

Monitoring of a Large Scale Ground Source Heat Pump System

S.Naicker, Dr. Simon Rees

Institute of Energy and Sustainable Development, Queens Building, De Montfort University,
Leicester

Abstract:

Application of Ground Source Heat Pump (GSHP) systems to provide heating and cooling for non-domestic buildings is seen as a viable and effective way of reducing carbon emissions and achieving renewable energy targets. Many experimental and monitoring studies have been concerned with domestic scale GSHP installations. This project is concerned with monitoring the performance of a GSHP heating and cooling system in a large educational building at De Montfort University. This work will provide high quality heat transfer and energy data that will be used for Borehole Heat Exchanger (BHE) model development and validation; heat pump model development; and study of system control and operating strategies. The paper describes the system and the design of the monitoring system. Analysis of the thermal conductivity test data is illustrated and preliminary monitoring data presented.

Key words: Ground Source Heat Pump (GSHP), Borehole Heat Exchanger (BHE), Thermal Response Test (TRT), Ground thermal properties

1. Introduction:

The advantages of Ground Source Heat Pump with regard to carbon emissions reduction and life cycle cost make Ground Source Heat Pump (GSHP) systems a very attractive option in the design of UK non-domestic buildings. The UK has lagged behind other EU countries in applying such technology but recent years have seen the completion of a number of large heating and cooling systems in non-domestic buildings. The Hugh Aston building at De Montfort University is a significant example. A domestic scale trial and monitoring project has recently been completed in the UK but data from non-domestic buildings (both in the UK and internationally) is scarce.

The application of GSHP systems and their optimal design can be improved through use of reliable system design and simulation models. To assess the validity of design models, availability of high quality field data is critical (Yavuzturk.C 1999). This paper describes the design, commissioning and data collection from a monitoring project of a large scale GSHP system at the Hugh Aston Building, De Montfort University, Leicester. The data is intended for used for:

- Large scale system performance evaluation;
- Borehole Heat Exchanger model validation;
- Heat Pump model development;
- Study of system operation and control strategies.

Accurate Estimation of ground thermal properties is critical for proper design of the Borehole Heat Exchangers used in non-domestic GSHP systems. The design tools being used for sizing

Borehole Heat Exchanger (BHE) rely on thermal conductivity data in particular (Austin W.A., 1998; Austin, W.A., C.Yavuzturk, and J.D.Spitler, 2000). In situ Thermal Response Test methods have been developed to ascertain thermal conductivity values for particular installations from test borehole measurements. Such a test was carried out by the contractors at the Hugh Aston building. This paper evaluates the (TRT) data to estimate the ground thermal conductivity that characterises the system. The suitability and reliability of this approach is discussed and application of a numerical parametric estimation procedure is proposed.

2. Background:

2.1 The Hugh Aston Building and its GSHP System

The Hugh Aston building has opened in spring 2010 and is the home of the DMU Faculty of Business and Law. The 15,607m² building includes a variety of accommodation including classrooms, offices, library, retail outlets and large lecture halls (Figure. 1). The building has been designed to be the University's foremost low energy building and has been awarded a BREEAM rating of excellent. The building includes a number of sustainable design features including grey water recycling, solar hot water generation as well as the geothermal heating and cooling system described here. The classrooms have been designed to operate using mixed-mode ventilation that incorporates night ventilation control. The GSHP system provides all the cooling for the building and a proportion of the heating system output.



Fig.1. The North Western elevation of the Hugh Aston Building at DMU

2.2 Ground Source Heat Pump System Operation and Performance

The long term behaviour of the borehole heat exchanger is strongly dependent on the seasonal heating and cooling energy balance. In commercial and institutional buildings cooling demands are dominant and the imbalance between cooling and heating demands result in a gradual increase in ground temperature over several seasons. This rise in temperature has a detrimental effect on overall efficiency and has to be carefully considered

when the heat exchanger is designed. Dominant cooling loads, in broad terms, result in designs with larger numbers of, or deeper, boreholes with consequentially higher costs. The system in the Hugh Aston building provides approximately three times as much cooling than heating and so is certainly cooling dominant.

Yavuzturk, C., and J.D. Spitler (2001) have used the operational data from a school building for model validation purposes. They authors have emphasised the need for continuity in experimental data if it is to be used for validation purposes. They found that the maximum deviations in the entering fluid temperatures were reported where the fluid flow was interrupted and the data were false. They recommended that further work should concentrate on carefully calibrated data collection systems which would monitor the system from beginning of the building operation. This is one of this project's objectives.

2.3 Borehole Heat Exchanger Models

The proper design of GSHP systems requires the application of heat pump and borehole heat exchanger simulation models. Long term transient performance of ground and system components significantly affects the performance of the system. Multiyear simulation of these systems becomes important tool for designing of such systems which can calculate annual building energy load and long term performance of ground thermal response (Fisher, D.E., and S.J. Rees, 2005). A number of BHE and Heat Pump models exist but validation efforts have been limited.

One of the approaches used in a number of BHE model implementations is that developed by Eskilson (Eskilson, 1987). Eskilson's model determines the thermal response of single bore hole to a unit step heat pulse through a two-dimensional explicit finite difference simulation and superimposes this temperature distribution to determine the response in multi borehole configurations. The non dimensionless temperature vs. time characteristic is called a 'g function'. The response of BHE to a unit step function can be used to derive the overall response. This model can provide long term response to the heat extraction and rejection but, as the interior of the borehole is only represented by a fixed resistance, it cannot accurately predict for short term response (Yavuzturk, C., S.J. Rees, and J.D. Spitler, 1999).

A rather different approach to modelling the BHE is to use a fully discretised numerical method. Yavuzturk, C., S.J. Rees, and J.D. Spitler, (1999) have developed a numerical model based on a two dimensional fully implicit finite volume formulation. It can be used for parameter estimation of ground thermal properties and calculation of the thermal response pulses for short time scale heat impulse on the borehole. The short time scale response factors have been used to extend Eskilson's long term response factors (the g-function) and make it useful for short time simulation. Austin, W., C. Yavuzturk, J.D. Spitler (2000) have suggested extending the model to three dimensional with actual representation of borehole geometry using boundary fitted grid.

A three-dimensional numerical BHE model based on the Finite Volume Method (the GEMS3D solver) is being developed at IESD. The model applies the finite volume method to solve general advection- diffusion equation on three dimensional boundary fitted grids. The three dimensional BHE model provides the facility to represent the fluid transport along the pipe and accounts the dynamic responses of circulating fluid. It also provides the facility to represent the different properties of the ground layers and set different initial ground temperatures along the depth (M.He, S.J. Rees, L.Shao, 2009). The data collected in this monitoring project will be used to validate this numerical model.

2.4 Heat Pump Models

Water source heat pumps have been used in building and environmental applications for many years and the modelling of heat pumps has been considered extensively for improved performance. Water-to-water heat pumps are used in the system being monitored. Most models are targeted at the design of heat pump systems and can be classified as deterministic models. Deterministic models are detailed models that represent the thermodynamic and heat transfer behaviour of individual equipment components explicitly. So called 'equation fit models' are widely used in the building energy calculations. This type of model has one or a few polynomial equations that characterise the heat pump performance. These equations are simply fit to commonly available catalogue data (Jin, H, 2002).

One disadvantage of deterministic models is that they need more detail information about the physical parameters and these are not often available for commercial equipment. For equation fit models, one disadvantage is that the model may not be valid beyond the range of the catalogue data used to determine the equation coefficients (Jin, H., and J.D. Spitler, 2002).

A third category of heat pump models is those that rely on parameter estimation. Such models incorporate physical models of the main heat exchanger and compressor components. Values of the component parameters (e.g. compressor displacement) are found using a parameter estimation procedure and catalogue data (Jin, 2002). The parameter estimation process compares model outputs with the full range of catalogue data such as load and source side entering fluid temperature, power consumption, heat transfer rate and flow rates. This type of model can make realistic predictions over a wider range of inputs.

The model developed by Jin (2002) was validated using experimental data from Oklahoma State University and the percentage error between the model prediction and experimental data was 9% for load side heat transfer, 20% for source side heat transfer and 12% for compressor power consumption.

Two things to note about the existing models highlighted above are that they have been developed for single-stage domestic scale equipment and that the models are essentially steady-state. As larger two-stage equipment is used in this project and the data is being collected at relatively high frequency there is an opportunity to develop dynamic models of larger commercial scale equipment and collect corresponding validation data.

2.5 System Simulation and Experimental validation of Ground Source Heat Pump System and Components

The overall performance of GSHP system is dependent on the interaction between the building, the heat pump equipment and the ground heat exchanger. Control system operation is also of importance. There is, accordingly, value in simulating the whole system and incorporate heat pump, heat exchanger and control system component models.

Gentry, J.E., *et. al* (2006) have simulated the performance of Hybrid Ground Source Heat Pump system using the component based simulation software HVAC Sim+. Seven months of five minutely experimental data were used for validation of system simulation. They concluded that best results were obtained using a parameter estimation based heat pump model instead a simple equation-fit model. Yavuzturk, C., and J.D. Spitler (2001) have used the operational data from an elementary school building in Lincoln, Nebraska for validation of short time step ground loop heat exchanger model. The model was simulated as part of TRANSYS environment.

It is proposed that the models validated using the data collected in this project are then used in similar simulation environments to investigate system operating and control strategies. This may be a valuable exercise in view of the complexity of the system and the fact that there are multiple heat pumps.

2.6 Thermal Response Testing and Analysis

The ground properties like thermal conductivity and specific heat capacity of the whole borehole are not directly measurable. These properties have to be derived from secondary measurement like heat transfer rate and temperature in an in-situ Thermal Response Test. A typical Thermal Response Test apparatus includes a power supply, water heaters to impose thermal load on the borehole, pump to circulate the water and sensors to measure flow and return temperatures of the circulating fluid. In the test a constant source of heat is used to increase the temperature of a recently completed test borehole. The heat source is applied over a period of at least 48 hours and the fluid temperatures recorded. The increase in temperature over this period can be correlated with the effective thermal conductivity of the ground. A method of measuring thermal response for the imposed heat flux was initially described by Mogenson (1983). There have been simultaneous developments of testing facilities for thermal response testing in the US by Austin (1998) and in the Sweden by Eklof and Gelin (1996). Thermal Response Test procedures use inverse methods of calculating thermal conductivity using some form of BHE model – usually a very simple analytical conduction heat transfer model. One such analytical model is that used by Ingersoll and Plass (1948). They applied the ‘line source’ analytical model for ground thermal property estimation. A similar ‘cylindrical source’ model (Carslaw and Jaeger, 1947) has also been used for test data analysis.

Austin, W.A., (1998) has used the parameter estimation techniques in conjunction with a two dimensional numerical model to determine thermal conductivity of the ground surrounding borehole. In order to predict the thermal properties of the ground an experimental apparatus has been built to impose heat flux on the borehole and measure temperature response through inlet and outlet fluid temperature. In parameter estimation method, various inputs particularly thermal conductivity, are adjusted systematically to a numerical model representing borehole and surrounding ground such that to the minimum value is obtained for the difference between the actual temperature response and the model- predicted temperature response.

3. GSHP System and Monitoring

3.1 GSHP System:

The Ground Source Heat Pump system at the Hugh Aston Building uses of four reversible heat pumps that supply all of the cooling needs and a portion of the buildings heating demand. The ‘source-side’ of the system consists of the BHE array and header pipes to which the heat pumps add or extract heat as it is circulated. Heat can be added or extracted concurrently by neighbouring heat pumps so that the temperature of the fluid entering the ground loop is dependent of the balance of heating and cooling being demanded at a particular time. The ‘load side’ of the system is divided between warm and chilled water headers and adjacent manifolds. Each heat pump can switch between adding heating water or chilled water to the respective headers. The manifolds are, in turn, connected to the building’s heating and chilled water distribution systems. Chilled water is supplied to the building’s central air conditioning equipment and local Fan Coil Units. Warm heating water is circulated to a number of zones that have under floor heating. The schematic arrangement of the main

components is shown in Figure 2. The heat pump arrangement and ground loop is shown in Figure.3&4.

Fig.2 Schematic layout of the GSHP System with the location of sensors for the measurement

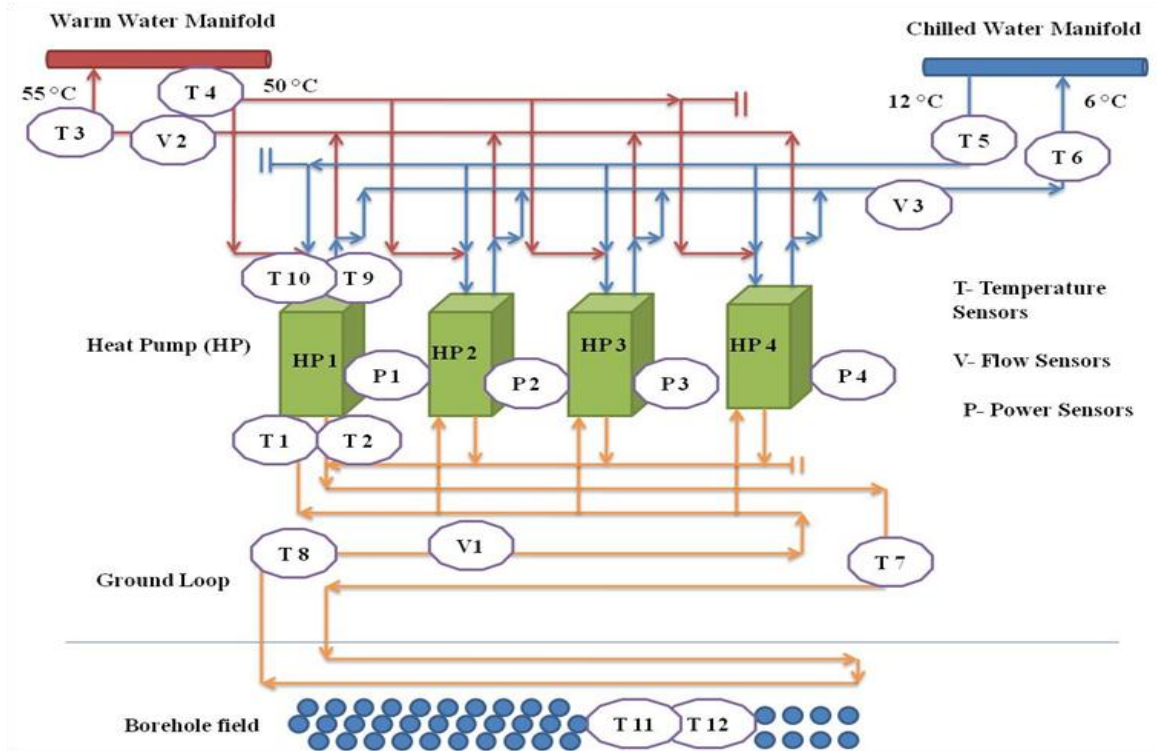


Fig.3. The Heat Pump Installation

Fig.4 The Ground Loop circulation pumps



3.1.1 Heat Pumps:

The System has four Water Furnace EKW130 heat pumps that are two stage reversible devices with two scroll compressors and plate heat exchangers. The rating point data from manufacturer’s catalogue for EKW130 are shown in Table.1

Table.1. Heat Pump EKW130 Ratings:

Capacity	Load Liquid Flow (L/s)	Source Liquid Flow (L/s)	Cooling		Load Liquid Flow (L/s)	Source Liquid Flow (L/s)	Heating	
			LLT 18°C LST 35° C				LLT 35°C LST-3 °C	
			Capacity (kW)	COP			Capacity (kW)	COP
Full	8.5	6.8	172.3	5.4	6.8	8.5	126.6	4.9
Part	8.5	6.8	85.7	5.4	6.8	8.5	65.2	4.9

LLT - Leaving Load Temperature

LST- Leaving Source Temperature

3.1.2 Borehole Heat Exchanger:

The source side of the system is served by 56 boreholes, each with a diameter of 125 mm and depth of 100 meters. The boreholes are in two arrays with 19 located outside the building and the remainder installed below the central courtyard. Each borehole has a U-tube inserted that consists of SDR11 pipe with outer diameter of 32 mm. The borehole is partly backfilled and grouted near the top. Grout thermal conductivity has been specified to be $2.0 \text{ Wm}^{-1}\text{K}^{-1}$. The borehole heat exchanger is served by a variable speed circulation pump with flow rate capacity of 30 l/s. The flow is varied in four speed steps depending on how many heat pumps are operating.

3.2 Instrumentation & Monitoring System

The overall efficiency of the GSHP system can be determined by comparing the heat exchanged with the ground with that delivered to the building – the difference between the two is provided by the refrigeration system compressors. Consequently the main measurements of interest in this exercise are the heat transfer rates in the ground loop and header systems. These are determined by primary measurements of fluid flow and return temperature and simultaneous flow rate. Measuring this data at relatively high frequency also allows the characteristics of the heat pumps and the control system operation to be monitored. Two temperature sensors have been incorporated down one of the boreholes.

3.2.1 Data Acquisition and Logging



Fig.5 Data Loggers – Fluke 2640 NetDAQ and 2635 Data Bucket Data Acquisition Units

Figure 5 shows the Data loggers located in the basement plant room that are used to record the primary temperature measurements. The Data Acquisition Units Fluke 2640 NetDAQ Networked unit and Fluke 2635 Data Bucket are chosen to collect Data over annual periods. The manufacturer’s software packages are used to build the data acquisition units and database, transfer the configuration to the instrument, acquire data from the instrument and manage the data base.

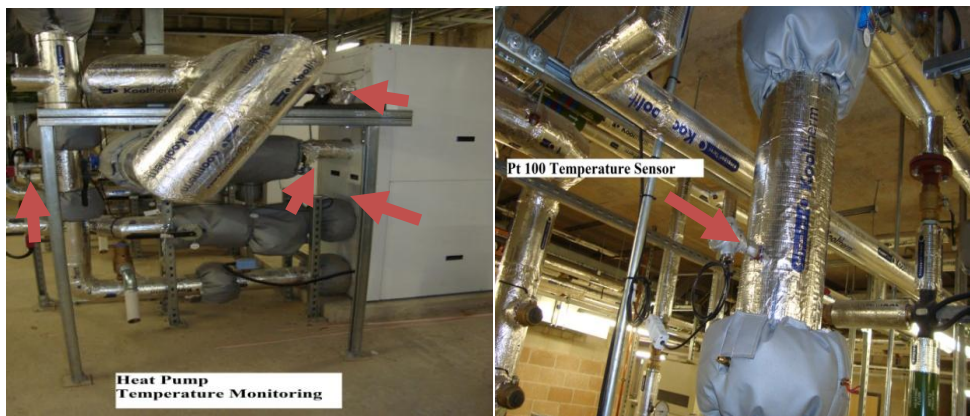
The data logger stores the measured value for every scan in its internal memory and these values are retrieved by a host computer. Each data logger provides 20 channels for measurement. For the RTD Pt100 temperature sensor, the resolution is 0.02°C and accuracy is (3 sigma) $\pm 0.05^\circ\text{C}$ for Hydra logger unit and for NetDAQ unit, the accuracy is $\pm 0.06^\circ\text{C}$

and the resolution is 0.003 °C. Calibration of the whole measurement system is discussed below.

3.2.2 Temperature Measurement:

The temperature measurements are required at inlet and outlet of the borehole field, chilled water header, and warm water header (see schematic in Figure 2). Resistance Temperature Detector (RTD) sensors have high accuracy and repeatability, they are chosen for the primary temperature measurements. The Omega Pt100 DIN head 160mm, 250mm length and 160mm diameter probes are a robust industrial type and are well suited to this plant room installation. Figure 6 shows the temperature sensor placement at the inlet and outlet of source and load sides of the heat pumps. Figure 7 shows the Pt 100 RTD placed at the inlet to the warm water header. The borehole temperatures are measured through consultant installed pre-calibrated 3000 Ohms thermistors. A four wire system is used for sensor connection throughout the installation.

Fig.6&7 RTD sensors at Load and source side of Heat Pump & at Inlet to Warm water header



3.2.3 Flow measurement:

Three ultrasonic flow meters are used for all volumetric flow rate measurements. This type of flow meter has the advantage of being non invasive but also of high accuracy. Ultrasonic waves are transmitted through the wall of the pipe and through the fluid. The signal pulses are received at a second clamp-on sensor. The motion of the fluid causes a shift in the transit time of the ultrasonic pulses that is correlated with fluid bulk velocity. The specification of the Katronic transit type clamp-on flow meter and sensors is listed in Table.2. The calibration of the flow meter has been carried out by the Manufacturer.

Table.2 Ultrasonic Flow meter KAT150 with K1N type sensor specification

Temperature range	(-30)130 °C
Diameter range	503000 mm
Velocity range	0.01... 25 m /sec
Resolution	0.25 mm/sec
Accuracy	1...3 % of measured value and ±0.5 % of measured value with process calibration.
Repeatability	0.15% of measured value ±0.015 m/sec

The sensors are positioned on carefully chosen positions of Ground, Cooling and Heating Loops in accordance with the manufacturer’s guidelines. Each flow meter is configured for the appropriate pipe thickness, pipe material, and fluid properties. Figure 8 shows the sensor placement on heating loop and Figure 9 shows the flow meter display.

Fig.8 Ultrasonic Flow meter Sensor



Fig 9 Ultrasonic Flow meter Display



The measurements are logged into internal memory of the meter and this is periodically downloaded using KAT flow software and RS232 port available at the meter. As the dynamic nature of the GSHP operation is of interest flow measurement data is currently logged every minute.

3.2.4 Temperature Calibration:

In order to minimise the uncertainty in the temperature measurements each sensor has been individually calibrated. This has been done by inserting the sensors in a temperature bath along with a high accuracy reference thermometer and correlating the measurements. A highly insulated container acted as the constant temperature bath and a Fisher Scientific traceable digital thermometer with accuracy $\pm 0.05\text{ }^{\circ}\text{C}$ and resolution $0.001\text{ }^{\circ}\text{C}$ used as a reference thermometer. Sensor readings were recorded using the same Fluke 2640 NetDAQ data logger used in the completed installation. The immersion and positioning of the sensors and thermometer in the bath was carefully controlled. The arrangement of temperature probe in the constant temperature bath is shown in Figure.10. The temperature in the bath was varied in a number of stages between near freezing and approximately $65\text{ }^{\circ}\text{C}$ during the calibration procedure. The sensor and reference thermometer values have been correlated and a linear correction defined for each sensor. The calibration correlation for sensor 9 and 10 is shown in Figure.11. These are very close to linear but show some offset

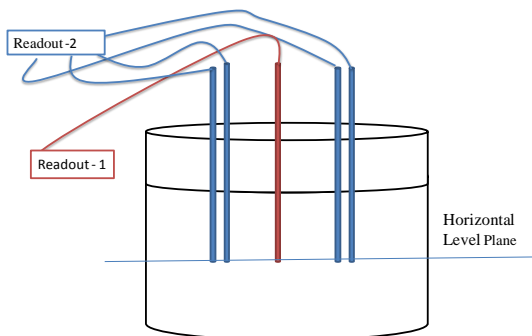
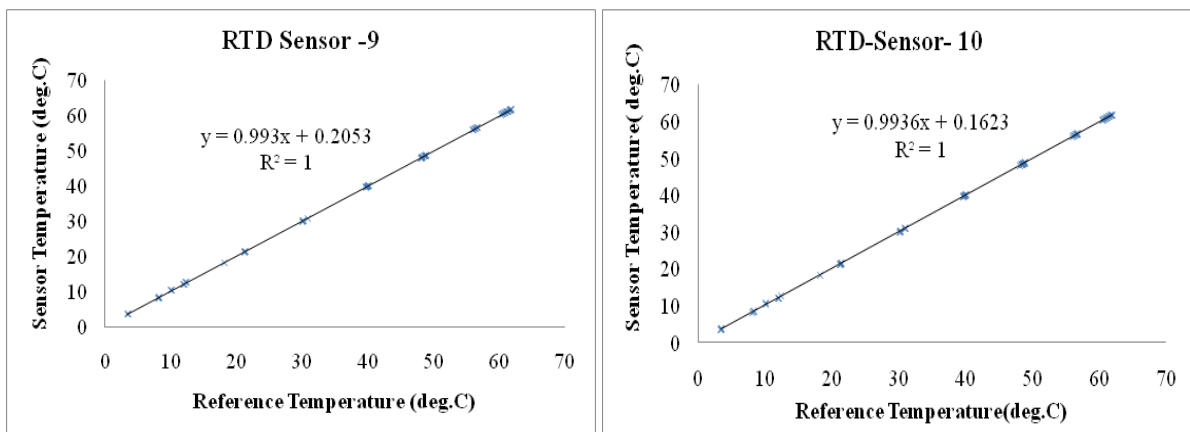


Fig.10.The arrangement of temperature probes in constant temperature bath

Fig.11 Data fitting – Regression analysis for sensor 9, 10



3.3 Details of Preliminary Data Collection:

Data logging started from the beginning of February 2010 during the installation and commissioning of the GSHP system. Some preliminary data analysis has been carried out and is presented here to illustrate what type of data is logged. Figures 12 and 13 present the temperature, flow rate and calculated cooling or heating load over a selected period for the ground loop (BHE) and warm water header respectively. The cyclic operation of the heat pump can be seen. In this period the loads were such that only one heat pump was in use. Figure 14 shows the borehole temperature at 5m and 100m depth and some slight increase in temperature over this period can be observed.

Fig.12 Temperature, flow rate and calculated heat extraction and injection over the chosen period for Groundloop

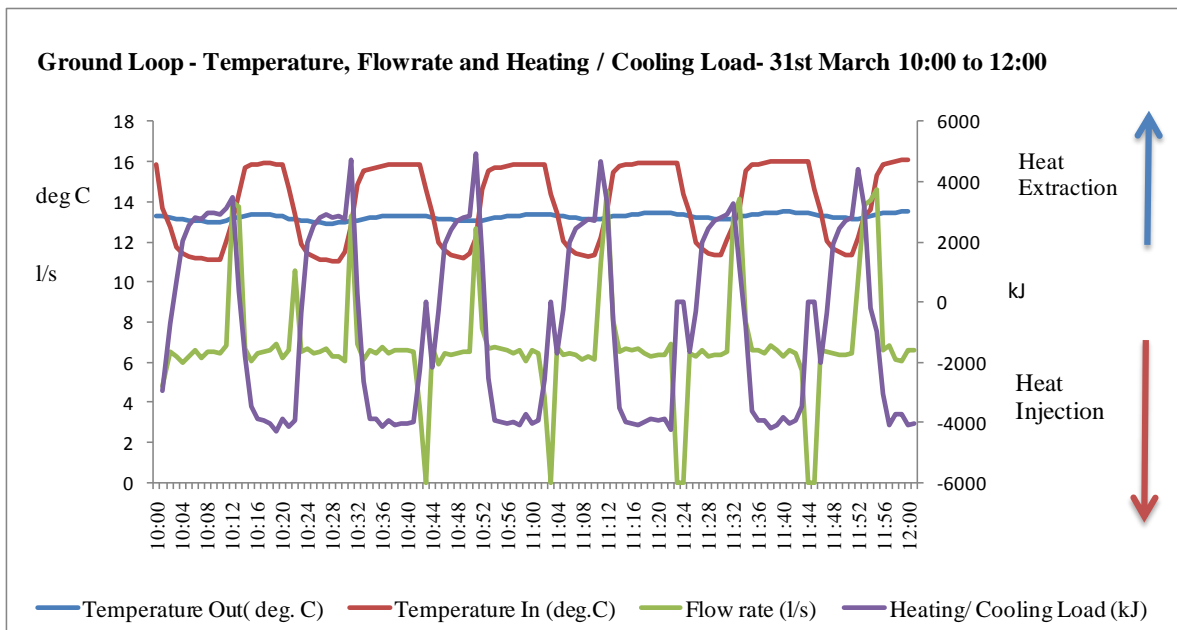


Fig.13 Temperature , flow rate and calculated heating load over the chosen period for Warm water header

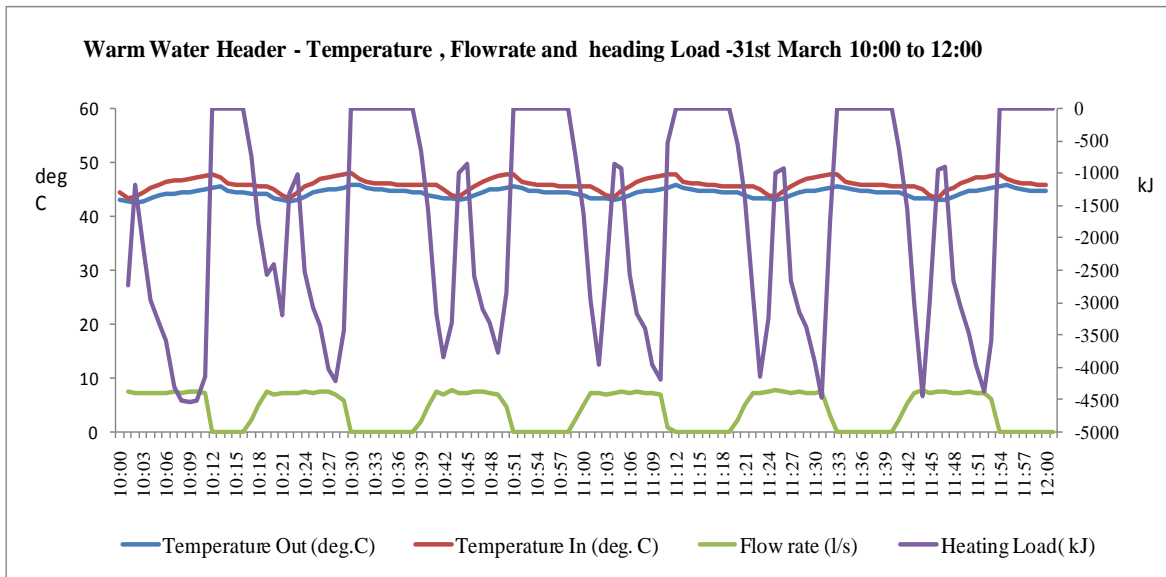
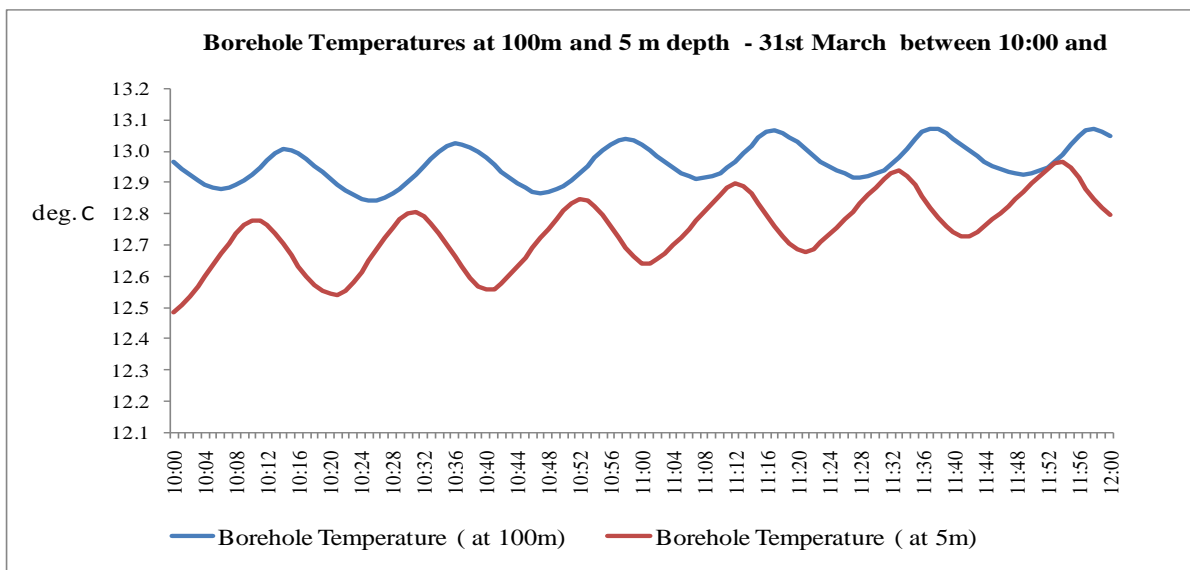


Fig.14 Borehole Temperature at 5m and 100 m depth



4. Estimation of thermal conductivity of the Ground:

The in-situ Thermal Response Test (TRT) data for the borehole field has been supplied by the installation contractor and we have made a preliminary analysis of the data using one of the common analysis methods that uses a line source conduction heat transfer model. The borehole field parameters are set out in Table.3. The test data includes flow and return temperature of the circulating fluid through BHE for the corresponding average imposed thermal power (i.e. heater output).

Table.3: Thermal response Test Data (Supplied by the Consultant)

Borehole diameter	0.125 m
Borehole Depth	100 m
Spacing between pipe	Average

Pipe size	0.032 m
Pipe material & specification	PE SDR11
Grout thermal conductivity	2.0 W m ⁻¹ K ⁻¹
Test Duration	47 hrs
Logging interval	60 sec
Constant Power supply	5734 W

4.1 Line source Model:

The line source model defines a logarithmic relationship between borehole temperature and constant heat input as follows,

$$T_f = \frac{Q}{4\pi KH} \ln(t) + \left(\frac{Q}{H} \left(\frac{1}{4\pi K} \ln\left(\frac{4\alpha}{r_0^2}\right) - \gamma \right) - R_b \right) + T_{sur} \quad \text{for} \quad t \geq \frac{5r_0^2}{\alpha}$$

Where,

$$T_f = \text{Circulating fluid mean temperature} = \frac{T_{in} + T_{out}}{2}$$

Q = Power supplied to circulating fluid (W)

K = Thermal conductivity

t = Start Time

γ = Euler's constant (0.5772)

r_b = Borehole radius

R_b = Thermal resistance (K/ (W/m))

T_{sur} = Undisturbed temperature of the ground

H = Effective borehole depth

α = Thermal diffusivity ($k/\rho c_p$ where c is the thermal capacity) (m²/s)

Analysis of data for the line source model has been done through plotting the average of flow and return temperature against natural log of time. The slope of the plotted trend line is used for estimation of the ground thermal conductivity using the following equation,

$$K = \frac{Q}{4\pi mH}$$

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. It is conventional to exclude some of this data from the analysis. This data often does not follow the same logarithmic trend as later data. Selection of the data in practice remains a matter of judgement for the analyst.

Figure 15 shows the test temperature on a logarithmic time scale with varying number of hours of the data excluded from the curve fitting. It can be seen that it is the data later in the test (after approximately 5 hours) that best fits a logarithmic profile. The logarithmic correlations fitted to different data ranges, and the corresponding thermal conductivity estimations, are shown in Table 4. Although a logarithmic profile can be fitted to a number of ranges very successfully, the derived slope and conductivity varies. This is illustrated in Fig. 16. This suggests that the regression coefficient is not a good indicator of the validity of the analysis. This is to be investigated further.

A numerical parameter estimation approach to estimation of thermal conductivity, similar to that developed by Austin *et al.*, is to be implemented using the numerical model developed by He *et al.* (2009).

Fig.15: The influence of elimination of first hrs data on slope of the regression line

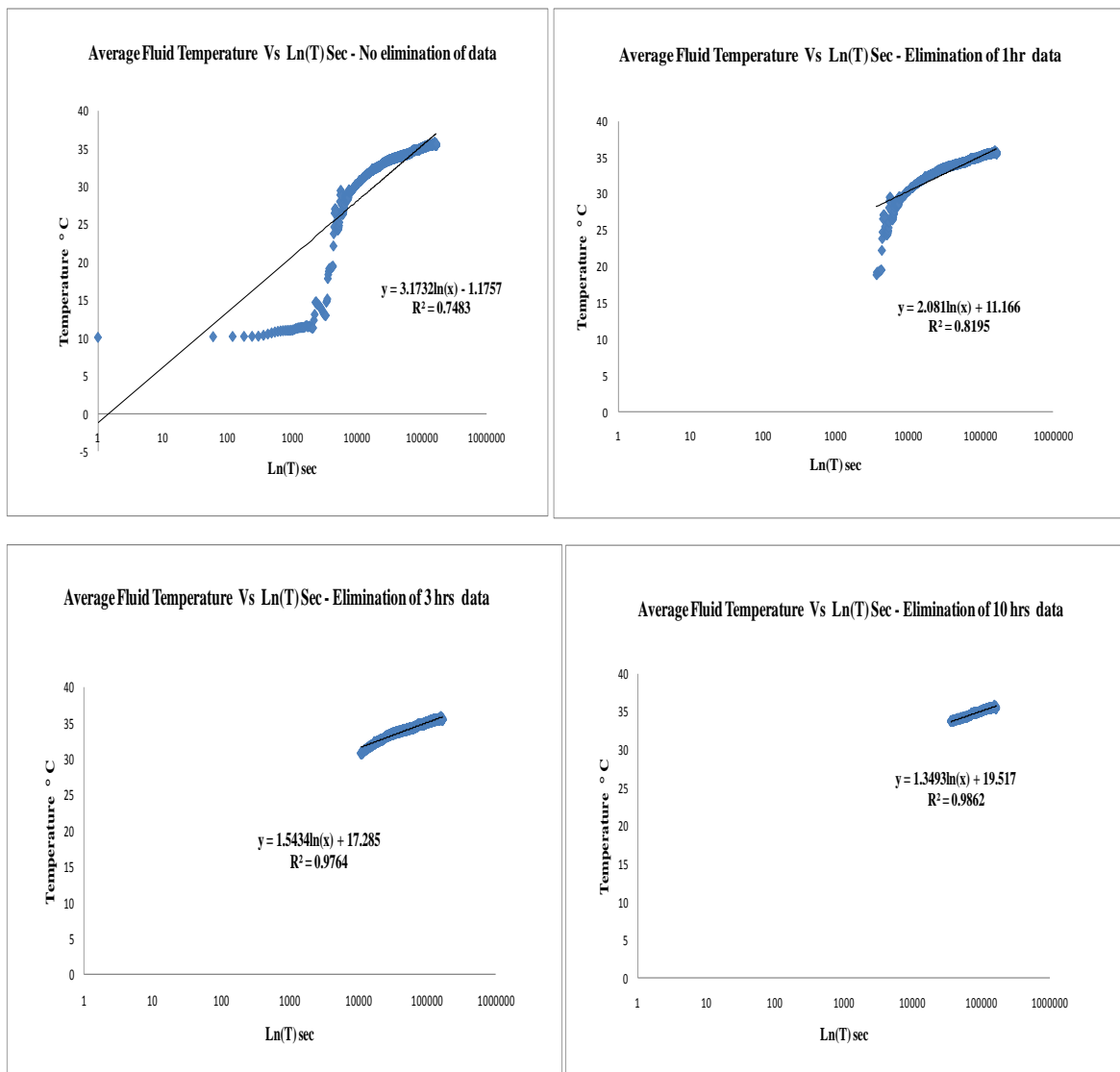
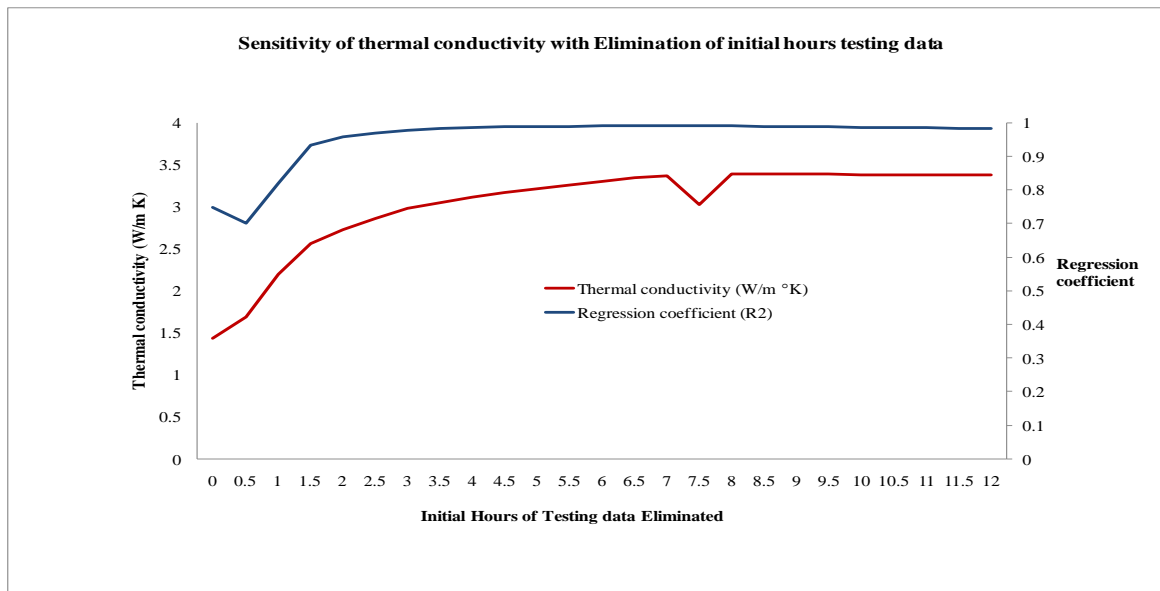


Table.4: The thermal conductivity estimation with hours of data elimination

No of hours Data eliminated	Slope(m)	Intercept (C)	Regression coefficient (R ²)	Thermal conductivity(W/m °K)
0	3.1732	1.1757	0.7483	1.4387
0.5	2.7039	4.1148	0.7004	1.6884
1	2.081	11.166	0.8195	2.1938
2	1.673	15.803	0.9573	2.7288
3	1.534	17.285	0.9764	2.9761
5	1.4188	18.715	0.9883	3.2177
10	1.3493	19.517	0.9862	3.3834

Fig.16: sensitivity of thermal conductivity with first hrs data elimination



5. Conclusions and Recommendations:

The performance of GSHP systems and the operational and first cost can be improved using accurate models in the design process. This paper has explored the necessity of high quality monitoring data and its importance for validation of BHE, heat pump models and system simulations. The GSHP system at the Hugh Aston Building, De Montfort University is being monitored over a three year period to derive data sets that can be used for model development and validation as well as analysis of the buildings performance. Details of the monitoring strategy and instrumentation systems have been discussed and some preliminary data presented. Preliminary analysis of the available thermal response test data has shown some of the inadequacies of the simple method based on the line-source model and the possible value of a more rigorous parameter estimation approach. Further work will include evaluation of overall system performance, application of the data to validation of a BHE model, development of a dynamic heat pump model and also study of system operating and control strategies.

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