TRT: how to get the right number

Thermal response testing for borehole heat exchangers – a validation of assumptions by Dr HJL Witte of Groenholland BV

THE current global climate discussion has stimulated enormous interest in energy savings and greenhouse gas emissions-reducing technologies. One of these technologies, and one that is rapidly gaining market interest, is the ground-source heat pump for heating and cooling houses and offices.

With a properly designed ground-source heat-pump system, primary energy and carbon emissions associated with space heating and cooling can be reduced by 30% or more. Moreover, the popularity of these systems is not due to energy efficiency alone. Other characteristics of these systems, such as their robustness, low maintenance cost and very long lifespan are often sufficient reasons in their own right.

The vertical borehole heat-exchanger (BHE), used as a thermal-source or thermal-sink, offers many advantages for the heat pump over other media such as groundwater or air. To thermally activate the ground, a heat exchanger, usually consisting of a number of high-strength PE100 loops inserted in holes drilled to depths of 50-150m, is needed.

The BHE provides the interface between the heat pump and the ground, and that is where good design is needed as the functioning of the ground-energy store, as well as the total cost of the system, depends to a large extent on the BHE. The caveat is that the energy flow in the ground is relatively slow. This allows the ground to be used as an accumulator of thermal energy, but also limits the instantaneous capacity (due to thermal build-up around the heat exchanger) and may increase borehole interference (due to thermal build-up in the store itself over longer time periods). It also means that the heat exchanger cannot be sized on capacity alone.

Let's first take a closer look at how the ground store functions and what the design question is.

HOW THE GROUND STORE WORKS

The thermal load is a result of the heat gains and heat losses of the building. In general there will be a demand for heat in the winter and a demand for cool in summer. During the winter the ground will cool down as heat is extracted, while in the summer the ground temperature increases as heat is rejected into the ground. Depending on the balance between heating and cooling, there is not only a seasonal, but also a temperature trend over the years.

The temperatures occurring in the ground are important for the functioning of the system, both in the short and the long term, as the performance and capacity of the heat pump depends to a large extent on the ground (source) temperatures.

For every K in temperature change, the co-efficient of the performance of the heat pump will change by about 3%. Therefore, it is preferable to choose the smallest (lowest in cost) ground store that delivers within the accepted temperature bandwidth during the operational lifespan of the system. In this way, the long-term, average design performance of the heat pump installation is warranted.

Temperatures in the BHE vary as a result of heat-pump cycling and possible diurnal loading (timeframe of minutes to hours; spatial scale of centimeters to decimeters). On this scale, the capacity of the borehole heat exchanger is important, as a result of the seasonal loading (timescale of days to months; spatial scales of metres) and as a result of the yearly balance (timescale being tens of years; spatial scale up to hundreds of metres). All of these temporal and spatial scales need to be considered during the design process.

In summary, the design of the borehole heat-exchanger system hinges on three principal questions:

1 What is the energy load on the ground?
2 Which heat exchanger and borehole construction is chosen?
3 What are the thermal properties of the ground?

The first question is derived from the physical building properties, building use and location. The diurnal, seasonal and yearly load profile, as well as the peak capacities, are needed. The second can be engineered, based on the required parameters and available materials.

The third question will be very difficult to estimate with sufficient accuracy from general principles or from available geological data alone. The thermal properties of the ground are the thermal capacity, the undisturbed temperature profile and the thermal conductivity. With respect to the latter, it needs to be realised that it is assumed that the main process of heat transport is conductivity (and not, for instance, mass transport due to convection or advection) – usually, but certainly not always, this will be the case.

Finally, establishing the actual thermal conductivity of a specific depth profile is quite difficult as the variation within virtually similar soil/sediment/rock types is very large due to the effects of water content, pore spacing and packing density, fracture patterns and other phenomena influencing heat conduction. Unfortunately, a geological formation, even at the defined level of a type locality, is not very homogeneous even in the best of circumstances.

THERMAL RESPONSE TEST

The thermal response test (TRT) is based on the premise that the temperature response of a material, when a thermal energy flux (forcibly heating or cooling the material at a certain location) is applied, is proportional to the thermal conductivity of the material. This relation is expressed by Fourier's law of conduction:

$$\dot{q} = -\lambda \nabla T$$

Where:

$\dot{q}$: heat flow (J/s)
λ : Thermal conductivity (W/mK)
∇T : Temperature gradient (K)

Using Kelvin's line source, a method can be devised to measure the conduction of a material by a needle probe (van Haneghem, 1981), where the needle is inserted in a material and heated. The temperature change of the needle can be measured and used to calculate the thermal conductivity of the material. This method is used in the laboratory, but also in agricultural studies to determine conductivity in shallow soil profiles.

In 1983, Mogeson was the first to propose such a test for the in-situ measurement of ground thermal conductivity using a borehole heat exchanger. In this case the spatial dimension of the 'needle' (borehole heat exchanger) cannot be ignored and is reflected in the measurement as an additional thermal resistance. For the TRT the infinite line source is defined as:

$$T_f = \frac{-(q_v \rho c(T_{out} - T_{in}))}{4\pi\lambda H}\left[\ln\left[\frac{4at}{r_0^2}\right] - \gamma\right] + \frac{q_v \rho c(T_{out} - T_{in})R_b}{H} + T_g$$

Where:

qv	Volume flow circulation medium	m^3/s
r	Density circulation medium	kg/m^3
c	Heat capacity circulation medium	J/(kgK)
T_{out}	Return temperature circulation medium	°C
T_{in}	Injection temperature circulation medium	°C
T_f	Average temperature circulation medium	°C
T_g	Far field (ground) temperature	°C
l	Ground thermal conductivity	W/mK
H	Ground loop length	m
R_b	Borehole resistance	K/(W/m)
γ	Euler's constant	-
t	Time	s
r_0	Borehole diameter	m
k	Co-efficient of the regression T_f with logarithmic time (t)	-
a	Thermal diffusivity (λ/C, where C is thermal capacity)	m^2/s

This formula is valid when:

$$t \geq \frac{5r_0^2}{a}$$

The thermal conductivity can be estimated from the data by:

$$\lambda = \frac{-(q_v \rho c(T_{out} - T_{in}))}{4\pi k H}$$

Where the parameter [k] equals the slope of a linear regression of temperature with logarithmic time. When l has been estimated, the borehole resistance (Rb) can be calculated using the line source formula above.

In 1995, the two first real in-situ response tests (type I tests) were developed in the US (Austin, 1998) and Sweden (Eklöf & Gehlin, 1996). These tests use direct heating of a fluid pumped through the borehole heat exchanger as a thermal forcing. With this method some problems were foreseen, such as that of maintaining a constant power flux and con-vection effects due to water heating in the borehole. Also, as the test uses heating, the experiment conditions are obviously not comparable to a heat-pump system operating in heat-extraction mode.

In 1997, Groenholland (van Gelder et al 1999, Witte et al 2002) presented the first test capable of both heating and cooling (type II test). This test machine used a reversible heat pump to generate the heating or cooling power, and employed an active control system (using a three-way valve and frequency-controlled pump) to maintain the required energy flux to a high precision. Also, it included full telemetry to both control and monitor the experiment.

To better the quantify effects of groundwater flow, and other processes affecting heat transport in the ground, this test was subsequently extended into a multi-pulse test (type III test) using a sequence of heating and cooling pulses at several energy levels (Witte & van Gelder, 2006). Obviously, such test results cannot be analysed using the simple line source model, but are evaluated using inverse numerical modeling with parameter estimation.

In the classical type I test, the temperature response of the ground can be partitioned, as seen in figure 1. The first part of the test reflects the transient borehole response and is not used. The jump from the undisturbed temperature to the start of the steady-state temperature increase is a measure of the borehole thermal resistance. This already implies, from the line source formula, that a very good measurement of the undisturbed ground temperature is important. The final part, the steady state temperature increase, actually measures ground thermal conductivity.

A number of important issues are:

- Selecting a heat flux that is large enough to sufficiently force the ground (achieve good signal-to-noise ratio) and also allow sufficient measurement time (not too rapid thermal saturation). Typical rates are 30-100W/m.
- Obtaining a sufficiently accurate soil-temperature profile.
- Ensuring a good-quality borehole heat-exchanger installation.

Moreover, depending on whether an accurate as possible measurement of soil thermal conductivity or a characterisation of a specific borehole installation as installed is required, the following may apply:

- Selecting test parameters to resemble actual plant operation (different extraction/injection levels, cycling, etc) or increase accuracy.
- Design borehole and experiment parameters for lowest borehole resistance or best resemblance to engineered borehole design.

The tests, in the incarnations previously explained, have been in use for over a decade now, with great success. Over 30 test apparatus are now in use worldwide routinely and deliver important information to designers on soil thermal conductivity, soil-heat capacity, subsurface temperature profiles and geothermal heat flux, as well as borehole heat-exchanger thermal resistance.

However, as the TRT evolves from a tool used by specialists with a fundamental understanding of the processes involved to more standard measurement methodology, the standard evaluation methods fall short. Mainly, the basic assumptions that the test makes, and the limitations on configurations where the test may be used, are not sufficiently analysed or considered in the standard evaluation method.

LIMITATIONS

The TRT is a measurement process, which, like any measurement, has a certain accuracy and precision that can be statistically defined. The definition of sensor error is fairly straightforward and state-of-the-art test equipment achieves theoretical accuracy of the soil thermal conductivity measurement of better than 10%. However, there are many processes affecting the accuracy of the measurement besides sensor error.

The discussion of all sources of error in a TRT is beyond the scope of this paper, but the validity of even a perfect (error-free) TRT experiment depends on a number of fundamental assumptions that are made concerning the process of heat transport. If these assumptions do not hold, the test results may be inaccurate, biased or even completely invalidated.

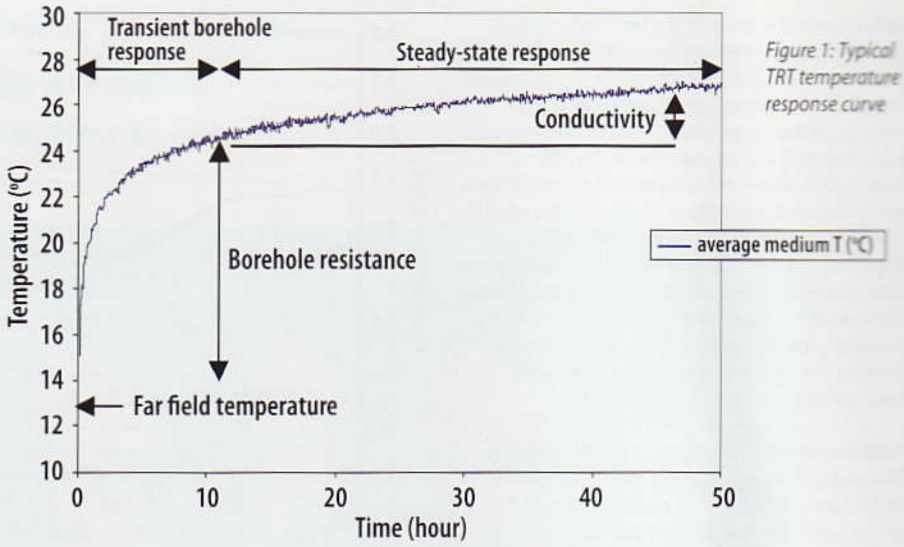

Figure 1: Typical TRT temperature response curve

PRINCIPAL ASSUMPTIONS OF THE INFINITE LINE SOURCE TEST

The borehole heat exchanger tested can be considered as an infinite line source

The first assumption to be tested is if the borehole heat exchanger can be considered to constitute a line source. In general, a borehole heat exchanger had a length of 80-150m and a diameter of 0.15-0.20m. These dimensions can be taken as reasonably close to an infinite line source as the edge effects at the top and bottom of the heat exchanger can be ignored. Also, the effects of the size of the borehole and pipe arrangement within them can be ignored after the first few hours of the test have passed, and the borehole wall can be taken as the source of the heat flux.

However, other types of heat exchangers can be tested. Examples are pre-fabricated foundation piles or in-situ constructed foundation piles. The first class usually consist of square, concrete constructions in which a number of polyethylene pipes are integrated during manufacturing. The second class is either augered or excavated foundation elements of larger diameters. A number of polyethylene pipes are fixed to the rebar before the concrete is poured in. In both cases, the length of the pile is limited and common lengths range between 10-25m. In the case of the in-situ piles, often the diameter is quite large as well (1-3m). Therefore, these geometries cannot be considered equivalent to an infinite line source and the effects at the top and bottom of the element, as well as the large diameter and large internal heat capacity, cannot be ignored.

> **"Depending on the balance between heating and cooling, there is not only a seasonal, but also a temperature trend over the years"**

One can imagine that the added effect of downward heat transport at the end of a relatively short heat exchanger will add a virtual length to the borehole heat exchanger and therefore lead to an overestimate of the soil thermal conductivity. On the other hand, near the surface a relatively larger part of the heat exchanger may be in unsaturated soil with lower heat conductivity, leading to an underestimate of the formation-specific conductivity.

For the large-diameter energy piles, composed of concrete with a high heat capacity and density, the thermal-storage effect cannot be neglected. In general this will again lead to an overestimated thermal conductivity. For these geometries, other analytical solutions have been developed (Bandos et al, 2008).

So far, no actual calculation of the minimum ratio D/L, between the diameter (D) and length (L) of the borehole heat exchanger has been proposed. It seems reasonable to assume, however, that a D/L <0.005 is acceptable. For a 100m-deep BHE with a diameter of 0.2m, the D/L is about 0.002. A 50m borehole exchanger will have a D/L of about 0.004. An energy pile will have a D/L >0.0125.

The conductivity of the soil is isotropic

This is, especially in sedimentary (unconsolidated) types of geology, hardly ever the case. The formation normally consists of a sequence of different materials (sands, clays, gravels, peat, etc) with various thicknesses, where each material has its own properties. For instance, due to packing, there may be a directional preference, similar to what is found with hydraulic conductivity. Moreover, often only part of the complete vertical profile will be water-saturated. Other situations often encountered are a geological profile consisting of hard rock, weathered rock or consolidated materials, with an overburden of loose or sedimentary materials, often with water bearing layers or seepage. Homogeneous geological profiles are normally the exception.

For the TRT and measurement of the thermal conductivity, the variation is not a great problem if the specific thermal conductivity of the profile is needed. For the design of a borehole heat exchanger, therefore, when the test heat exchanger is installed to a similar depth as the production borehole, the TRT will yield values of conductivity that can be used directly in the design software. If this is not the case, care should be taken.

If, for instance, the deeper part of the profile is composed of a layer of markedly different conductivity and the final borehole heat-exchanger depth is lengthened significantly (space restrictions on site) this may result in an under-design as the specific conductivity value used will be too high.

Conversely, if a test is performed on a short borehole (with, for instance, a peaty or clayey cover layer or unsaturated soil profile on top), and

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subsequently the depth of the heat exchanger is increased, an over-design may result.

For an inhomogeneous soil profile, it is possible to derive conductivity values for individual layers through additional temperature measurements at these depths. These can be obtained in different ways, such as fiber-optic temperature measurements in the heat-exchanger pipes. However, although it is possible to measure the different temperature responses, it is usually not as easy to measure the temperature differences (and therefore power rates) at those different depths. It is therefore fairly straightforward to measure differences between horizons, but not so easy to accurately quantify those differences.

Process of heat transport is by conduction only

This is a key assumption as the line source theory, which allows us to measure conductivity with the TRT, as well as the actual result obtained, depends on it. Next to conduction, the heat-transport processes that occur are due to mass transport or radiation. Radiation occurs at the surface and can add energy to the system due to incoming radiation from the sun, while energy is being lost during the night due to long-wave radiation. On the timescale of the experiment, the effects of radiation can normally be ignored.

Mass transport in the ground occurs through groundwater flow. We can distinguish groundwater flow in porous or fractured media. In porous media, all heat exchangers in an area will experience more or less the same groundwater flow, and the groundwater flow is fairly constant in the layer where it occurs (although marked differences between layers may occur).

Lateral groundwater flow, or advection, occurs as a result of a pressure gradient. The amount of water that can flow through a zone depends on the pressure difference and hydraulic conductivity, expressed in Darcy's law:

$Q = -K \nabla P$

Where:

Q:	Darcy velocity	m/s
K:	Hydraulic conductivity	m/s
∇P:	Pressure gradient	

The actual velocity and length of path travelled also depend on the porosity. The Darcy groundwater flow divided by the porosity gives rise to the effective groundwater flow. For fractured media, the calculation of groundwater flow is much more complex. For a large volume the average groundwater flow in fractured media can be calculated using an equivalent porosity term. For a borehole heat exchanger, however, it is much more relevant if it 'hits' a fracture or not, which is a matter of a probability that depends on the fracture density and spatial distribution in the soil volume.

The effect of groundwater flow on a TRT can be made visible by calculating the constancy of the regression solution as more data is added (figure 2). If the solution in the heating phase of the experiment does not converge to a stable estimate of ground thermal conductivity, but continues to rise, this is a clear indication of groundwater flow affecting the test.

The explanation for this is that the amount of heat transferred to the water depends on the temperature difference between the groundwater and the fluid in the borehole heat exchanger, and this difference increases as the fluid heats up during the experiment, so apparent conductivity becomes progressively higher.

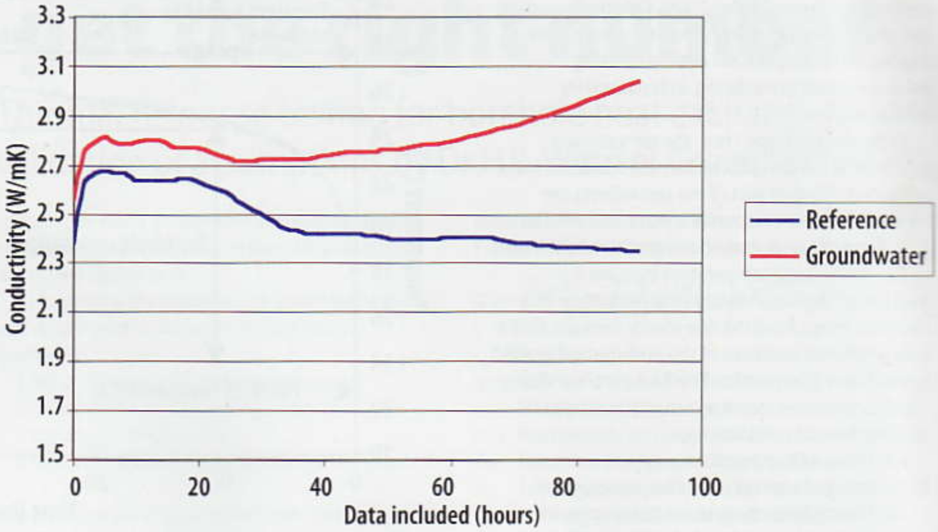

Figure 2: constancy of conductivity estimate using the line source approach in an experiment with and without groundwater flow

Apart from subsurface flow, other possibilities such as rainwater runoff (on hillsides or in an inadequately backfilled borehole), or even pumping from a well or excavation or drilling close to the test site, need to be considered.

It is not easy to quantify the amount of groundwater flow from the test result, but Groenholland has used pulse tests to arrive at such a quantification of groundwater flow effects. Very high flow rates will result in an infinite conductivity as the temperature response of the borehole heat exchanger is constant (all heat transported away immediately).

Another effect of groundwater, especially in the borehole, may be convection occurring due to the lateral temperature gradient. Even micro-convection cells in the borehole pore spaces will reduce borehole resistance and, on a larger scale, ground thermal conductivity will appear higher. In a heating experiment this effect is more pronounced as the changes in viscosity and density work with the convection force, while in a cooling experiment the higher viscosity at lower temperatures acts as a brake on convection. Therefore, the differences found in borehole resistance and conductivity between heat injection and heat extraction experiments on the same borehole are probably due to convection effects.

"Tests are now being routinely performed worldwide and becoming an integral part of the ground-source heat-pump designer's toolkit"

Borehole resistance is, after an initial transient phase, steady state

The borehole affects the test in a number of ways. The borehole is normally parameterised as a resistance term (borehole resistance), but when the front of a temperature field propagates through the borehole (which happens at each change in heat flux) the resistance is not steady-state but transient. At that moment the data from the test cannot be used to calculate the borehole resistance or conductivity and a certain amount of time has to pass before accurate estimates can be obtained. Other effects that can occur are: infiltration of rainwater through the top of the borehole, or a siphon effect between different layers. Both may result in infinite conductivity and zero borehole resistance, and are caused by improper sealing of the borehole. Also, the borehole may be unstable or collapse due to improper backfilling or deterioration of the backfill material.

This will dramatically affect the results as the heat-exchanger pipes may become exposed and active borehole length changes. Also, high-resistance boreholes will yield poor test results as the test time increases and a large temperature difference is needed to generate a heat flux to the ground. Obviously, letting the borehole rest and cure between the drilling works and installation of the loop and the start of the experiment is obligatory.

The energy flux is constant

Although this is an assumption of the test method, it is more characteristic of the test equipment and not of the ground. Nevertheless, it is a very important assumption of the line source method. The type I tests that depend solely on electrical heater elements and have no active control over the energy input suffer especially from this problem.

Fluctuations in grid or generator power will change the power input into the borehole heat exchanger and affect the test results. These changes can be stepped (sudden change in grid power) or more gradual and may exhibit cyclic behaviour. Examples of causes of changes in electrical power can be changes in ambient temperature (affecting generator output), day-night cyclic demand on the grid ,or lower demand on the grid at weekends.

The main way of dealing with non-constant power input is through the use of inverse numerical modelling or de-convolution techniques.

CONCLUSIONS

TRTs, developed in the 1990s, provide invaluable information for the design of ground-source, closed-loop, heat-pump systems. From the drilling of the trial borehole and the installation of the loop, practical information such as drilling conditions, soil stratigraphy and groundwater level can be determined.

In the test, the subsurface temperature profile, soil thermal conductivity and borehole resistance are measured while an estimate of thermal capacity is also usually obtained.

Modern tests, like the multi-pulse test, developed and patented by Groenholland, are versatile and use accurate test procedures that yield detailed, additional information on the heat-transfer process in the ground, including groundwater advection and convection.

However, the validity of the test depends on whether the assumptions made actually hold. It is therefore important to test these assumptions on a routine basis as the test is not performed in controlled laboratory conditions, but in situ in the field where many unexpected things happen.

In addition to the fundamental assumptions, other sources of error also need to be considered. In a recent inventory, Groenholland identified at least 11 different sources of error, from sensor error and heat-transfer fluid characteristics to statistical errors and errors in the methodology applied to the data.

> **"The validity of the test depends on whether the assumptions made actually hold"**

In practice, however, in a well-planned experiment, and using properly prepared and calibrated equipment, a test failure of a test is very rare indeed and almost always attributable to 'freak' events like unforeseen excavation and pumping near the test site, unusually heavy rains or, in very rare cases, instrument failure. Often, by using an alternative evaluation method, possibly in combination with extending the test time, useable results can still be obtained.

Tests are now being routinely performed worldwide and becoming an integral part of the ground-source heat-pump designer's toolkit. We hope that, with this paper, we have made clear that while TRTs are becoming a more routine type of measurement, the quality and usability of the test depends on a good understanding and evaluation of the test method, assumptions and conditions.

Without such understanding, the results are just a number and, too often, a wrong number at that.

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