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Title of Submission: Design and development of a low-cost thermal response rig

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Abstract

A thermal response test (TRT) is a controlled insitu test during which a known quantity of heat energy is injected into a closed loop heat-exchanger pipe while the heat dissipation rate into the surrounding ground is monitored. Results from a test can be interpreted to determine a number of ground thermal parameters with are vital design requirements for any medium to large scale ground source energy system. This paper describes the design and construction of a low cost TRT rig and compares the results obtained from a test using the constructed rig and a commercially built rig in order to evaluate the accuracy of the constructed equipment. The TRT rig is designed in accordance with the following principles: keep construction costs low, improve the cost-efficiency of TRT testing by incorporating remote data transmission capability and ensure attainment of sufficient accuracy to satisfy the design requirements of ground source energy systems. Analysis of data collected by the TRT rigs result in a calculated thermal conductivity of 1.9 W/mK in both cases. This value falls within the range expected for the tested geological formation and confirms the accuracy of both test rigs.

Keywords: Renewable energy, site investigation, research & development, thermal response testing, TRT, design.

Notations

BHE borehole heat exchanger

D internal pipe diameter (m)

f Darcy-Weisbach friction coefficient

F flow rate (dm^3/s)

g gravitational acceleration (m/s^2)

H depth of the borehole heat exchanger (m)

$h_{fittings}$ head loss due to fittings (m)

h_f friction loss (m head of water)

L length of borehole heat exchanger piping (m)

OD outer pipe diameter (mm)

Q injected heat power (W_e)

$\vec{q}$ local heat flux (W/m^2)

R_b effective borehole thermal resistance (mK/W)

r_b borehole radius (m)

SDR standard dimension ratio

S_{vc} volumetric heat capacity (Ws/l/°C)

t time (s)

$T_{injected}$ BHE injected fluid temperature (°C)

T_{return} BHE return fluid temperature (°C)

T_0 initial undisturbed ground temperature (°C)

$T_f(t)$ temporal evolution of mean fluid temperature

UCD	University College Dublin
v	heat transfer fluid velocity (m/s)
α	thermal diffusivity (m^2/s)
ΔT	temperature gradient (K/m)
γ	Euler's constant (0.5772)
ξ	minor loss coefficient
λ	thermal conductivity (W/mK)

Introduction

Ground source heat pumps can be used to harness low-grade heat from the earth's sub-surface for supply of space heating / cooling and hot water to structures. Ground source energy is currently an exciting and dynamic industry and requires much more investment in training research and development (Boennec, 2008). Ground source energy may be broadly categorized into 'open loop' or 'closed loop' systems. Open loop systems involve pumping water from sources such as lakes, ponds and wells and returning it to either a re-injection well or to a surface discharge system following exchange of heat energy. Closed loop systems involve the circulation of a heat-transfer fluid through pipes which are buried in the ground (or other media) and can range in size from single-borehole installations which could be used to supply space heating / cooling and hot water to single family dwellings or a small office, to large multi-borehole installations suitable for heating / cooling large multi-storey buildings.

Thermal response testing is a fundamental design requirement of any medium to large scale closed loop ground source heating / cooling infrastructure installation (Signorelli et al., 2007, Katzenbach et al., 2009, Wang et al., 2010). TRT's may be used to determine ground thermal conductivity properties and backfill / grout thermal resistance which are in turn used to investigate installation feasibility and to ensure that the installation infrastructure (borehole heat exchangers – BHE's) is appropriately sized to meet the building energy demands. They can also be used in order to determine the initial average ground temperature over the length of a BHE and whether or not a groundwater flow across the site exists (which can have design implications). In contrast to countries with well-established ground source energy industries, current ground source system design practice in Ireland does not routinely involve project-specific measurement of ground thermal properties, often because of the lack of appropriate experience and training of designers and also due to the perceived high cost of the test. This can lead to a situation where designers of ground source energy systems often estimate key thermal properties based on generic published values – while this approach can be acceptable for the design of very small systems, larger systems necessitate a more scientifically rigorous design approach.

The First Thermal Response Testing Rigs

The first mobile insitu TRT rigs were independently developed at Luleå Technical University in Sweden and at Oklahoma State University in the USA in the mid 1990's (see Figure 1) based on the theory that the heat transfer properties of a borehole and of the surrounding ground may be calculated based on data recorded by monitoring fluid temperature changes induced by the injection of heat energy at a constant rate into a borehole heat exchanger. Several other TRT rigs have been constructed since the mid 1990's, however very few publications are available which openly describe the complete design and construction of these rigs (Mattsson et al., 2008).

Figure 1. First mobile insitu TRT rigs a) Swedish test rig, b) USA test rig (images courtesy of Sanner et. al (2005))

Although the TRT rigs shown in Figure 1 were developed as far back as 1995 (Gehlin and Spitler, 2001), the method itself, the necessary equipment and the procedure are still being developed (Saljnikov et al., 2007, Katzenbach et al., 2009). In addition, previous experience has shown that differing results from TRT's have been achieved due to geographic position and composition of soil at given locations (Saljnikov et al., 2007) due to the fact that the thermal conductivity of a material is influenced by its density, temperature, particle shape, porosity, moisture content and mineral composition (Mattsson et al., 2008) and also due to external environmental effects such as ambient air temperature and weather conditions which vary significantly from country to country and can affect the accuracy of test results.

Thermal Response Test Operation

The majority of TRT rigs developed throughout the world operate by means of circulating water in a borehole heat exchanger which is heated at a constant rate by one or more resistance heaters (this is known as the 'constant heat flux' method whereby power injection is kept constant and the difference between the BHE injected and return fluid temperature is allowed to vary). Figure 2 shows the basic test set-up for a constant heat flux method thermal response test, based on the University College Dublin (UCD) rig configuration.

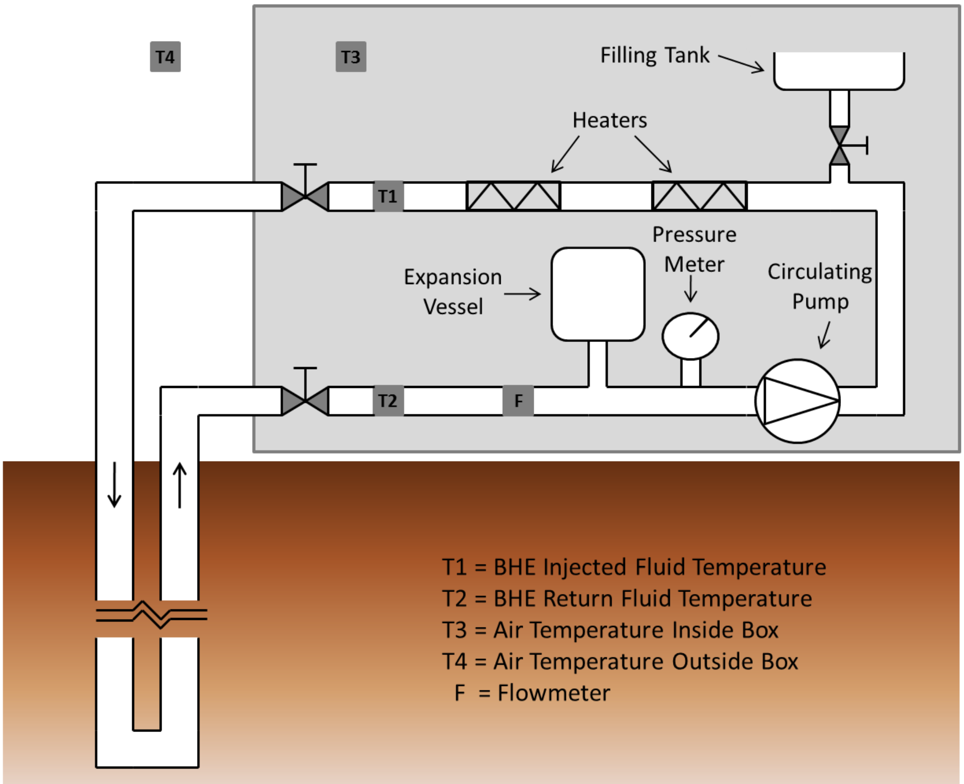

Figure 2. Basic TRT set-up (UCD rig)

An alternative to the constant heat flux thermal response test is the 'constant heat temperature' thermal response test, whereby the power injection is varied during the test so that the difference between the BHE injected and return fluid temperature remains constant (Wang et al., 2009). Although the constant heat temperature method has some advantages over and above the constant heat flux method (such as the potential for improved isolation of test results from environmental effects), recent studies investigating the merits and drawbacks of thermal response testing based on the constant heat temperature method compared to the constant heat flux method have shown that the constant heat flux method is sufficiently accurate to meet the design requirements of ground source heat pump systems (Wang et al., 2010). In addition to TRT rigs based on the constant heat flux method and the limited development of rigs based on the constant heat temperature method, a very small number of rigs have been developed which incorporate the ability to either inject heat or extract heat (Witte et al., 2002), essentially by replacing the resistance heaters with a reversible heat pump. Three such rigs have been constructed worldwide (Sanner et al., 2005).

Published values stating the required thermal response test duration vary significantly and further research in the area is needed (Lim et al., 2007). Several publications state that 36 - 50 hours is a sufficient time frame for a reliable and accurate prediction of ground thermal properties (ASHRAE, 2002, Sanner et al., 2005) while others state that durations of up to 144 hours may be required (Zervantonakis and Reuss, 2006, Sharqawy et al., 2009). This variability in reported test duration requirements is a consequence of the fact that the duration of a thermal response test is defined by the time taken for the circulating fluid to attain a steady state condition with the ground surrounding the borehole heat exchanger – this duration is site-specific. As a consequence, the most common way to determine the required duration of a thermal response test is to have an engineer / trained operative on-site throughout the duration of the test, periodically downloading and analysing test data to check whether or not steady state conditions have been achieved. This requirement to have an engineer / trained operative on-site throughout the test period adds a significant cost to performing thermal response tests. In order to eliminate this requirement, the thermal response testing rig described in this paper has been equipped with remote data transmission capability so that the operative can download and analyse the data from the office.

TRT Evaluation Theory

Fourier's law of heat conduction (Equation 1) forms the theory behind thermal response testing. It states that the temperature response of a forcibly heated or cooled material at a certain location is proportional to its thermal conductivity.

$$\vec{q} = -\lambda \Delta T \qquad (1)$$

where $\vec{q}$ represents a local heat flux (W/m^2), λ represents thermal conductivity (W/mK) and ΔT represents a temperature gradient (°C)). Following performance of a thermal response test, ground thermal properties may be determined using one of several heat transfer models, namely, the analytical line source method (LSM), the cylindrical source model and several other numerical models (Florides and Kalogirou, 2008), each of which is based on Fourier's law of heat conduction. They cylindrical source model and other numerical models are not used to analyse data in this paper and as such will not be described. Readers should refer to publications such as Eskilson (1987), Gehlin (2002), Saljnikov et al. (2007) or Signorelli et al. (2007), among others, for detailed descriptions of these models, and for a more in-depth description of the analytical line source model which will be briefly described in the following paragraphs. The analytical line source method is used to analyse thermal response test results in this paper as it allows direct comparison of ground thermal property measurements collected by the UCD and third party thermal response tests in a clear and uncomplicated manner, relative to the other available methods.

The analytical line source method adopts the analytical solution for the response to unsteady heat conduction applied to an infinite medium with homogeneous and isotropic properties. The approach assumes negligible vertical heat flow along the length of the borehole heat exchanger and constant lateral heat flow so that the temperature field around the borehole heat exchanger is only dependent on time and radial distance from the borehole axis (Signorelli et al., 2007).

Equation 2, where λ is defined in Equation 3 and m is a constant, can be written to describe the temporal evolution of the mean fluid temperature $T_f(t)$ (i.e. the average of the injected and return fluid temperature with respect to time) during the test. The effective thermal conductivity (λ) of the ground formation is calculated by plotting a graph of the mean fluid temperature against the natural logarithm of time, determining the slope (k) of the linear portion of the graph and substituting into Equation 3 where Q (W_e) is the injected heat energy over the duration of the test and H (m) is the depth of the borehole heat exchanger. Equation 3 is valid only when the lower time criterion described in Equation 4, where t is time (s), r_b is the borehole radius (m) & α is the thermal diffusivity (m^2/s), is achieved. The lower time criterion attempts to account for the fact that the temperature development of the BHE (i.e. the portion of piping installed below the ground surface) system is mainly influenced by the borehole backfilling and not the surrounding soil during the early stages of thermal energy flux application.

$$T_f(t) = k\ln(t) + m \qquad (2)$$

$$\lambda = \frac{Q}{4\pi kH} \qquad (3)$$

$$t > \frac{5{r_b}^2}{\alpha} \qquad (4)$$

The analytical line source theory assumes that heat transfer in the ground in the vicinity of the borehole during a test can be assumed to be purely conductive, radial in direction and constant along the borehole, therefore the borehole heat exchanger can be approximated by a line source. The rise in temperature at any distance (r) from the borehole centre (or 'line source') at time (t) after the commencement of constant injected heat power (Q) may be calculated by means of Equation 5 (edited from Florides and Kalogirou (2008) after Ingersoll and Plass (1948))

$$T_f(t) - T_0 = \frac{Q}{4\pi\lambda H}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = \frac{Q}{4\pi\lambda H}E\left(\frac{r^2}{4\alpha t}\right) \qquad (5)$$

where u is an independent variable and E is the so-called exponential integral which can be approximated by the expression shown in Equation 6 for large values of the parameter $\alpha t / r^2$. The maximum error associated with the expression shown in Equation 6 is 10% when $\alpha t / r^2 \geq 5$, and reduces to 2.5% when $\alpha t / r^2 \geq 20$ (Florides and Kalogirou, 2008, Gehlin, 2002), thus the accuracy of the expression increases as the heat flux progresses further beyond the borehole wall (note that the error referred to here is that which relates to the use of the expression shown in Equation 6 only, errors which may eventuate from the performance of thermal response tests in the field are therefore additional to this error). The velocity of the heat flux is dependent on the ratio between thermal conductivity and heat capacity of the ground i.e. the ground thermal diffusivity (α).

$$E\left(\frac{r^2}{4\alpha t}\right) = \ln\left(\frac{4\alpha}{r^2}\right) - \gamma \qquad (6)$$

The approximation shown in Equation 6 is then substituted into Equation 5, introducing an additional term (QR_b / H) to take account of the spatial dimension of the BHE (i.e. because the BHE is not an infinite line source, but a solid cylinder with thermal resistance R_b) and by taking the line source temperature at the borehole radius ($r = r_b$). This allows transcription of an Equation in linear form which describes the evolution of the mean fluid temperature (Equation 7, edited from Esen and Inalli (2009)):

$$T_f(t) = \frac{Q}{4\pi\lambda H}\ln(t) + \frac{Q}{H}\left[\frac{1}{4\pi\lambda}\left\{\ln\left(\frac{4\alpha}{r_b^{\,2}}\right) - \gamma\right\} + R_b\right] + T_0 \qquad (7)$$

where γ is Euler's constant (0.5772), R_b is the effective borehole thermal resistance (mK/W) and T_0 is the initial undisturbed ground temperature (degrees Celsius). Equation 7 can be rearranged with respect to the effective borehole thermal resistance to form Equation 8.

$$R_b = \frac{H}{Q}\left[T_f(t) - \left\{\frac{Q}{4\pi\lambda H}\right\}\left\{\ln(t)\right\} - T_0\right] - \frac{1}{4\pi\lambda}\left[\ln\left(\frac{4\alpha}{r_b^{\,2}}\right) - \gamma\right] \qquad (8)$$

Equation 8 may then be used to calculate the effective borehole thermal resistance for each time step of the test and consequently a mean value can be determined to represent the tested borehole heat exchanger. It is important to note that the results obtained from thermal response tests using the evaluation theory described previously are only valid for use in ground source energy system design if a high groundwater flow is not present at the site. Excessive groundwater flow across the BHE results in a calculated thermal conductivity value which includes convective heat-transfer effects, resulting in a 'masking' of the true thermal conductivity of the formation and therefore rendering the results unusable for system design. Results obtained from a test can be evaluated to assess whether or not a high groundwater flow exists by using the evaluation theory described previously, and calculating a value for thermal conductivity in stepwise fashion. In cases where no or low groundwater flow conditions exists, the value obtained for thermal conductivity should converge to a steady-state within a few hours. In cases where high groundwater flow exists (depending on the magnitude of the flow) the value obtained for the thermal conductivity may not converge to a steady state value or may result in a value for thermal conductivity which is excessively high relative to what would be expected. Banks et. al (2009) found the phenomena of excessively high values of apparent thermal conductivity to exist in three out of 26 thermal response tests carried out in the UK.

UCD TRT Rig Component Selection

Components for the UCD TRT rig were selected on the basis of ensuring the rig is capable of operating with sufficient accuracy to satisfy the design requirements of ground source heat pump systems, ensuring the selected components could operate over the range of testing conditions likely to be encountered and lastly with due regard to cost control. The total cost to construct the UCD thermal response testing apparatus was €4,900 – this cost is significantly below the current purchase price of thermal response testing rigs which is in the region of €48,400 (Based on a quotation received from a TRT manufacturing company). The TRT rig described differs from many previously constructed rigs in that it: (i) is constructed with readily available off-the-shelf components rather than specially manufactured components; (ii) is equipped with remote data transmission capability, (iii) monitors ambient air temperatures inside and outside the rig enclosure in order to provide improved confidence in the effectiveness of the thermal insulation used and hence the accuracy of test interpretation; and (iv) is designed and constructed wholly by the primary author of this paper which aids in ensuring a full and well-rounded understanding of any anomalies in test results while also demonstrating that specialist manufacturing skills need not be procured in order to construct a functioning TRT system.

This section of the paper provides an outline of the main design calculations & considerations carried out during the selection of the primary components used in the construction of the rig. Table 1 lists, describes and outlines the operational range and accuracy of the various selected components.

Table 1. Component summary

Component	Description	Range / Accuracy
Circulating pump	Grundfos Magna 2000 Series	See pump curve (Figure 3)
Inline heaters	Omega FTH Series (3 & 6 kW)	3 kW, 6 kW & 9 kW
Flow meter	Omega FV103	Range : 0 to 1.58 L/s Accuracy: ± 2% of full scale flow
Water temperature sensors	Pt100 Class A	Range: - 200 to 350 ^{o}C Accuracy: Approx. ± 0.2 ^{o}C
Air temperature sensors	Pt100 Class A	Range: - 50 to 100 ^{o}C Accuracy: Approx. ± 0.2 ^{o}C
Data acquisition system	NI cRIO-9074	Range of measurement types is dependent on modular instrumentation systems installed
Data transmission system	Dovado 3GN router	Download speed up to 24Mbps
Piping system & fittings	Primarily UPVC Class E	Max pressure 15 bar

The data acquisition system is connected to a data transmission system (essentially a router with a wireless broadband connection) so that results from a thermal response test may be uploaded to a server periodically. The test operative may then log in to the server from any location and download the test data for analysis. Assuming that no operational issues are encountered on site, this capability allows the test operator to periodically download and analyse the test data from the office and travel to site when they are satisfied that steady state conditions have been achieved.

Circulation Pump Selection

The circulation pump was sized such that it could overcome head losses due to circulation through the TRT rig and BHE piping in addition to providing some excess capacity. An important design consideration for the circulation pump was ensuring that it had the capacity to operate over a range of BHE depths and BHE pipe diameters and with a range of different heat transfer fluids if necessary. As such, the heat transfer fluid velocity (v, m/s) used in the sizing calculations was selected on the basis of doubling the minimum required flow rate required for turbulent flow conditions for each of the pipe diameters under consideration. The frictional head loss (termed ‘major loss’) on the heat transfer fluid (typically water in the case of the UCD TRT rig) due to flow through a borehole heat exchanger pipe was estimated using Darcy’s formula which is shown in Equation 9. The length of the test BHE piping ('L' in Equation 9) used in the calculations was 400 m such that BHE depths of up to 200 m may be tested.

$$h_f = \frac{fLv^2}{2gD} \qquad (9)$$

where h_f is friction loss (m head of water), f is the Darcy-Weisbach friction coefficient (dimensionless), g is gravitational acceleration (assumed to be 9.8 m/s^2) and D is the internal diameter of the pipe under consideration (m). The Darcy-Weisbach friction coefficient was calculated using the Blasius equation ($f = 0.316 / Re^{0.25}$) for turbulent flow as described in Chadwick and Morfett (1998). The Reynolds Number (Re in the Blasius equation) was calculated for each pipe diameter shown in Table 2 so that the flow in the pipe remained turbulent at all times.

The head loss due to fittings (termed 'minor loss') was estimated using Equation 10. The major and minor head losses were then added to give a value of total head loss (in m head of water) for the range of pipe diameters and design flow rates considered (shown in Table 2, where SDR is the standard dimension ratio of the respective pipes i.e. the ratio of the outside diameter of the pipe to the pipe wall thickness).

$$h_{fittings} = \frac{\xi v^2}{2g} \qquad (10)$$

where $h_{fittings}$ is the head loss due to fittings (m) and ξ is the minor loss coefficient of the fitting under consideration.

Table 2. Head loss at design flow rate

Pipe OD (mm)	SDR	Design Flow Rate (m^3/hr)	Minor Loss (m)	Major Loss (m)	Total Head Loss (m)
50	18	1.01	5.11	0.53	5.64
40	16	0.79	3.59	1.09	4.68
32	16	0.65	2.59	2.21	4.80
25	16	0.50	2.03	4.60	6.63

Figure 3 shows the pump curve for the selected circulation pump. A vertical dashed line is super-imposed onto the Figure starting at the x-axis (at flow of 1.01 m^3/hr), drawn upwards on the Figure and brought horizontally across to the y-axis at the point of pump curve interception. This simple sketch indicates that the pump is capable of overcoming a head of approximately 10.8 m at a flow rate of 1.01 m^3/hr which compares favourably with the requirement for the pump to overcome a total head loss for a 50 mm OD pipe of 5.64 m as shown in Table 2. A similar exercise can be carried out in order to show that the selected pump has sufficient capacity for the potential range of pipe diameters and BHE lengths considered.

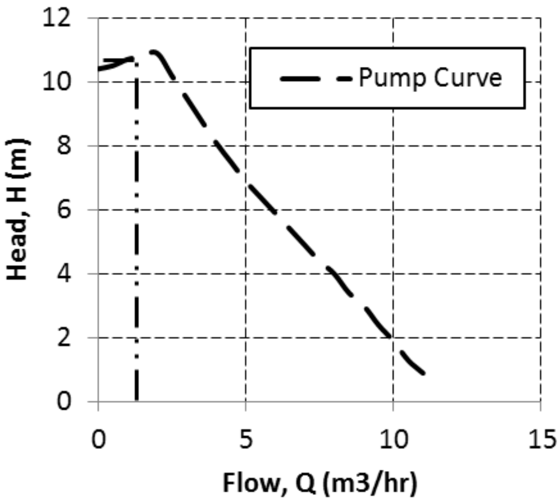

Figure 3. Pump curve for selected circulation pump

Heating Element Selection

Inline water heaters for the rig were selected in order to allow speed of installation, ensure that the heat transfer fluid had a relatively inhibited channel through which to pass and to provide a solution which would provide good heat transfer from the heating elements to the circulating fluid. Differing borehole heat exchanger depths, configurations and site specific conditions mean that an in-built heat input flexibility is an important element for TRT rig design. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2002) suggest that thermal response tests should be carried out with a heat input rate of 15 to 25 W/ft (50 to 80 W/m) of bore depth in order to reproduce the impact of typical loads on actual ground loops. The draft guidelines produced by Sanner et. al (2005) for the working group of Annex 13 of the International Energy Agency's 'Implementing Agreement on Energy Conservation through Energy Storage', suggest values of applied thermal load of 30 W/m for low conductivity formations and 80 W/m for high conductivity formations. In order to address this issue, two heaters rated at 3 kW and 6 kW were installed in series allowing testing to be operated at 3, 6 or 9 kW heat input rates. This means that if testing in accordance with one of the previously suggested heat input rates, the UCD TRT rig would be capable of testing ground depths ranging from 37.5 m to 180 m or 37.5 m to 300 m respectively. Figure 4(a) shows the layout of the UCD rig at completion stage. Figure 4(b) shows the rig in operation on a site in Norfolk in the UK and gives the reader an indication of the scale of the system.

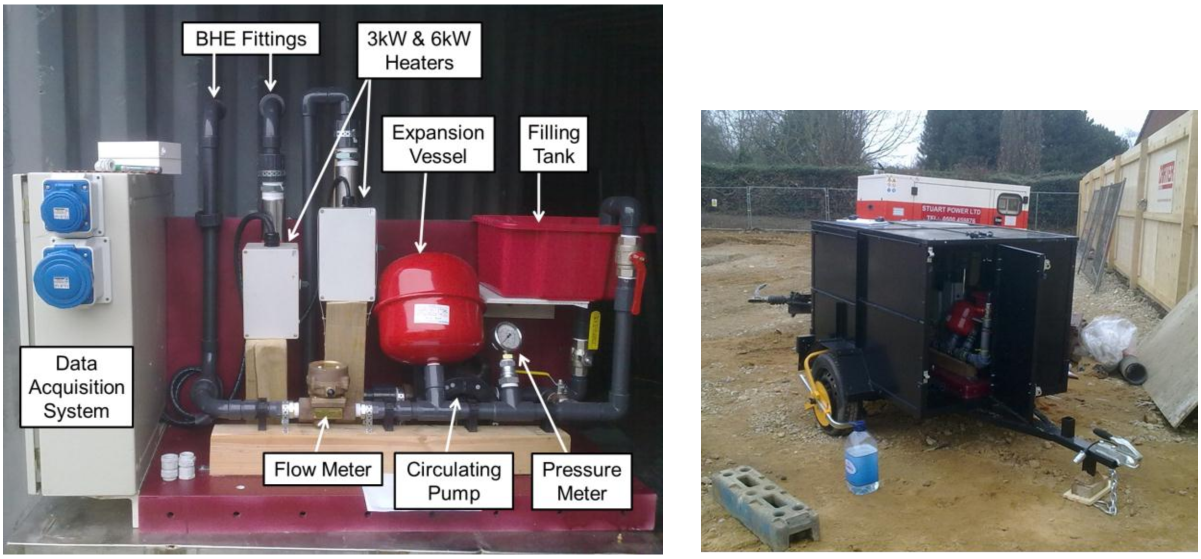

Figure 4. UCD TRT rig (a) at completion of construction and (b) operating on-site

Test Set Up Details

Two TRT rigs, denoted 'UCD TRT rig' and 'third party TRT rig' in this paper, were brought to the test site in the UK in February 2011. The test set up for each of the TRT rigs is described in Table 3. Both rigs operated at their respective full heating power capacities and tested boreholes using the same heat transfer fluid, pipe configuration, pipe diameter, pipe thickness, pipe material, borehole diameter, backfill material and borehole heat exchangers of similar depth. In both cases, the heat power supplied to the borehole heat exchanger (Q) is calculated using equation 11 where $T_{injected}$ is the BHE injected fluid temperature (°C), T_{return} is the BHE return fluid temperature (°C), F is the flow rate in the BHE (dm^3/s) and S_{vc} is the volumetric heat capacity (Ws/l/ °C) of the circulating fluid.

$$Q = (T_{injected} - T_{return}).F.S_{vc} \qquad (11)$$

Table 3. Test set up

Parameter	UCD TRT rig	Third Party TRT rig
Heater power input (Q)	9 kW	9.8 kW
Flow rate	0.57 L/s*	0.42 L/s
Heat transfer fluid	Water	Water
Test duration (t)	5.5 hrs	15 hrs
Pipe configuration	Single U	Single U
Pipe depth (H)	201 m	201 m
Pipe outer diameter	40 mm	40 mm
Pipe wall thickness	3.7 mm	3.7 mm
Pipe material	Polyethylene	Polyethylene
Borehole diameter	140 mm	140 mm
Backfill Material	Pea gravel	Pea gravel

**Note: In the case of the UCD TRT rig, the flow rate in Table 3 refers to the flow rate at the start of the test. The flow reduced slightly as the test progressed and was recorded as 0.44 L/s at the end of the testing period (see Figure 6 for a profile of the flow rate during the test) due to thermal expansion of the borehole heat exchanger pipes and the associated drop in system pressure – this is further explained in the results section.*

The test site was located in Norfolk in the east of the UK. Ground conditions consisted of made ground from 0 to 1 m, sand and gravel from 1 m to 21 m, soft fractured chalk and flint from 21m to 75 m and firm chalk and flint from 75 m to 204 m below ground level. A review of literature (Bowden and Lees, 2010, Read et al., 2007) reveals that this is broadly in line with the ground conditions that would have been expected in the area. Water was struck at 23 m below ground level and the water standing level was also 23 m below ground level. The borehole was drilled using a drilling rig with a 140 mm diameter rock roller drill bit to a depth of 204 m below ground level. The u-shaped borehole heat exchanger pipe was installed to a depth of 201 m below ground level. A 152 mm casing was used to a depth of 27 m below ground level, below which the formation did not require casing. Weather conditions were generally good for the duration of the thermal response tests except for a small amount of light rain falling towards the end of the testing regime.

Quoted values for the thermal conductivity of chalk are reported to be in the range 1.25 to 2.33 W/mK (Rollin, 1987, Busby et al., 2009, Headon et al., 2009) and of limestone (chalk is a form of limestone) are 1.5 – 3.0 W/mK (Banks, 2008). The thermal conductivity of moist sand falls in the region of 1.0 W/mK. A depth weighted average thermal conductivity can be calculated to provide an initial estimate of the expected thermal conductivity of the ground formation. This results in an anticipated thermal conductivity value in the range of 1.2 to 2.8 W/mK. A thermal response test would likely confirm that the thermal conductivity of the formation lies within the range previously stated, however in accordance with standard ground source system design practice, a single estimated value is required. A weighted average is again calculated, taking a value of 1.0 W/mK for the first 21 m below ground level and a value of 1.8 W/mK from 21 m to 201 m below ground level. This results in an initial estimated thermal conductivity value of 1.72 W/mK.

Thermal Response Test Results

The initial ground temperature can be calculated by either circulating the heat carrier fluid around the TRT rig and borehole heat exchanger prior to commencement of heating or by lowering a temperature meter down the length of the borehole and manually logging temperature readings at set intervals (Gustafsson, 2009, International Ground Source Heat Pump Association, 2008). In this case, both methods were carried out in order to check the accuracy of the fluid temperature probes installed on the TRT rig. The temperature profile generated from lowering a temperature meter down the borehole (shown in Figure 5) results in an average temperature of 11.33ºC. The initial temperature as measured by the UCD TRT rig compares well with a value of 11.28ºC. This initial temperature value is used later in the design process for ground source energy systems.

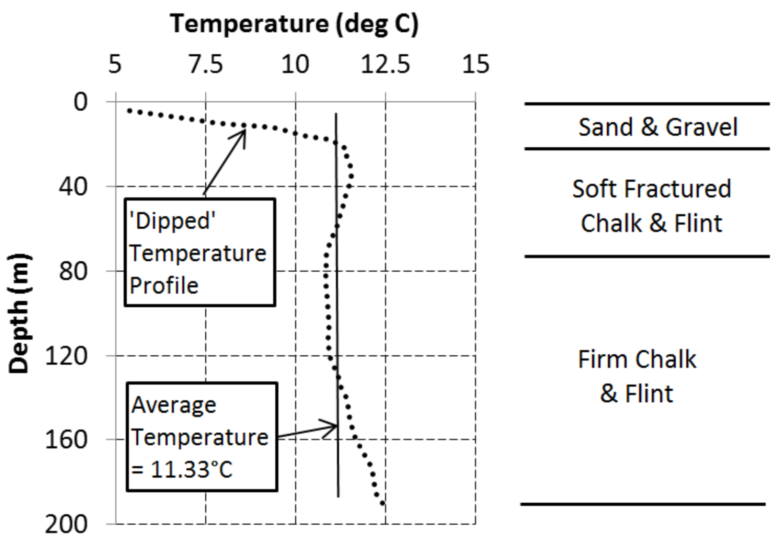

Figure 5. Pre TRT temperature profile alongside geological cross-section

Figure 6 shows the temperature development during the thermal response test as measured by the pt100 fluid temperature sensor probes. The temperature profile for both the injected and return temperatures (T(Down) & T(Up) respectively) appear to be quite smooth, however there is a small number of 'dips' in the temperature where the resistance heaters switch off for a period of approximately 50 seconds and then turn back on again. Examination of the test data has shown that this has occurred only five times over the 350 minute heating period and appears to have a negligible effect on the results of the test due to the smooth profile of the circulating fluid temperature development over the duration of the test.

As discussed earlier in this paper, there is significant variation in the reported recommended thermal response test duration. The data presented in this paper is based on a 350 minute heating period (approximately 5.5 hours), which is at the lower end of heating durations suggested by many researchers. Although longer test durations are generally considered to be preferable, the data presented is considered acceptable due to the formation of steady state conditions between the circulating fluid and the ground surrounding the borehole heat exchanger. The reason for curtailing the duration of the test was due to a steady reduction of flow over the duration of the test; reducing from 0.57 L/s at the start of the test to 0.44 L/s after 350 minutes at which stage the flow ceased circulating. It is believed that this reduction in flow rate is a result of thermal expansion of the heat exchanger pipes in the ground caused by the heated circulating fluid. This expansion in heat exchanger piping results in a drop in pressure of the fluid circulating around the system until there is not enough pressure at the intake side of the circulating pump to continue circulation

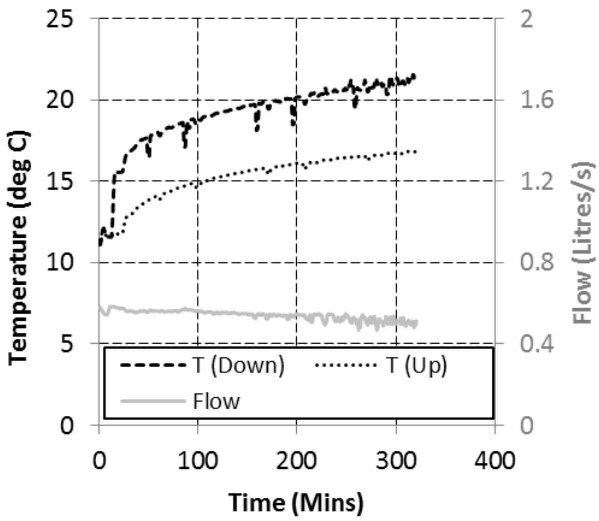

Figure 6. Temperature and flow development (UCD TRT)

The injected and return fluid temperature measurements for each time step were averaged in order to calculate a mean temperature development profile over the duration of the test. This average temperature development was then plotted on a graph against the natural logarithm of time (Figure 7 (a)). The next step was to remove the initial temperature data readings so that only readings relating to stable heat transfer in the ground was being evaluated, resulting in a plot based on a reduced data set where only the linear portion of the data remained (Figure 7 (b)). A number of 'temperature spikes' are evident on the plot in Figure 7(b) – this is due to the small size of the data set (caused by the short testing time) and due to temporary dips in the heating power described earlier. The slope of the line (k) of this plot was then calculated and substituted into Equation 3 along with the relevant data from Table 3 resulting in a calculated effective thermal conductivity (λ) of 1.9 W/mK. The value of 1.9 W/mK obtained by the UCD TRT rig is within the range expected for the formation and compares well with the value obtained by the third party TRT rig which also measured a thermal conductivity value of 1.9 W/mK. Our first estimate of 1.72 W/mK is shown to be below the thermal conductivity calculated following the thermal response tests – this is possibly due to the presence of flint, which typically has a high silica content, and aptly illustrates the importance of carrying out thermal response tests when designing ground source energy systems.

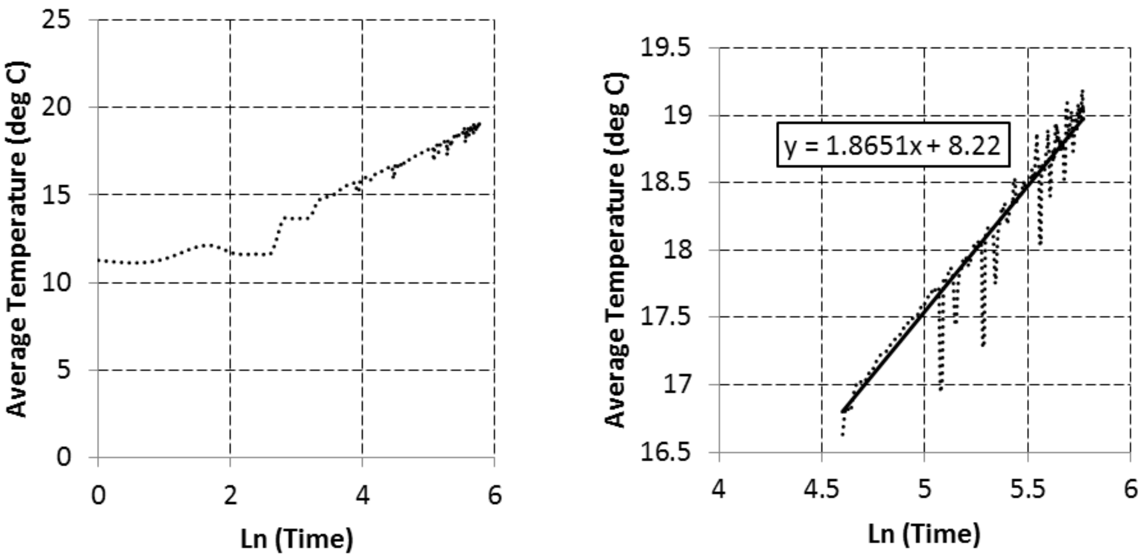

Figure 7. (a) Average temperature vs. ln time) and (b) with 'early data' removed (UCD TRT)

According to the line source model, R_b (the effective borehole thermal resistance, mK/W) may be calculated using an iterative 'curve fitting' approach. This was done using Equation 7 for each time step of the TRT data, with the injected heating power (Q) set to 9 kW, the borehole heat exchanger depth (H) set to 202 m, the thermal conductivity (λ) set to 1.9 W/mK, the thermal diffusivity (α) set to 8.27 x 10^{-7} m^2/s, the borehole radius (r_b) set to 70 mm and the initial ground temperature (T_0) set to 11.3°C. This curve fitting approach yielded a calculated fluid temperature distribution, denoted 'fitted data' in Figure 8, which is superimposed on a plot of the average of the injected and return fluid temperatures from the thermal response test with time, denoted 'TRT data' on Figure 8. The relationship described by the equation was fitted to the TRT data curve, resulting in a calculated effective borehole thermal resistance value of 0.262 mK/W. The value of R_b calculated is a little on the high side and could be reduced in one of several ways. Maximizing the spacing between the injection and return borehole heat exchanger pipes in order to minimize the distance between the heat exchanger pipes and the borehole wall, ensuring that flow in the borehole heat exchanger pipes is turbulent at all times so that a high heat transfer efficiency is maintained at all times and using a thermally enhanced grout or material with a higher heat transfer coefficient than the pea gravel which was used in this instance would all help to reduce the effective borehole thermal resistance.

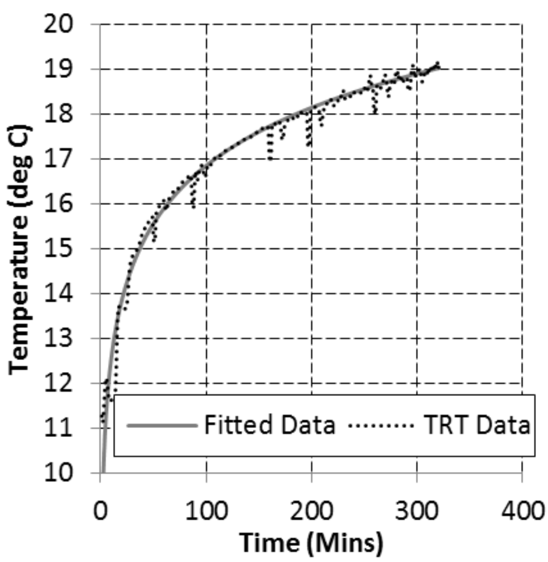

Figure 8. Mean fluid temperature from TRT data and fitted relationship

Minimization of external influences is critical to the accuracy of results obtained from thermal response tests. For example, loss of heat from the TRT piping system during the test is undesirable and must be mitigated against as much as possible. This is achieved in the UCD TRT rig by double-insulation of the piping within the rig and of the piping between the TRT unit and the BHE connections. The effectiveness of the insulation is monitored by measuring the air temperature within the rig T(Box) and comparing against the outside ambient air temperature T(Amb) over the duration of the test. Figure 9 shows that the difference between T(Box) and T(Amb) remains quite small for the duration of the test period, indicating that there is very little heat loss from the piping system into the TRT unit and therefore providing increased confidence that the data collected may be analyzed to provide a true representation of the thermal properties present at the site.

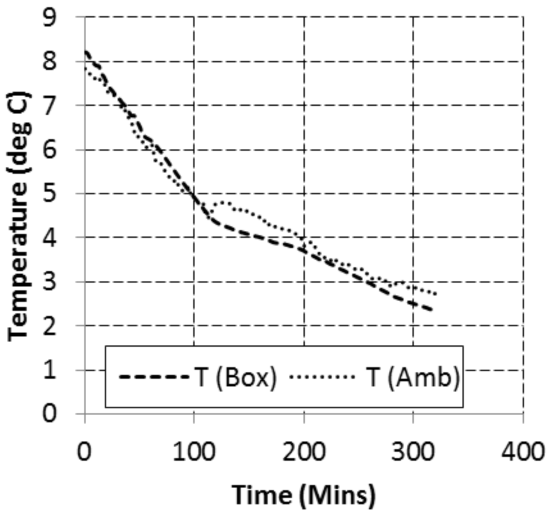

Figure 9. Air temperature inside & outside rig housing (UCD TRT)

Conclusions

Thermal response testing is a vital design requirement for any medium to large scale ground source heat energy project however current ground source system design practice in Ireland does not routinely involve project-specific measurement of ground thermal properties, often because of the lack of appropriate experience and training of designers and also due to the perceived high cost of the test. There are a number of ways to evaluate data obtained during a thermal response test all of which are based, at a high level, on Fourier's Law of Heat Conduction. The Analytical Line Source Method is currently the most commonly used evaluation method and is described in this paper.

A low cost constant heat flux method thermal response testing rig constructed with readily available off-the-shelf components, equipped with remote data transmission capability, with the added test-control functionality to monitor ambient air temperatures inside and outside the rig enclosure during a test to provide increased confidence in test results has been constructed by the primary author of this paper. The total cost to construct the UCD thermal response testing apparatus was

€4,900 – this cost is significantly below the current purchase price of thermal response testing rigs which is in the region of €48,400 (Based on a quotation received from a TRT manufacturing company). The main design calculations and considerations carried out during the selection of the primary components used in the construction of the rig, along descriptions and commentary on the range / accuracy of all rig components are openly presented. The accuracy of the UCD TRT rig has been verified by comparison of measured data from the UCD rig (albeit with a reduced testing time, necessitated by the thermal expansion and subsequent reduction in system pressure issue) against results obtained from testing with a commercially built third party TRT rig on the same site. Both TRT rigs obtained a value of 1.9 W/mK which sits within the expected range for the chalk / flint geological formation present at the test site.

Published values stating the required thermal response test duration vary significantly. This variation is largely due to the site specific nature of the measured parameters. Analysis of the data from the thermal response test carried out using the UCD TRT rig and comparison against data obtained from a commercially built rig operating on the same site indicates that a shorter testing period (approximately 5.5 hours) is adequate for the evaluation of thermal conductivity in this case, although longer testing periods would be preferable in order to improve confidence in verifying that steady state conditions have been reached. Several authors recommend further research work in this area.

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