, 2016. DOI:10.1007/978-3-319-45057-5

Sliwa, T. and Rosen, M.A. Efficiency analysis of borehole heat exchangers as grout varies via thermal response test simulations. *Geothermics*, *69*, 2017. pp.132-138.

Sliwa, T., Leśniak, P., Sapińska-Śliwa, A. and Rosen, M.A. Effective Thermal Conductivity and Borehole Thermal Resistance in Selected Borehole Heat Exchangers for the Same Geology. *Energies*, *15*(3), 2022, p.1152.

Wagner, V., Bayer, P., Kübert, M. and Blum, P. Numerical sensitivity study of thermal response tests. *Renewable Energy*, *41*, 2012, pp.245-253.

Watson, S. M., Falcone, G. and Westaway, R. Repurposing Hydrocarbon Wells for Geothermal Use in the UK: a Preliminary Resource Assessment. In: *World Geothermal Conference* 2020+1, Reykjavik, Iceland, 24-27 October 2021.

Westaway, R., Younger, P.L. Unravelling the relative contributions of climate change and ground disturbance to subsurface temperature perturbations: case studies from Tyneside, UK. *Geothermics*, 64, 2016, 490–515.

Westaway, R. Rock thermal properties for Newcastle Helix site. Internal University of Glasgow report for NetZero GeoRDIE project: unpublished, 2020.

Xia, Z.H., Jia, G.S., Ma, Z.D., Wang, J.W., Zhang, Y.P. and Jin, L.W. Analysis of economy, thermal efficiency and environmental impact of geothermal heating system based on life cycle assessments. *Applied Energy*, *303*, 2021, p.117671.

Yang, H., Cui, P. and Fang, Z. Vertical-borehole ground-coupled heat pumps: A review of models and systems. *Applied energy*, *87*(1), 2010, pp.16-27.

Younger, P.L., Manning, D.A., Millward, D., Busby, J.P., Jones, C.R. and Gluyas, J.G. Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: the Newcastle Science Central deep geothermal borehole. *Quarterly Journal of Engineering Geology and Hydrogeology*, *49*(4), 2016, pp.350-363.