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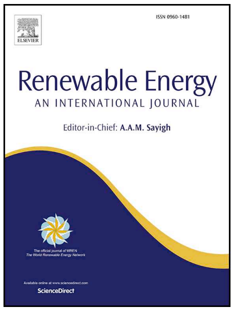

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Long-term high frequency monitoring of a large borehole heat exchanger array

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Abstract

Borehole heat exchangers are a key technological element of geothermal energy systems and modelling their behaviour has received much attention. The aim in the work reported here has been to produce a reference data set that can be used in analysis of large borehole heat exchanger systems and validation of models of such. A monitoring exercise to collect high frequency data from a large ground heat exchanger array consisting of 56 boreholes over 38 months since the start of operations is reported. The system is associated with a mixed-use university building that has both heating and cooling loads. Ground heat exchange was found to be dominated by rejection of heat over the monitoring period and modest seasonal increases in temperatures. The ground heat exchanger installation has been additionally characterised by analysis of thermal response test data to estimate the effective ground and grout thermal properties. The utility of the measurements as a reference data set by presenting a model validation study is furthermore demonstrated. This has highlighted some features of the data that are more significant in systems of larger scale. These reference data are being made openly available for further work on performance analysis and model validation.

Keywords: Geothermal, Borehole Heat Exchanger, Monitoring, Validation

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1. Introduction

Mitigation of potential global warming and achieving environmental impact targets [1] requires greater uptake of efficient heating and cooling technologies such as geothermal heat pumps and up-scaling of thermal energy storage capacities. Geothermal heat exchange achieved through closed-loop borehole heat exchanger (BHE) systems is a key technological element of both ground source heat pump systems (GSHP) that provide heating and cooling for buildings [2] and underground thermal energy storage systems (UTES) at large scales [3].

Borehole heat exchanger systems are commonly used to allow the ground to be used as a heat source or sink in GSHP systems and so gain the thermodynamic advantages of the relatively stable ground temperatures. Although BHE array systems enable advantages in efficiency and operating cost, they also constitute a large element of the overall capital cost of such systems. Consequently, there is considerable interest in design methods for BHE that are technically robust but also allow some optimisation of cost to be achieved [4]. The technical challenge in designing such ground heat exchanger systems is primarily being able to predict long-term temperature trends in groups of interacting boreholes. This inevitably requires computer models implemented in design software or thermal system simulation tools. Accordingly, there have been significant efforts to develop a number of models of BHE, in singular form and arrays, and corresponding validation studies in recent years.

The aim has been to produce a reference data set that can be used in analysis of large borehole heat exchanger systems and validation of models of these types of system. A monitoring exercise to collect high frequency data

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from a large borehole heat exchanger array at a University building with a GSHP system that provides both heating and cooling is reported. The data were collected over approximately three years since the start of system operation. Prior to completion of the system, a thermal response test (TRT) was conducted on one of the boreholes in order to validate the design. We describe the application of thermal response test analysis methods to the test data in order to characterise the installation. In the later sections of the paper we demonstrate the utility of the data has been demonstrated through application in a model validation study.

Data from this study has already been used in an analysis of borehole heat exchanger design procedures [5] and is openly available from an Institutional Data Repository [6]. The data reported here—where the focus is on borehole array properties and behaviour—is complemented by a separate paper on overall system performance [7].

2. Borehole heat exchangers

In many countries employing ground source heat pump technology the most common form of ground heat exchanger consists of one or more vertical borehole heat exchangers using closed-loop pipe arrangements and circulating either water or an anti-freeze solution as the heat transfer fluid. The pipe arrangements found in practice include co-axial forms, two U-tubes inserted together and connected in series (double U-tube) or, most commonly, a single U-tube. The tubes may be surrounded with backfill material, partially grouted to seal the borehole near ground level, or fully grouted. Further details of the heat exchanger array are provided later.

Models of BHE are widely used to predict the thermal response of the ground and heat transfer fluid and there have been a number of analytical or numerical BHE models that have been reported. BHE models are used for TRT analysis, BHE design and GSHP system simulation, and can be classified based on modelling approaches such as analytical, numerical models or hybrid models and extent of dimensional representation. The models also vary based on the ability to represent multiple boreholes (i.e. with thermal interaction) and fluid transport. The physical processes modelled in many cases are limited to conduction heat transfer and relatively few consider groundwater flows or convective effects. Detailed reviews of analytical, numerical and hybrid models of BHE can be found in Florides et al. [8], Yang et al. [9], and He [10].

2.1. Available experimental data and validation studies

A number of attempts have been made to validate models of BHE using experimental data. Some of these have been mostly concerned with short duration tests with artificially imposed thermal conditions and others with long-term monitoring of multiple borehole arrays. Yavuzturk and Spitler [11] comment on such data sets that suitable data should be complete with high-quality independent measurement of the thermal properties of the ground and accurate measurement of at least the inlet and out temperature fluid temperatures and the fluid flow rate. In view of the persistence of the effects of prior thermal conditions, the measurements should ideally be recorded from the beginning of system operation. Cullin et al. [5] have pointed out the rarity of data sets that represent multiple years, have continuous data, a range of different system sizes, climate conditions, and range of system parameters such as number and depth of boreholes.

One early monitoring exercise was carried out at the Maxey Elementary School building [11]. The ground heat exchanger of the GSHP system includes 120 boreholes in a 10 by 12 array configurtion. Each borehole had a depth of 73.2 m, diameter of 114.3 mm and was spaced 6.1 m appart. The diameter of U-tube was 25.4 mm with the gap between the borehole and U-tube filled with bentonite grout for the top 3 m. The monitored data includes measurement of the flow rate, inlet and outlet temperatures. The system was operational from May 1995 but a number of practical issues delayed the start of monitoring until November 1995. Yavuzturk and Spitler [11] comment on the limitations of the data and its impact on the validation exercise.

Yavuzturk and Spitler [11] used monitored data from the Maxey Elementary School to validate their short time response BHE model. This validation study included the comparison of predicted heat pump entering fluid temperature with corresponding actual values. The deviation between actual and predicted temperatures were found to be greater during periods of low flow rate or spurious or frequently disrupted data. The best agreement between prediction and actual heat pump entering temperature was found when the data-set has continuous data and the flow rate was moderate or high.

An experimental facility for the study of hybrid GSHP systems was established at Oklahoma State University (OSU) and has been reported on by Hern [12] and Gentry [13]. This facility includes a ground heat exchanger array with three BHE with a diameter of 114 mm, depth of 75 m and spaced 6 m apart. The ground thermal conductivity was reported as 2.55 W m^{-1}K^{-1} and the undisturbed temperature is 17.3 °C. Minutely data have been collected from March 2005 to June 2006.

He [10] has reported using OSU data for validating a three-dimensional BHE numerical model in two ways, short time scale validation and long-time scale validation. In the short time scale validation study, the hourly data have been used for first 14 days of March 2005 to build the thermal history of the borehole and on the 15th day, minutely values have been used to validate short time behaviour of the BHE. In long time scale validation, hourly average values of inlet temperatures and flow rates have been given as input to the model, and simulated hourly outlet temperature and Heat transfer rate have been compared with experimental values over 16 months.

Rees [14] has also used the OSU experimental data to validate a two-dimensional numerical BHE model. Like He [10], the validation has been carried out in two ways. Firstly, a short time scale validation study compared the simulated minutely borehole outlet temperatures with actual experimental values over a month. This high frequency data was useful in that it allowed the models ability to capture the time delays caused by fluid transit through pipe system and its thermal capacity to be evaluated. Secondly, the simulated monthly heat transfer and monthly mean outlet temperature were compared with experimental data over 16 months to evaluate the models ability to capture longer-term (longer length scale) effects.

Ruiz-Calvo and Montagud [15] have provided operational details of a system at Valencia Polytechnic University and provided a long-term reference data set. This system has a ground heat exchanger consisting of 6 BHE with a diameter of 150 mm, depth of 50 m, spaced 3 m apart in a 2 by 3 rectangular formation. The boreholes are backfilled with soil and its thermal conductivity is 1.6 W m^{-1}K^{-1} with the undisturbed ground temperature reported to be 19.5 °C. Minutely data have been collected for a period of 6 years from 2005 to 2011 at the inlet and outlet of the BHE and heat pump along with power consumption data. The system operated for weekdays and operated in heating mode between late October and April. In first three years, the system was operated only 15 months out of first 36 months which includes eight months with the system turned off or no data.

Ruiz-Calvo and Montagud [15] have used the data set of Valencia system to validate the GLHEPRO design software [16] using one year of data between May 2009 and Apr 2010. The software was found to predict the thermal response of BHE with acceptable accuracy such that the monthly average temperature predictions were found to agree closely with the monitored values.

Cullin et al. [5] used data sets from four different real systems for validating two commonly used methods for designing BHE. The four data sets are the OSU data, Valencia Polytechnic University data, data from the ASHRAE headquarters building [17] along with the data reported herein. The two design methods studied were the ASHRAE handbook methodology and the GLHEPRO simulation-based design tool [16]. These were applied to calculate the design lengths of the BHE array given the building load/energy information, the physical parameters of the BHE and targets for minimum and maximum exiting fluid temperatures (heat pump entering fluid temperatures). The calculated design length of the BHEs were compared with the actual BHE depths and it was found that the simulation-based model gave results more consistent with the installed lengths than the ASHRAE method. The data collection reported here represented the largest BHE array in the study and so provided a unique contribution.

2.2. Thermal Response Testing and Analysis

The thermal properties of the ground are critical parameters in the design and operational performance of closed-loop ground heat exchanger systems. BHE depth, and so capital cost, is particularly sensitive to thermal conductivity and to a lesser extent thermal diffusivity of the ground and grout materials. In many non-domestic systems it is economic to carry out Thermal Response Testing (TRT) to experimentally derive property values. It should be said that such properties are 'effective' values that represent properties averaged over some length-scale. As most design methods assume homogeneous properties the main interest is in the effective values of thermal conductivity and diffusivity over the whole borehole depth. In this study the installation has been characterised in terms of the ground and borehole thermal properties by making use of TRT data derived at the start of the installation process and so some background is provided here.

Commonly practised TRT approaches follow that of Mogensen [18] in which a constant heat flux is imposed on the fluid of a single BHE installation and thermal response is studied in terms of measured fluid temperatures [19, 20]. A typical TRT equipment arrangement is shown in Fig. 1. The typical TRT equipment includes a pump for circulating fluid through test borehole, electric heaters for imposing thermal load, valves, pipes and water supply. There are typically instruments to measure inlet and outlet borehole temperatures, the flow rate of the circulating fluid and power supplied to the heaters. Data loggers are used to record these measurements at predetermined time intervals over a period of 48 hours or more [21, 22, 23]. Besides the fluid temperature response data a parameter required for site-specific design is the undisturbed (initial) ground temperature (T_g). This is quite straightforward to find from the initial fluid temperature measurements or possibly by traversing the installed U-tube to find the temperature variation with depth before the start of testing.

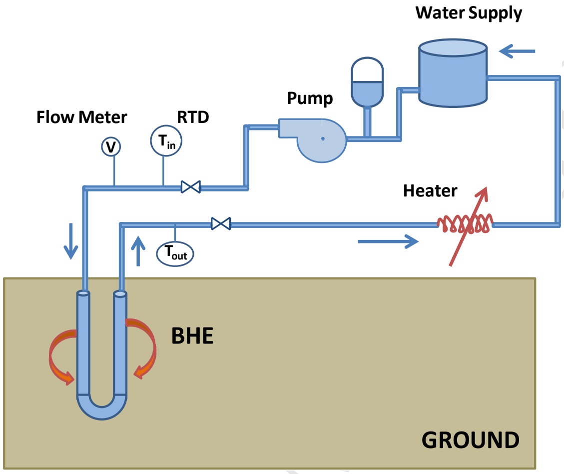

Figure 1: Typical TRT apparatus showing temperature and flow measurement locations.

Thermal Response Testing of this type is essentially an inverse method approach to estimating the effective borehole and ground thermal properties. In this inverse approach some form of model of the BHE response is applied to find a best fit with the experimental measurements. The thermal property values required to make this best fit are then taken as the estimates of the properties of interest. There are a number of types of model that could be used and a number of ways of arriving at a best fit. The often applied method is to apply an infinite line-source model of thermal response and use a semi-graphical approach to finding the best fit. A more formal way to arrive at the best estimate is to carry out a formal (algorithmic) parameter estimation with a model. A number of models have been used in this way and different parameter estimation methods applied. In this work both a simple line-source and graphical analysis and a parameter estimation approach using a numerical model have been applied as described below.

2.2.1. Estimation using a line-source response model

The line source model of conduction heat transfer induced by an idealized infinite line heat source [24, 18] defines a logarithmic relationship between temperature and constant heat input. In simplified form the equation for the response is as follows,

$$T_f = \frac{q}{4\pi\lambda}\Big[\ln\Big(\frac{4\alpha t}{r_b^2}\Big)-\gamma\Big]+q.R_b+T_g \qquad (1)$$

where,

$T_f =$ mean circulating fluid temperature,

$q =$ Power supplied per unit length,

$\lambda =$ Thermal conductivity,

$t =$ Time,

$\gamma =$ Euler's constant (0.5772),

$r_b =$ Borehole radius,

$R_b =$ Thermal resistance,

$T_g =$ Undisturbed temperature of the ground,

$\alpha =$ Thermal diffusivity.

Analysis of data for the line source model is done by plotting the average of flow and return temperature against the natural logarithm of time. The slope (m) of a linear trend line can be shown by examination of Eq. 1 to be related to the effective ground thermal conductivity, λ_g^*, by,

$$\lambda_g^* = \frac{q}{4\pi m} \tag{2}$$

The form of the model in Eq. 1 is strictly valid only for times $t \geq (5r_b^2)/\alpha$. It also assumes that the heat flux input is constant throughout the test—something that can be hard to achieve in practice. It should be remembered that heat has to be transferred through the borehole pipes and surrounding grout material before it affects the ground outside the borehole. Consequently, the first hours of data are sensitive to the borehole and grout properties rather than the ground properties and so the model is not expected to fit the data well in the first hours of the test. The effective thermal diffusivity can not be assessed using this type of model.

2.2.2. Estimation using a numerical model

Austin et al. [22] used a formal parameter estimation technique in conjunction with a two-dimensional numerical model to determine the thermal conductivity of the ground surrounding the borehole. In parameter estimation methods, various inputs such as thermal conductivity are adjusted systematically in a numerical model representing the borehole and surrounding ground such that the minimum value is obtained for the difference between the actual temperature response and the model-predicted temperature response—typically quantified by the sum of the squares of the errors (SSE) over a defined test period. Several parameter estimation (optimisation) techniques can be used to arrive the minimum value including classical steepest gradient approaches and genetic algorithms [25]. In implementing this approach there is some interest in minimizing the number of evaluations of the numerical model as a single calculation can be computationally demanding. Jain [26] examined this question and found that, of the steepest gradient type algorithms, O'Neill's implementation of Nelder-Mead simplex method [27] with exploratory search was the most effective. Accordingly, this is the algorithm that has been applied in this work.

Shonder and Beck [28] developed a one-dimensional numerical model for TRT analysis that accounts for inlet and outlet pipes as one equivalent co-axial pipe and introduced parameters for the effective heat capacity of the pipe and the fluid mass. The one-dimensional model was combined with a steepest gradient parameter estimation technique to evaluate the thermal conductivity of ground and grout. The model has been validated using experimental data from tests with sand with a close agreement with the known thermal conductivity.

Spitler et al. [29] report using two versions of Finite Volume model to the parametric analysis of TRT data. One model approximated the pipe geometry by sections of a polar grid and the other used a boundary-fitted grid to represent the U-tube pipe geometry more explicitly. In general, using parameter estimation methods and numerical models opens further possibilities for deriving further parameters and arriving at better estimates. For example, simultaneous estimation of both effective grout and ground thermal conductivity along with estimation of grout and ground thermal diffusivities. Given a model capable of modelling groundwater flow it is also possible to estimate effective hydraulic conductivity and Darcian flow velocity. Often it is also possible to have heating power as a time-varying data input and so firstly deal with variations in power during the test and secondly to deal with stepped heat inputs or combinations of heating and cooling [19].

In this work an implementation of finite volume model used by O'Neil (née Deng) [30] and He [10] using a two-dimensional mesh and incorporating the option of Darcian groundwater flow has been adopted. This model uses a block-structured mesh that is able to represent the pipes, grout and ground geometries along with heterogenous material properties explicitly. The form of mesh used to represent a single borehole is illustrated in Fig. 2.

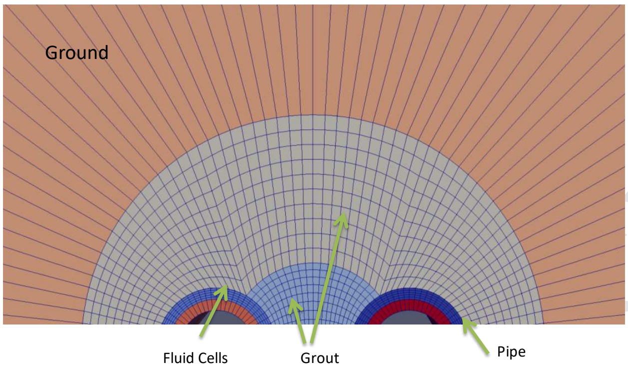

Figure 2: The block-structured mesh representation of the borehole heat exchanger.

3. The heat exchanger installation

The Hugh Aston building located in Leicester, UK, opened in spring 2010 and is the home of the De Montfort University Faculty of Business and Law. The building has a floor area of 16,467 m^2 and comprises three linked wings of between five and seven storeys formed around a central courtyard. The building includes a variety of accommodation including classrooms, academic offices, a mock courtroom, large lecture theatres, meeting rooms, library, IT facilities and retail outlets. The building includes some sustainable design features including grey water recycling, daylight-linked lighting, solar shading, night ventilation, solar hot water generation as well as the geothermal heating and cooling system described here. The GSHP system provides chilled water for all Fan Coil Unit (FCU) and Air Handling Unit (AHU) cooling (360 kW peak capacity) of the building and provides heating through underfloor heating systems (330 kW peak capacity).

The source side of the system is served by 56 borehole heat exchangers, each with a diameter of 125 mm and depth of 100 m. Fig. 3 shows a visualization of the building in relation to the BHE array and Fig. 4 shows a plan of the array. The average distance between adjacent boreholes is 5 m, and the boreholes are in 2 arrays with 19 located to the south of the building and the remainder installed within the central courtyard. All the BHE are effectively configured in parallel i.e. experience the same inlet temperature. Each borehole has a single U-tube inserted that consists of high density polyethylene (HDPE) pipe with an outer diameter of 32 mm.

The topography of the site is essentially flat although, approximately 100 m away, the surrounding campus slopes down towards the River Soar. The site is located over the formation known as the Mercia Mudstone Group (formerly Keuper Marl) which is a confining upper limit of the Sherwood Sandstone Group aquifer [31]. In the 19th century there was some local water extraction for industrial purposes but the region of concern is not regarded as a viable aquifer and no water extraction currently takes place in this urban area. Detailed drilling logs are not available but geological information has been collated from detailed records of neighbouring wells that are now disused and geotechnical investigations on the campus. This information is summarised in Table 1.

The drilling operation reports indicated upper layers composed mostly of sandy clay over rock mostly of red marl and mudstone over most of the borehole depth and this is consistent with the available records. Drilling conditions were favourable and the target depth of 100 m was achieved consistently and so all BHE can reasonably be assumed to be a uniform 100m deep. The boreholes were backfilled with drill cuttings in the lower 75 m with grouting completed in the upper 25 m.

The GSHP system has four water-to-water heat pumps located in a basement plant room adjacent the courtyard. The heat pumps each have two single-speed scroll compressors and are fully reversible. Accordingly, they

Depths	Material
0–0.5 m	brick fill and soft clay
0.5–2 m	clay
2–2.3 m	stiff friable grey marl
2.3-6 m	grey rock marl
6–13 m	red marl
13–46 m	red marl and gypsum
46–48 m	sandstone
48–50 m	marl
50-100 m	sandstone

Table 1: Ground material layers at test site derived from local well and site investigation records.

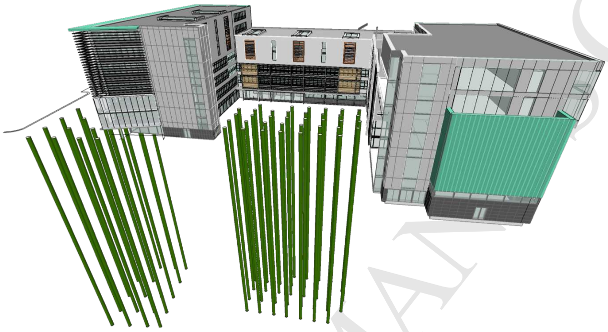

Figure 3: A visualization of the Hugh Aston building and the borehole heat exchanger array (after [7].

are configured to allow two-stage operation in either heating or cooling mode. The system is designed so that each heat pump can deliver heating or cooling with no more than three heat pumps operating in each mode. It was fully expected that heating and cooling would be required simultaneously. In practice the number of occasions when more than two heat pumps are required is relatively small. The heat pumps are connected to a common ground loop header system so that any heat pump can extract or reject heat to the circulating fluid as building demands require.

The ground loop hydraulic circuit has a single variable speed pump controlled to vary the flow in steps according to how many heat pumps are operating. The maximum heat pumps operating at any particular time can be four. Consequently, the ground loop pump is controlled with four speed steps: 53%, 69%, 85%, and 99%. These percentage speeds were determined during commissioning to achieve the corresponding flow rates required: 7.5 L/s, 15 L/s, 21.5 L/s. Consequently the fluid temperature reflects the mix of heating and cooling demanded and the flow rate depends on the total number of heat pumps in operation. Further details of heating and cooling load-side arrangements are given in the companion paper [7].

3.1. Instrumentation

The monitoring of the Borehole Heat Exchanger array started in January 2010 and continued up to February 2013 i.e. a duration of 38 months. The flow and return temperatures of BHE and flow rate measurements have been made with calibrated instruments and recorded at sixty-second intervals.

The primary fluid temperature measurements have been measured at the inlet and outlet of the borehole field at the point where it leaves the ground and enters the plant room. Resistance Temperature Detector (RTD) sensors have high accuracy and repeatability and were chosen for the temperature measurements. Robust industrial pattern Pt100 RTD sensors are inserted into pockets in the pipework for temperature measurements. Each sensor, including the cable and data logger channel, was carefully calibrated prior to installation in the pipes to minimise the error in measurements of temperature difference. A four-wire system is used for sensor connection with data

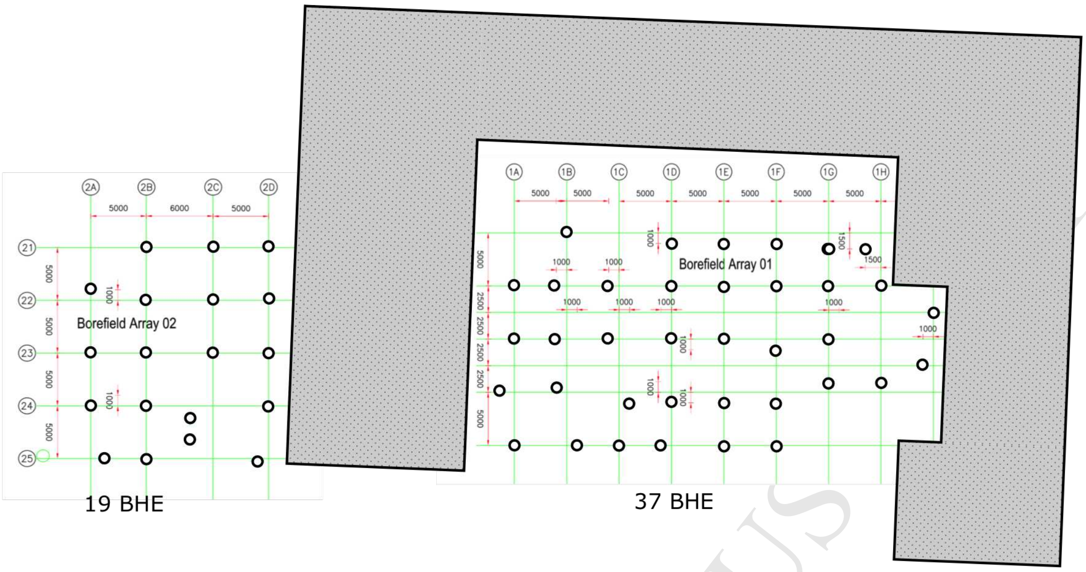

Figure 4: Plan of the borehole field layout in relation to the building outline. Most of the boreholes are located in a courtyard. All borehole heat exchangers are connected in parallel.

loggers throughout the installation. A clamp-on ultrasonic flow meter has been used to measure volumetric flow rates on the ground loop. The ultrasonic flow meter has the advantage of being non-invasive but also of high accuracy (±0.5 % measured value). The calibration of the flow meter and correct installation has been verified in-situ by the manufacturer.

The total uncertainty of the heat transfer rate has been evaluated by combining all the uncertainties arising from each source of errors in quadrature. Although the uncertainty in each measurement has been evaluated (see the related thesis [32] for details) overall uncertainty in the heat balance is dependent on the size of the temperature differences over a particular period in relation to the uncertainty in the temperature measurements. The uncertainty in temperature difference measurement has firstly been estimated based on repeated calibration tests where the flow and return sensors were calibrated in pairs. The overall uncertainty has then been evaluated by considering the frequency of occurrence of temperature differences in the monitoring data. The estimated uncertainty in temperature difference is calculated to be ±0.04 K. Uncertainty in the fluid properties and flow rate has also been considered before calculating the time varying uncertainty in overall heat transfer rates. Accordingly, the BHE array heat transfer rate uncertainty is estimated to be no more than ±2.7 % for nearly 80 % of occurrences.

The monitoring data sequence was disrupted for a few short periods and in these cases the records were filled by making use of the available BMS temperature data or inferring flow rates from knowledge of the pump control status and temperature profiles. This process and the periods effected has been documented and lodged with the data.

4. Results

4.1. heat exchange characterisation

In presenting the results of the monitoring exercise the data indicating the overall behaviour of the heat exchanger array are firstly sumarized. The minutely values of ground loop flow and return temperatures, and circulating fluid flow rates, over the whole 38-month monitoring period (January 2010 to February 2013) have been reduced to daily averages and shown in Fig. 5. These values of fluid temperature are shown alongside the corresponding daily mean drybulb temperature.

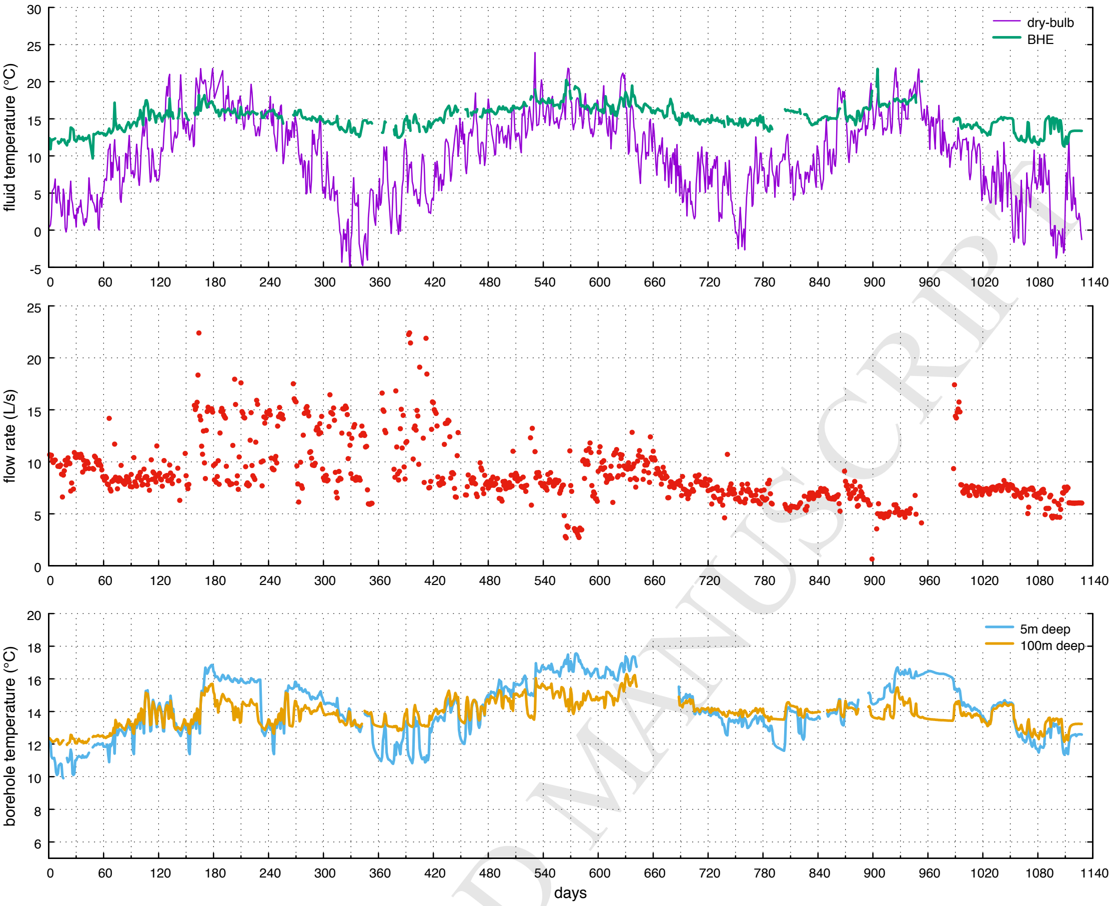

Figure 5: Daily mean temperatures and system flow rates over the monitoring period.

During operation of the system the ground loop return temperature varies between 11 °C and 19 °C and flow temperature changes between 9 °C and 27 °C. The seasonal trends and relationship to climatic conditions are evident, with months showing the highest fluid temperatures corresponding to higher drybulb temperatures. The fluid temperatures are both noticeably higher than the coincident drybulb temperature in winter and lower than the coincident drybulb temperature in summer. A modest year-by-year increase in fluid temperatures can be seen between the first and second years of operation e.g. be comparing the mid-winter minimum or mid-summer maximum temperatures. In the last year of the monitoring period, operation was interrupted due to maintenance issues and overall heat exchange reduced. Accordingly, the fluid temperatures do not show the same upward trend compared to the first two years of operation.

It was noted earlier that the ground loop circulating pump is intended to operate at four nominal levels depending on the number of heat pumps running. The flow rate data in Fig. 5 indicates the ground loop operates the majority of the time at the lowest flow rate (periods with zero flow are excluded from the averaging process). This was commissioned to be 7.5 L/s but can be seen to vary about this value over the whole monitoring period. It was observed that during the middle of the monitoring period (July and August 2011) there were faults in setting the flow rate so that the daily mean falls to approximately 3 L/s. There is a period after day 960 (month 32) where the flow rate falls to zero. This is a period where the system is known to be shut down due to a sub-surface leak found in the ground loop circuit. The flow rate data also indicates that the number of times more than one heat pump is required to meet heating and cooling loads is relatively small. This is reflected in the load-side demands discussed in the related paper on system performance [7].

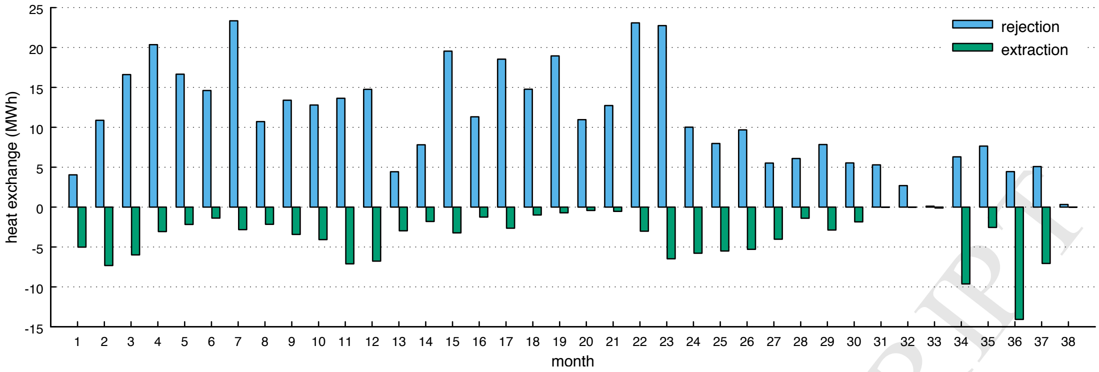

Figure 6: Monthly ground heat exchange over the monitoring period. Month 1 corresponds to January 2010.

Monthly heat extraction, heat rejection, and net heat exchange for the BHE over three years is shown in Fig. 6 and is derived from monthly integration of the minutely heat transfer rates. The lowest monthly heat rejection is 0.27 MWh during September 2012, and the highest is 23 MWh during July 2010. The maximum monthly heat extraction is 14 MWh during December 2012, and the lowest is 0.003 MWh during July 2012. There is persistent heat rejection during the winter as some of the cooling loads are related to spaces with relatively high internal gains. Heat is demanded simultaneously to supply underfloor heating in circulation areas of the building.

When heat exchange is expressed as mean hourly heat transfer rate, the maximum heat extraction was found to be 53 kW and the maximum heat rejection to be 73 kW. These rates are substantially less than the system design capacity (330kW). It is also interesting to consider the maximum heat exchange per unit length of heat exchanger. This was found to be 13.3 $\mathrm{W\,m^{-1}K^{-1}}$ when rejecting heat and 9.4$\mathrm{W\,m^{-1}K^{-1}}$ when extracting heat. These normalized values are rather low compared with other installations and design guides so that it can be said that the BHE is operating well within its limitations and allowing the heat pumps to work in favourable source-side conditions. In this project it was not possible to access the design information to compare performance with the expected temperature limits. It is therefore difficult to comment further on the cause of this favourable situation (in terms of system efficiency) as the building system efficiency and user operating patterns are all sources of significant uncertainty.

4.2. *Thermal Response Testing*

In order to provide sufficient data for application to model validation studies, the effective thermal properties of the boreholes have been evaluated. This has been done by evaluating thermal response test (TRT) data provided by the installation contractor immediately prior to completion of the BHE array. A conventional line-source thermal response model has been applied to the analysis and also a combination of numerical model and parameter estimation methods.

4.2.1. *TRT data*

A borehole at the corner of the array was completed in the same manner as those in the rest of the array and used for TRT purposes. The test fluid for this borehole was water rather than the 20% propylene glycol solution used in the final array installation. The test equipment followed the pattern indicated in Fig. 1. The engineering data relating to the test are set out in Table 2.

Fluid inlet and outlet temperatures were recorded at one minute intervals during the TRT. Although the power input was verified it was not logged continuously nor was the flow rate. More than one test was carried out but the only test used here is one known to be conducted continuously under steady flow and power conditions. The recorded fluid temperatures are plotted in Fig. 7 with the initial few minutes of the test shown on an enlarged time scale. The data from the very early stages of the test show some non-ideal fluctuation in the temperature. These are thought to be due to flushing of stratified fluid from the U-tube. This is not thought to be detrimental as the results for ground conductivity are typically derived from data later in the test [22].

Parameter	Value	Units
Borehole depth	100	m
Borehole diameter	125	mm
Pipe nominal size	DN 32 (SDR-11)	mm
Pipe material	HDPE	-
Pipe thermal conductivity	0.4	$\mathrm{W\,m^{-1}K^{-1}}$
Pipe heat capacity	1805	$\mathrm{kJ\,m^{-3}K^{-1}}$
Grout thermal conductivity	2.0	$\mathrm{W\,m^{-1}K^{-1}}$
Grout depth	25	m
Logging interval	60	seconds
Heating power input	5734	W
Nominal flow rate	0.1	L/s
Test fluid	water	-
Initial temperature	11.7	°C

Table 2: Thermal response test borehole specification.

The use of data from the early stages of the test in the subsequent analysis (i.e. excluding data points for some period when considering the match with the model) is of concern for more than one reason. Firstly, as evident in Fig. 7, the data may be atypical of test conditions and contain spurious transients. Secondly, and depending on the model being applied to the analysis, the response in the initial period can be expected to be mostly sensitive to the properties of components and the geometry of the borehole itself rather than the surrounding ground. The line-source model does not represent the borehole components explicitly and so cant be expected to model the initial hours accurately. Numerical models, in representing the pipes and grout geometry explicitly, should be able to represent this part of the test more effectively although circulation of the fluid longitudinally in the pipe is not represented in most models. Consequently, the sensitivity of the results to excluding different amounts of the initial test data when calculating the SSE or fitting the linear trend lines has been investigated in the following analysis.

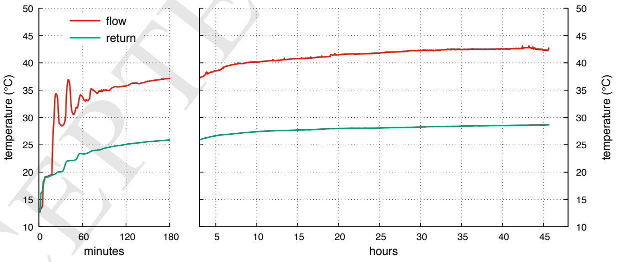

Figure 7: Thermal response test fluid temperatures. The initial period is shown using an enlarged time scale on the left.

Some comment needs to be provided regarding initial ground temperatures and their uncertainty. In analysing the initial TRT data the best estimate of this temperature was found to be 11.7 °C. In later analysis of the initial system fluid temperatures a slightly higher value of 12.3 °C was arrived at. This uncertainty may be due to the differences in the calibration of the instrumentation (no information on calibration of the TRT rig was available) but the higher value at the start of the monitoring period may be due to other reasons. Some points to note are that: (i) the TRT test was carried out with water rather than glycol and at a cold time of year; (ii) instrument calibration may be better in the monitoring system, (iii) there had been several hours of circulating pump operation in the system during commissioning but prior to the start of true operation and monitoring. In the model validation study reported later in this paper we found results to be insensitive to this value. Consequently a value of 11.7 °C. has been used in the TRT data analysis.

It should be noted that as grouting is only completed for the upper quarter of the boreholes, and even though the grout conductivity was specified, the borehole resistance or grout thermal properties predicted by later analysis do not consider any variation of properties with length. Any such estimates can only be viewed as 'effective' values. However, it is conceivable that such variation of properties with length could be considered in other numerical models.

4.2.2. Line-source model parameter estimation

Estimation using a line-source model of thermal response is carried out here by plotting the data on a log-time scale and fitting a linear trend line ($T = a\ln(t)+c$)to find the slope as outlined earlier. The results of this plotting are shown in Fig. 8. A plot using the whole data set and one showing the first ten hours data excluded are shown. The fit with the linear trend can be seen to be more acceptable using only the later data. This could be expected in view of the idealized nature of the heat source representation in the model.

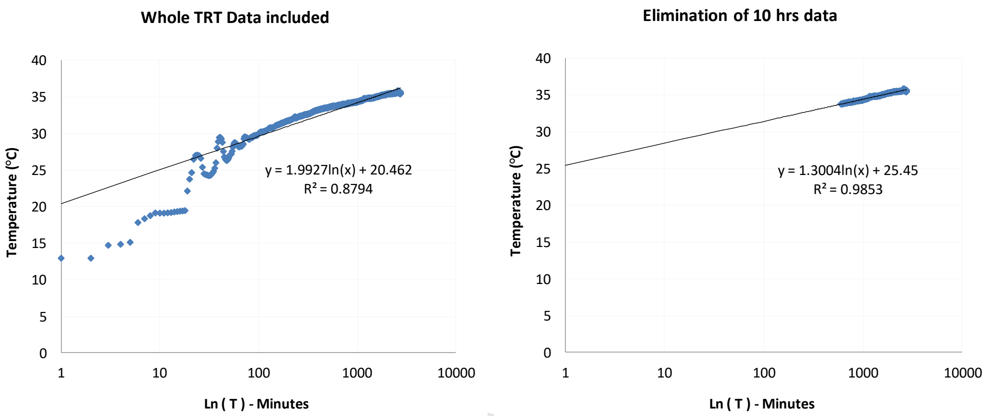

Figure 8: Thermal response test data plotted with a logarithmic time scale and fitted against a linear trend. The upper figure shows all test data included and the lower figure shows an improved linear fit with the first ten hours of data excluded.

Although a logarithmic profile can be fitted to some ranges very successfully, the derived slope and conductivity varies. The results with varying levels of data excluded are shown in Table 3. The exclusion of data beyond three hours was found to have very little influence on the estimated thermal conductivity value. The difference between the estimation by eliminating three and ten hours data is approximately 0.06%.

Number of hours omitted	Slope (a)	Intercept (c)	Regression coefficient (R^2)	Thermal conductivity λ_g^* (W m^{-1}K^{-1})
0	1.993	20.462	0.879	2.291
1	1.556	23.579	0.970	2.933
2	1.446	24.381	0.983	3.157
3	1.383	24.840	0.988	3.301
4	1.344	25.125	0.990	3.396
5	1.316	25.336	0.991	3.470
10	1.300	25.450	0.985	3.511

Table 3: Effective ground thermal conductivity estimates using the line-source response model and varying omission of the initial test data.

4.2.3. Numerical model parameter estimation of two parameters

The parameter estimation approach to the inverse problem with two parameters unknown (effective ground (λ_g^*) and grout thermal conductivity (λ_{gr}^*)) have initially been applied. In these calculations, heat transfer is entirely by conduction i.e. groundwater flow is ignored. The mesh used here has the pipes positioned with an 'average' spacing. Some uncertainty in this spacing has to be accepted as there is nothing to keep the two legs of the U-tube apart or centralized and variation in position along the borehole can be expected. In the test installation it has been noted that only the top of the boreholes are grouted and i compaction of the backfill material in the lower portion of the boreholes is highly uncertain. For these reasons, the grout thermal conductivity estimated must be regarded as an 'effective' value that could potentially be quite different to the stated grout thermal conductivity used at the top of the borehole.

In applying boundary conditions to the numerical model to simulate TRT conditions, the electrical power input is used to specify a fixed flux condition at the inner pipe surfaces. (In general this can be a time-varying value but in this test power was not continuously monitored and a constant value was applied.) The primary output of the model is then the pipe surface temperature. The fluid convective resistance was calculated from the known fluid properties and flow rate so that the temperature differences between the pipe surface and fluid could be calculated and subsequently the mean fluid temperature for comparison with the measured fluid temperatures. In this parameter estimation of the thermal conductivities, the values for thermal capacity have been fixed at mid-range values: 2.39×10^6 J m^{-3}K^{-1} for the ground thermal capacity and 1.85×10^6 J m^{-3}K^{-1} for the grout [33].

Table 4 presents the estimation of λ_g^* and λ_{gr}^* values with the calculated Sum of Square of the Error (SSE) and Root Mean Square Error (RMSE) for different extents of data included in the analysis. Error is defined as the difference between the measured and predicted mean fluid temperature at a particular time step. It can be seen that removal of more than two hours of initial data does not make a significant difference in the estimation of thermal conductivities or the magnitude of the final RMSE value.

Hours omitted	λ_g^* (W m^{-1}K^{-1})	λ_{gr}^* (W m^{-1}K^{-1})	SSE (K^2)	RMSE (K)
0	3.065	0.675	408.3	0.39
1	3.123	0.668	34.77	0.11
2	3.167	0.663	27.48	0.10
3	3.228	0.657	20.38	0.09
5	3.247	0.665	16.49	0.08
10	3.396	0.64	10.63	0.06

Table 4: Effective ground and grout thermal conductivity estimates using the numerical parameter estimation approach and varying omission of the initial test data.

Progress of the Nelder-Meade-O'Neil parameter estimation algorithm with each step is illustrated in Fig 9. This shows the convergence of the thermal conductivity parameters towards their final estimated values and the corresponding decrease in the error levels. In this case the first ten hours of the data were omitted. Initial values of λ_g^* and λ_{gr}^* are fixed far away from expected result to show the process of optimisation which terminates at the 163rd step in this case. It can be seen that the calculated effective grout thermal conductivity is rather lower than the stated 2.0 W m^{-1}K^{-1} of the upper grout material. This relatively low value is not unreasonable given the backfill material is not mechanically compacted in any way and so porosity may be high.

Effective ground thermal conductivity estimates from numerical parameter estimation and line source methods are compared in Fig. 10. This comparison is made for a different number of initial hours of data eliminated. The values generally rise slightly as the number of initial hours omitted is increased. It is noticeable that the range of values calculated using the numerical procedure is relatively small (3.06–3.51) whereas the line source approach has a noticeably lower value (2.29) when all the data is included and a wider range of values overall (2.29–3.51). The possible reasons for this have already been noted—both the limitations of the initial data and the line source model. These comparisons suggest that the numerical approach is more robust due to its explicit representation of the borehole component geometry. The numerical approach should also be more robust due to the fact that it is able to deal with power fluctuations during the test (including combinations of heating/cooling pulse) but this has not been studied here.

The sensitivity of the predicted TRT temperatures to different parameter values has been examined by making

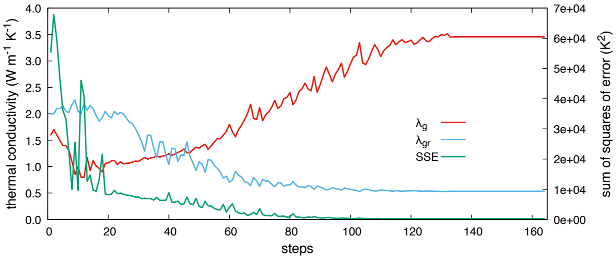

Figure 9: Progression of the parameter estimation process through steps in the Nelder-Mead-O'Neil algorithm (the case with ten hours of data omitted).

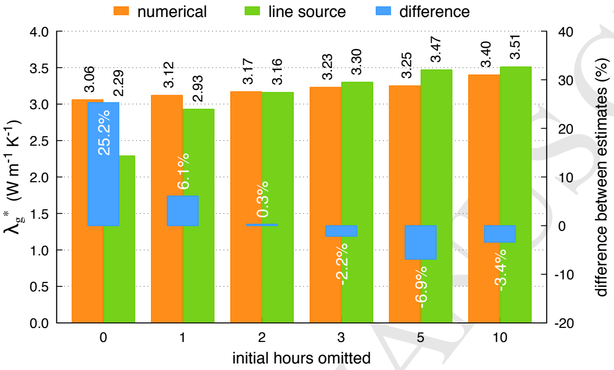

Figure 10: Comparison of ground thermal conductivity estimates made with the line source and numerical parameter estimation methods

direct search of the error space according to different combinations of values of grout and ground effective thermal conductivity [32]. This showed that the impact of a slightly higher value of ground thermal conductivity can be partly offset by lower values in grout effective thermal conductivity. A true minimum point in the error space is identifiable but the error surface is rather flat in the region around the minimum.

Allowing more free parameters in the parameter estimation to see if better results can be obtained was attempted. Table 5 presents the estimated values of the thermal conductivities and heat capacities of the grout and ground with a purely conduction model and again with advection of heat by groundwater flow addd to the model. The predicted thermal response during the test period with these two variations of the model are shown in Fig. 11. The overall conclusion drawn is that the difference in results between the conduction and advection model parameter estimation is insignificant. In fact, the RMSE found after estimating five parameters (0.078 K) was no better than the best case with only two parameters (0.06 K) in this particular case. There therefore seems no particular reason to pursue the possibility of groundwater movement and include it in any models of the BHE array.

After this analysis using either two or four free parameters, there are two estimates of ground thermal conductivity to consider: 3.4 and 3.447 W/m.K in Tables 4 and 5 respectively. These should be associated with two different sets of values for grout conductivity (0.64 and 0.656 W/m.K) and thermal capacity as noted above and in Table 5. It seems the difference between using the two sets of values in a conduction model would be insignificant so that 3.4 W/m.K is a reasonable value for ground thermal conductivity to two significant figures for the installation monitored. If applying these values to a model intended to simulate the heat exchanger array, consistency would require the corresponding thermal capacities be applied.

In making use of TRT data to estimate ground thermal properties for design purposes, the thermal conductivity is usually the primary parameter of interest and thermal capacity is estimated in a more conventional way from knowledge of the geological conditions and reference values for such materials. This is reasonable as system design is firstly a question of understanding the relationship between heat exchange rates and the required fluid temperature in relation to ground temperature gradients. From a mathematical point of view, temperature distribution is driven by a Neumann boundary condition at the borehole wall in which thermal conductivity is the physical parameter in question and thermal capacity (diffusivity) does not appear. Thermal capacities (diffusivities) do appear in the transient form of Fourier's equation defining the long-term behaviour of the ground temperatures however. It is suggested that it is unsurprising that the TRT analysis is not sensitive to the thermal capacity. Is is also suggested that a much longer set of thermal response data would be required to arrive at a parameter estimation method sensitive to thermal capacity. The whole data set arrived at from the monitoring exercise could be used in this way but would require a much greater computational effort when applying a numerical model in parameter estimation—something not attempted in this project.

λ_g^* (W m^{-1}K^{-1})	λ_{gr}^* (W m^{-1}K^{-1})	ground heat capacity (J m^{-3}K^{-1})	grout heat capacity (J m^{-3}K^{-1})	groundwater velocity (m s^{-1})	SSE (K^2)	RMSE (K)
3.489	0.6331	2.30×10^6	2.26×10^6	0.0	20.4	0.086
3.447*	0.656	2.58×10^6	2.70×10^6	0.0	18.8	0.082
2.999	0.6754	2.39×10^6	2.02×10^6	2.00×10^{-6}	16.7	0.078

Table 5: Results of numerical parameter estimation with four and five estimated parameters. One hour of initial data has been omitted. * indicates results with a dense mesh

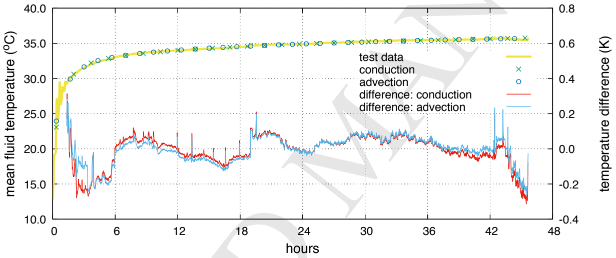

Figure 11: Comparison of the measured TRT mean fluid temperatures and those predicted by the numerical models with the final estimated parameters. Results are shown for the models with and without groundwater effects.

5. Validation case study

In presenting the data from the monitoring exercise an attempt is made to show the utility of the data by applying it in a BHE model validation exercise. The approach is to use the measured flow rates and BHE array inlet temperatures as boundary conditions in the model and to examine predicted outlet temperatures and heat exchange rates in relation to measured values. The aim in this paper is not to put forward a new model or justify its acceptability but rather to show how the data can be used in studies of this type and highlight some unique features that may usefully stress such models. The study presented below highlights two aspects of the data and model behaviour. We firstly examine fluid temperature predictions on short (sub-hourly) time scales. Secondly the long term behaviour and model results in terms of monthly heat exchange over the whole monitoring period is considered.

In many cases BHE models ignore axial fluid transport through the U-tube pipes and make simplified assumptions about the relation between inlet and outlet temperatures and the overall BHE heat exchange rate. In such cases the thermal mass of the fluid and the damping and temporal effects due to fluid transport are ignored [34, 35]. This can be argued to be reasonable for study of long time-scale effects but if there is interest in studying control system interaction and the dynamic behaviour of the heat pump system, such short-term effects are likely to be important.

The model applied here combines a two-dimensional (in a horizontal plane) numerical ffmodel of the borehole with a nodal model of the U-tube pipes [14]. This model uses the numerical model to calculate the borehole and ground heat transfer rates with convective boundary conditions derived from a heat exchanger analogy. This element of the model is combined with nodal models of the pipes to capture the effects of transport delay and diffusion of heat along the pipes. The model accounts for the delay according to fluid velocity and length of circuit and also the thermal mass of the fluid in the pipes. The model was initially validated using data from a borehole array consisting of three boreholes monitored for approximately sixteen months [36]. This model is intended to capture short timescale effects but it is recognized that it may be limited to situations without strong borehole interaction i.e. short to medium timescales and/or well-balanced seasonal loads. In this work an attempt has been made to represent the significant thermal mass and additional delay associated with the near-surface horizontal pipes by applying a multiplier of two (based on simple analysis of the known pipe arrangements) to the U-tube pipe length and related thermal mass.

The two-dimensional nature of the numerical model means that the model is computationally efficient for long timescale analysis. The BHE array in the monitoring exercise in this case has a nominal borehole spacing of approximately 5 m (see Fig. 4). Over the 38 month monitoring period, and given the load is relatively well balanced, a strong interaction between adjacent boreholes is not expected. Hence applying a 2D model of a single borehole to represent the whole array response may be reasonable.

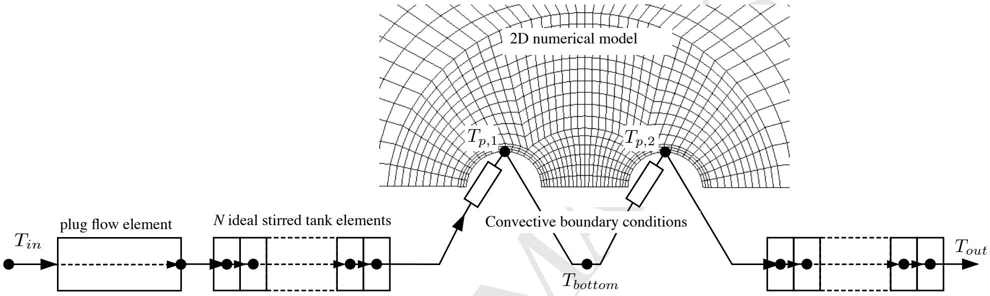

Figure 12: The extended numerical model concept combining a two-dimensional mesh and models of pipe fluid transport in each half of the U-tube (after [14]).

Table 6 shows BHE dimensions along with the properties of the pipe, grout and fluid. Fluid properties are taken to be those of propylene glycol at 20 % concentration and mean temperature of 15 °C. The tabulated values include thermal conductivity and the thermal capacity of soil and grout that have been found earlier using TRT parameter estimation.

Parameter	Value	Units
Initial ground temperature	11.7	°C
Pipe outside diameter	32.0	mm
Pipe inside diameter	26.0	mm
Pipe thermal conductivity	0.4	$\mathrm{W\,m^{-1}K^{-1}}$
Pipe heat capacity	1805	$\mathrm{kJ\,m^{-3}K^{-1}}$
Grout thermal conductivity	0.656	$\mathrm{W\,m^{-1}K^{-1}}$
Grout heat capacity	2576	$\mathrm{kJ\,m^{-3}K^{-1}}$
Ground thermal conductivity	3.4	$\mathrm{W\,m^{-1}K^{-1}}$
Ground heat capacity	2700	$\mathrm{kJ\,m^{-3}K^{-1}}$
Fluid thermal conductivity	0.485	$\mathrm{W\,m^{-1}K^{-1}}$
Fluid heat capacity	3962	$\mathrm{kJ\,m^{-3}K^{-1}}$
Fluid density	1020	$\mathrm{kg\,m^{-3}}$
Fluid dynamic viscosity	0.0024	Pa s

Table 6: The borehole heat exchanger parameter values used in the model validation study.

5.1. *Validation over short timescales*

In order to examine the model performance over short time scales results for one typical summer day from the first year of the monitoring period are presented. The results have been calculated using the same minutely time step interval as that of the monitored data. Figure 13 shows a comparison of fluid temperatures during the whole of June 23, 2010. On this day, inlet temperatures are generally higher than the corresponding outlet temperatures for the whole day so that there is net heat rejection. In general, system operation tends to be very cyclic with often only one compressor being repeatedly turned on and off during the day (see [7] for more comment on this). On this particular day, the flow rate measurement is indicative of two heat pumps operating with some cycles showing three heat pumps coming into operation. During building operating hours of between 8 am to 10 pm the cycle duration is long and there are few periods with zero flow. However, early morning and late at night demands are much lower and the cycle duration is short and intermittent during these periods. During most of the day, with higher system demands and longer cycle durations, the prediction of outlet temperature is very satisfactory. The prediction is less accurate during periods with shorter cycles.

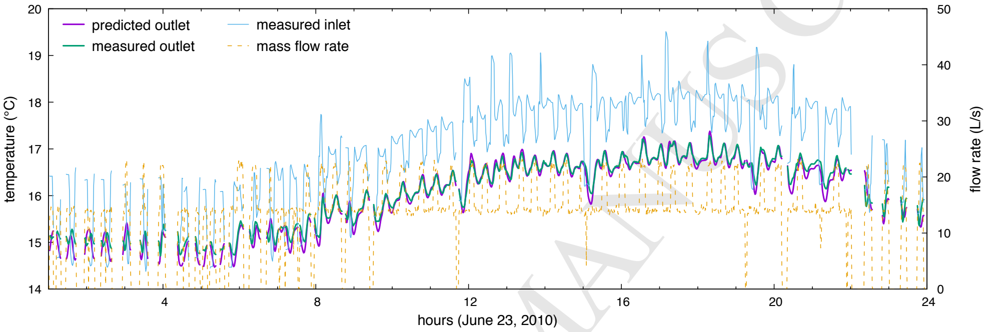

Figure 13: Monitored fluid temperatures and flow rates for June 23, 2010 and predicted outlet temperatures.

The data for June 23 is typical in showing that outlet temperatures do not immediately respond to changes in inlet temperature or flow rate. To examine this phenomena, and the models ability to make corresponding predictions, the hours of 11am to 1pm of June the 23 in Fig. 14 and 15 are presented. In Fig. 14 the heat pump starts a cycle at approximately 11:45am as indicated by the change in flow rate and, a few minutes later, step increase in inlet temperature. It can be seen that the outlet temperature does not increase for several minutes and that the step change profile is not evident. Similarly, the inlet temperature falls shortly after 12pm but this change is not immediately reflected in the outlet temperature. The swings in outlet temperature are clearly damped compared to the inlet temperature over the following cycles.

In Fig. 14 the model results are from a simulation with the two-dimensional numerical model but without any explicit representation of the pipe fluid flow. In this case the inlet temperature is applied to the convective boundary condition of the numerical model and there is no representation of time delay or the thermal capacity of the fluid in the circuit: much as it is in other models and design calculation methods. The predicted outlet temperature response can accordingly be seen to respond instantly. In this case the difference in predicted and measured outlet temperatures in this time range are a maximum of 0.65 K. In Fig. 15 the predictions are those of the complete model including the nodal representation of the pipe flow (as Fig. 12). The predicted outlet temperatures can be seen to be delayed and damped so that the prediction follows the measured response in a much more realistic manner. In this case the difference in predicted and measured outlet temperatures in this time range are a maximum of 0.17 K. This serves to highlight the effect of the significant thermal mass of the fluid and the time delay in circulating the fluid around the hydraulic circuit in a large BHE array. Some transport delay effects were noticed in the study of three BHE at OSU but to a much lesser extent [36, 7].

5.2. *Validation over long timescales*

Examining predictions of long-term heat transfer allows other elements of the model to be stressed and other features of the data to be identified. Over long (seasonal) time scales the effects related to fluid transport discussed

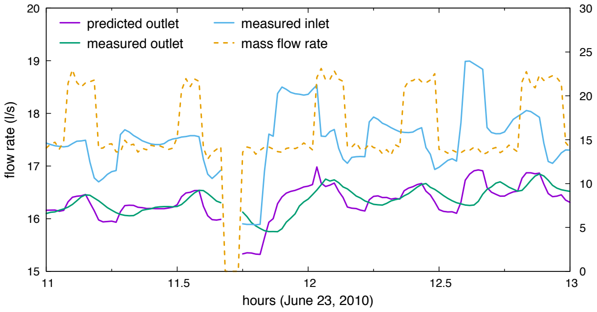

Figure 14: Monitored fluid temperatures and flow rates for 2 hours of June 23, 2010 and predicted outlet temperatures. Fluid transport is excluded from the model in this case.

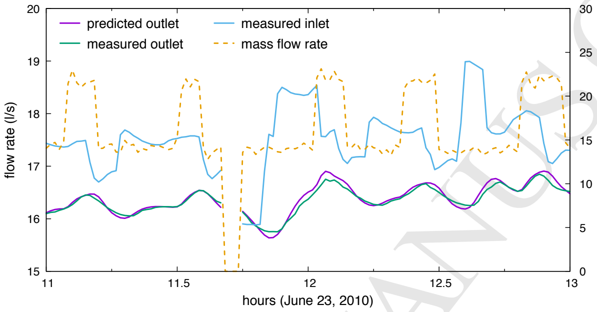

Figure 15: Monitored fluid temperatures and flow rates for 2 hours of June 23, 2010 and predicted outlet temperatures. Fluid transport is included in the model in this case.

above are not expected to be significant. Transient conduction is expected to dominate thermal behaviour and properties such as ground heat capacity are expected to effect overall trends in temperatures and heat transfer rates. In the model applied here, this means the numerical model and the related parameter values are stressed rather than the pipe model.

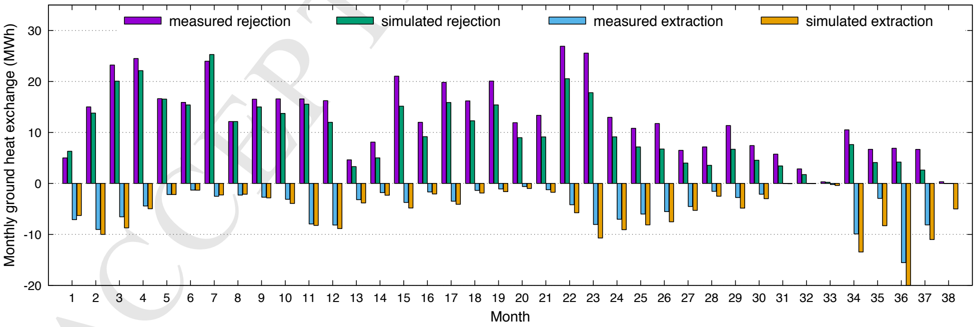

Figure 16: A comparison of modelled and monitored monthly heat reject and heat extraction over the whole monitoring period.

In Fig. 16 the predicted monthly heat exchange over the monitoring period is shown separated into heat extraction and rejection. In most months heat rejection rates are slightly smaller in magnitude than measured values. During the first year the agreement between model results and measured values is generally good. As time progresses, the deviation between model and measured values increases however. In the third year of monitoring the predicted heat extraction is noticeably greater than the measurements suggest. One reason the model may be deficient over longer periods is that all borehole are assumed to respond the same way i.e. without mutual interaction. This was not expected to be a significant limitation given that loads are relatively well balanced during the monitoring period and such effects often take several (five to ten) years to emerge in unbalanced systems. However, it is acknowledged that this may be an issue that could be addressed by a numerical model with multiple boreholes included explicitly or a different approach such as response factor methods.

A noticeable difference in BHE array behaviour between the first and third year of operation is that overall operating hours are reduced. There are more periods with either higher frequency cycles or longer periods with zero flow. There are particular periods where the flow is zero for significant periods. This was due to some leakage problems and the system being effectively shut-down in month 33. This is illustrated by the daily flow rate data shown in Fig. 5.

This deficiency in model fidelity in periods of zero flow raises a number of questions. For obvious reasons there has been little work on what occurs in situations where the fluid in the borehole heat exchanger is static. In this model (as expected in many models) the boundary condition at the pipe (or borehole) is treated as adiabatic when the flow falls to zero. In this situation, heat in the solid domain continues to dissipate by conduction processes: temperatures could be expected to drift towards the mean ground temperature. At the same time, any temperature differences between the pipes (due to short-circuiting effects) would dissipate as temperatures inside the borehole equalize. The numerical model could be expected to predict these effects to some extent.

Effects that are not considered in the model that may be relevant in include: (i) buoyancy effects in the fluid or surrounding ground; (ii) groundwater induced advection of heat; (iii) interaction with the atmosphere. Given that the geological formation contains a lot of clay and that there was no particular evidence of groundwater in the TRT analysis we expect issues (i) and (ii) to be of secondary importance. Conditions at the upper surface boundary with the atmosphere could have effects in firstly changing the bulk heat transfer from the upper layer of the ground and secondly exchanging heat with the near-surface horizontal pipework. We suggest that these issues need further investigation in order to better understand and represent conditions with zero flow. Similar limitations in model accuracy at periods of low or interrupted flow have been noted in other validation studies [11, 36] as noted in the introduction.

Again, the intention has not been to develop a model or prove its validity using the monitoring data in this work. Consequently it has not been the objective to address any of the modelling issues highlighted above by way of alternative modelling approaches or improvements. Rather, the intention has been to highlight some of the features of the data and its utility in such validation studies. It is accordingly suggested that what appears to be the challenging nature of the BHE array behaviour in the later months of the monitoring period is a useful feature of the data set.

6. Conclusions

As design (and cost estimating) methods for borehole heat exchanger systems rely strongly on transient heat transfer models, it is important that such models are validated. The aim in the work reported here has been to evaluate the performance of a relatively large ground heat exchanger system and derive a high quality data set that can be used in model validation studies. The data set is novel in relation to the size of the heat exchanger array considered: 56 boreholes. It is also significant that the data has been recorded with high temporal resolution over a 38 month period since the start of system operation.

The primary data collected for model validation purposes and analysed here are the total ground loop flow rates and the inlet and outlet temperatures. Given the known fluid properties, heat exchange rates have also been presented. Other data such as heating and cooling system loop temperatures and power consumption data has also been made available for open access via an institutional data repository [6] and has been commented on in a related paper [7]. The data presented here has also been used by others in a study of ground heat exchanger design procedures [5].

An overview of the behaviour of the borehole heat exchanger array over the monitoring period has been presented. The thermal conditions are characterised by a modest seasonal increase in temperature over the first two years of operation corresponding to predominantly cooling dominated system loads. On most days there is a demand for both heating and cooling. This is consistent with conditions in a mixed use building in a temperate climate such as the UK university building monitored. Daily minimum and maximum temperatures are within a relatively narrow range suggesting that the heat exchange rates are lower than those anticipated in the design process.

In order to characterize the installation and provide thermal properties data for application in model validation studies, an analysis has been made of data from an initial thermal response test carried out by the contractor. This has given the opportunity to study different approaches to analysing this data to derive effective thermal properties: primarily ground thermal conductivity. It was found that conventional analytical approaches to analysis of the test data were sensitive to the extent of data included. Numerical models were also used in a parameter estimation analysis and considered different sets of free parameters. Parameter estimation procedures were found to be more robust. Inclusion of groundwater flow as an estimated parameter suggested that groundwater advection of heat was insignificant in this system. Although thermal capacities were estimated, results were rather insensitive to the parameter values and so a larger uncertainty in their values is expected. Further work on thermal capacity estimation using longer data sets may be worthwhile to investigate this further.

In order to demonstrate the utility of the measurements as a reference data set for model validation studies, such a study using a recently developed simplified model of a BHE has been made. The study suggests the model has limitations in modelling such an array over long time scales: this was anticipated. More importantly, the study demonstrates some useful characteristics of the data. Firstly, it was found that the thermal capacity of the circulating fluid and the delay associated with transport of fluid around the long circuit had a noticeable effect on outlet temperature response. The model studied here successfully captured these effects but it was demonstrated that simpler models may find this feature of the data challenging to predict. Secondly, longer term prediction of heat exchange rates were more challenging in the third year of operation where there were periods of short operating cycles and interruption to the flow. This raises questions of how thermal conditions without fluid flow are treated by models and whether more attention needs to be paid to the modelling of the shallow horizontal distribution pipes. It is believed that these features of the data set add to its value as a reference in model validation studies and distinguish it from prior studies of small systems. It is hoped that future workers will find the data useful in other studies of BHE array behaviour.

Acknowledgements

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Data Statement

The data collected in this work has been made publicly available at the University of Leeds Research Data Archive `https://doi.org/10.5518/255` [6]. This archive includes the high frequency temperature and flow rate data for each loop along with heat pump and circulating pump electrical demands. Data definitions and error protocols are documented with this data.

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HIGHLIGHTS

Paper title: Long-term high frequency monitoring of a large borehole heat exchanger array

- A large scale geothermal heating and cooling system has been monitored
- A detailed data set has been developed with high-frequency measurements
- Data is being made available from 38 months of monitoring
- Discussion of characterization by TRT analysis is presented
- Application to a model validation exercise is presented and unique features of large system behaviour identified