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A virtual borehole for thermal response test unit calibration: Test facility and concept development

Parham Eslami Nejad **Messaoud Badache** **Alexia Corcoran** **Michel Bernier**

ABSTRACT

Precise calculation of the borehole length requires good estimation of the ground thermal conductivity. In practice, the ground thermal conductivity is measured in-situ at a specific location using what is referred to as a thermal response test (TRT) unit. This paper presents a novel virtual borehole (VB) concept for calibrating TRT units. The VB replaces a real borehole with an above-ground compact heat exchanger and a chiller unit to mimic the thermal behavior of the ground with a user-set virtual ground thermal conductivity. In an attempt to develop the VB concept, three control scenarios are examined to emulate the ground thermal response for different thermal conductivity values. A test bench was built at the CanmetENERGY-Varennes research laboratory to validate the VB concept experimentally. A test is performed to calibrate a commercially available TRT unit for a thermal conductivity value of 3 W m^{-1} K^{-1}. The TRT unit connected to the VB reported a value of 3.18 W m^{-1} K^{-1} representing a 6% error.

INTRODUCTION

Ground source heat pump (GSHP) systems are receiving significant interests due to energy efficiency. However, to design them correctly, thermal properties of the ground where the ground heat exchangers (GHE) are installed, must be estimated precisely. Ground thermal conductivity (k), borehole thermal resistance and the undisturbed ground temperature (UGT) are among the most important parameters for design and are commonly estimated from in-situ thermal response tests (TRT) (Gehlin 1998). During a TRT, a constant and known thermal load is injected into the GHE and accurate measurements of the time history of the inlet and outlet fluid temperatures are recorded. The ground thermal conductivity is then deduced from these measured values.

Thermal response tests include the measuring period and the subsequent data analysis. The latter requires a relatively precise GHE mathematical model. The accuracy of the model has a major impact on the thermal conductivity value reported by the TRT units.

Different models have been used to evaluate the experimental data obtained from TRTs. Most models are based on either analytical approaches or numerical methods. Complete reviews of various analytical and numerical models have recently been presented (Rees 2016; Spitler and Gehlin 2015). In brief, the modeling of the GHE has undergone many improvements since it was first suggested in 1983 by Mogensen (Mogensen 1983). Starting from the infinite line source (ILS) model (Sharqawy, et al. 2009), the infinite cylinder source (ICS) model (Eskilson 1986), the finite line source (FLS) model (Bandos, et al. 2011) going to more complex two and three-dimensional numerical models by Bozzoli, et al. (2011) and Marcotte and Pasquier (2008). TRT result analysis is based on the ILS and ICS

Parham Eslami Neajad (parham.eslaminejad@canada.ca) and Messaoud Badache are research scientists at CanmetENERGY Natural Resources Canada. Alexia Corcoran was an intern at CanmetENRGY during this study and a graduate student at Polytechnique Montréal. Michel Bernier is a professor in the Mechanical Engineering Department at Polytechnique Montréal.

models that represent relatively simple and rapid methods for estimating the ground thermal properties. However, numerical approaches are more accurate and can capture more complex phenomena in the ground, such as ground water movement and variable heat injection and fluid mass flow rates. For instance, Bandos, et al. (2011) proposed a correction method to account for heat losses to the ambient, Sass and Lehr (2011) account for ground water advection while other studies (Beier and Smith 2003; Choi and Ooka 2015) improved the analysis by using multi-injection rate thermal response tests.

Concerning the TRT unit itself, significant improvements have been achieved since the design proposed by Mogensen (1983) including mobile TRT units allowing both heat injection and extraction. Some TRT units deviate from the standard approach and use different measurement techniques to perform a TRT. For instance, Raymond, et al. (2015) proposed to use a heating cable without supplying any flow to the GHE; Witte, et al. (2000a) proposed a telemetry system; Acuña and Palm (2013) used a distributed ground temperature measurement technique using optical fiber; and Rohner, et al. (2005) proposed downhole measurements using light submersible wireless probes.

Although research and development on TRT units has evolved significantly, conventional TRT units are still widely used in the industry. Individual measurements (temperature, flow rate, power input) inside the TRT unit are often calibrated. There has also been past attempts to perform round-robin testing of some TRT units. However, there is no method to calibrate a particular unit as a whole, including the data analaysis. The virtual borehole concept presented here proposes to simulate the behavior of a ground heat exchanger to calibrate TRT devices with user-selected ground thermal conductivities.

VIRTUAL BOREHOLE CONCEPT

In a TRT unit, several measuring devices are used to collect the required data including fluid mass flow rate and inlet and outlet fluid temperatures to the borehole. These data are typically used in conjunction with a one-dimensional heat transfer model (ILS for example) for evaluating the thermal conductivity of the ground. Both measurements and result interpretation introduce uncertainties in the process.

The VB proposed here is shown in Figure 1. It consists of a compact heat exchanger and a cooling unit. The TRT unit to be calibrated is connected to the VB as it would be to a borehole in an in-situ TRT. The chiller and compact heat exchanger are carefully controlled using a pre-defined control scenario to mimic the thermal behavior of the ground heat exchanger. In other words, the VB creates a thermal condition for the TRT unit to react thermally just like if it were connected to a real borehole located in a medium with a known ground thermal conductivity.

The control unit reduces the mass flow rate (using a 3-way mixing valve) or/and increases the temperature of the cooling loop to increase the average temperature of the heating loop (on the TRT side) over time exactly as it would happen during a real test. The thermal conductivity value interpreted by the TRT unit is then compared against the value set by the control unit.

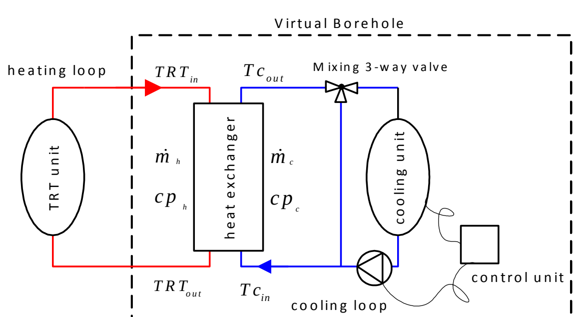


Figure 1: Virtual Borehole (VB)

GOVERNING EQUATIONS

The heat exchanger shown in Figure 1 is thermally insulated. Thus, it is assumed that the amount of heat injected from the heating loop is equal to the amount of heat removed by the cooling loop. It is further assumed that the rate of heat injection and mass flow rate of the TRT unit are constant.

Heating loop

The heat exchange rate on the heating side of the VB is calculated using the following equation.

$$q_{TRT} = \dot{m}_h \times cp_h \times \underbrace{\left(TRT_{in}(t) - TRT_{out}(t)\right)}_{\Delta T_{TRT}} \xrightarrow{\dot{m}_h \text{ and } q_{TRT} \approx \text{const}} \Delta T_{TRT} \approx const \qquad (1)$$

where $TRT_{in}(t)$ and $TRT_{out}(t)$ are, respectively, the fluid temperatures at the inlet and outlet of the heat exchanger in the heating loop, $\dot{m}_h$ and cp_h are the mass flow rate and specific heat of the fluid circulating inside the heating loop, and q_{TRT} is the amount of heat injected into the heat exchanger by the TRT unit.

Cooling loop

The heat exchange rate on the cooling side of the VB is calculated using the following equation.

$$q_{cooling} = \dot{m}_c(t) \times cp_c \times \left(TC_{out}(t) - TC_{in}(t)\right) \qquad (2)$$

where $TC_{in}(t)$ and $TC_{out}(t)$ are, respectively, the fluid temperatures at the inlet and outlet of the heat exchanger in the cooling loop, and $\dot{m}_c$ and cp_c are the mass flow rate and specific heat of the fluid circulating inside the cooling loop. Given that heat losses from the compact heat exchanger are negligible:

$$q_{TRT} = q_{cooling} = q \qquad (3)$$

Heat exchanger

Any type of heat exchanger can be used between the cooling unit and the TRT device as long as it can be precisely modeled using either an analytical model or an experimentaly-derived performance map. In the present study, a plate heat exchanger is used and it's efficiency is quantified experimentally for different test conditions. Based on the effectiveness-NTU method, the heat transfer rate from the heat exchanger is given by:

$$\begin{gathered} q = \varepsilon \times (\dot{m} \times cp)_{\min} \times (TRT_{in} - TC_{in}) \\ (\dot{m} \times cp)_{\min} = (\dot{m} \times cp)_h \end{gathered} \qquad (4)$$

It is assumed that the fluids in both loops are the same (pure water) and that the minimum fluid capacity ($\dot{m} \times cp$) always occurs in the cooling loop.

Borehole model

A so-called TRC (Thermal Resistance Capacitance) model developed in the TRNSYS environment is used to generate the time evolution of TRT_{in} in equation 4. The transient behavior inside the borehole is modeled using a resistance-capacitance approach (Godefroy and Bernier, 2014) while the analytical solution of the infinite cylinder source is used on the outside of the borehole. The TRC model used in the present study has been validated by comparison with the results of a thermal response test (Chiasson and O'Connell 2011). In this validation, the model reproduced the measured fluid temperatures with an average deviation of 0.12 °C.

CONTROL SCENARIOS AND PRELIMINARY CALCULATIONS

Depending on the control scenario used, either the mass flow rate, the fluid temperatures or both can be varied to mimic the thermal response of the ground. In this paper, three senarios are presented.

Scenario #1: Constant $\dot{m}_C$

In this scenario, the fluid mass flow rate in the cooling loop remains essentially constant. Therefore, the heat exchanger efficiency variation is negligible. However, marginal changes in the fluid specific heat and heat exchanger efficiency due to temperature changes can still be taken into account for calculating TC_{in}. The value of TRT_{in} calculated using the borehole model is substituted in Equation (4). Therefore, the time evolution of TC_{in} is simply calculated as follows:

$$TC_{in}(t) = TRT_{in}(t) - \frac{q}{\varepsilon \times (\dot{m} \times cp)_c} \tag{5}$$

The calculated TC_{in} profile (Equation 5) is given to the control unit in order to be reproduced using the chiller. Since this control scenario is less complicated to implement, it is used later in this paper.

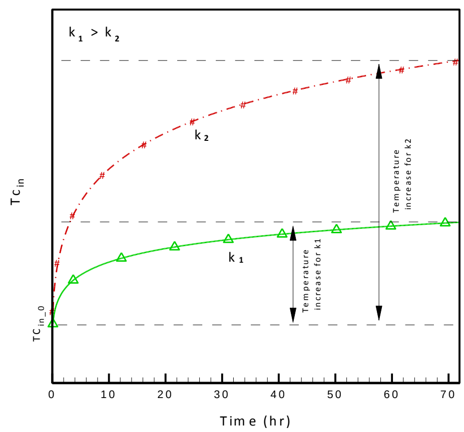


Figure 2: Qualitative change in TC_{in} for scenario #1

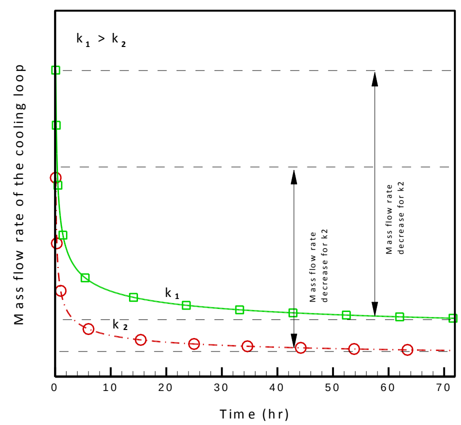


Figure 3: Qualitative change in cooling loop mass flow rate for scenario #2

Figure 2 presents the qualitative change in TC_{in} required to reproduce the ground thermal response under constant heat injection by the TRT unit for two thermal conductivity values k_1 and k_2 (k_1>k_2). The temperature increase range presented in the figure depends on the heat injection rate, borehole dimensions, preset ground thermal properties, heat exchanger performance and mass flow rate of the cooling loop. As shown in figure 2, high ground thermal conductivities lead to smaller TC_{in} increases. Also, during the first 10 hours, the TC_{in} increase is steep for both thermal conductivities. This rate of increase has to be handled by the control unit.

Scenario #2: Constant TC_{in}

For the second scenario, it is assumed that the chiller and control unit are able to supply a constant fluid temperature at the inlet of the compact heat exchanger during the test. However, the mass flow rate of the fluid in the cooling loop ($\dot{m}_C$) has to be reduced over time (and is always lower than the one in the heating loop) to increase the mean temperature of the heating loop under the constant heat injection rate of the TRT unit. This scenario is more complex to handle experimentally as the reduction in the mass flow rate is relatively steep. Furthermore, the compact heat exchanger efficiency changes during the test because of flow rate changes. These efficiency variations have to be evaluated beforehand in a separate test. Similar to scenario #1, the calculated TRT_{in} profile supplied by the borehole model is substituted in Equation (4). An iterative approach is used to calculate the fluid mass flow rate of the cooling loop at every time step based on TRT_{in} and the heat exchanger efficiency variation with time:

$$(\dot{m} \times cp)_c(t) = \frac{q}{(TRT_{in}(t) - TC_{in}) \times \varepsilon(t)} \tag{6}$$

$$TC_{in} = \text{constant}$$

The time evolution of $(\dot{m} \times c_p)_c$ (Equation 6) and the constant value of TC_{in} are reproduced by the control unit by acting on the chiller and the 3-way valve. Assuming that the fluid specific heat remains constant during the test, Figure 3 presents the qualitative evolution of the fluid mass flow rate of the cooling loop required to reproduce the ground thermal response for two thermal conductivity values k_1 and k_2 ($k_1 > k_2$). The mass flow rate change in the first few hours is relatively steep and the control unit might have difficulties in following this trend. The range of the mass flow rate reduction depends on the heat injection rate, borehole dimensions, preset ground thermal properties and heat exchanger performance.

Scenario #3: Hybrid

A "Hybrid" scenario can be envisioned to diminish the relatively steep temperature and mass flow rate variations in scenario #1 and #2 occuring at the beginning of the test. In scenario#3, either the temperature or the mass flow rate of the cooling loop changes linearly for a certain period of time (t_0) and then remains constant throughout the rest of the test. With this approach, the other parameter (e.g. temperature if the mass flow varies linearly) changes less steeply and the increase/decrease range is less significant. Decrease patterns other than the linear one used here could also be selected to facilitate the control of the other parameter.

$$(\dot{m} \times cp)_c(t) = \frac{q}{(TRT_{in}(t) - TC_{in}(t)) \times \varepsilon(t)} \tag{7a}$$

$$TC_{in}(t) = \begin{cases} at + b & t < t_0 \quad (a \text{ and } b \text{ are arbitrary parameters}) \\ \text{constant} & t \geq t_0 \end{cases}$$

or

$$TC_{in}(t) = TRT_{in}(t) - \frac{q}{\varepsilon(t) \times (\dot{m} \times cp)_c(t)} \tag{7b}$$

$$(\dot{m} \times cp)_c(t) = \begin{cases} ct + d & t < t_0 \quad (c \text{ and } d \text{ are arbitrary parameters}) \\ \text{constant} & t \geq t_0 \end{cases}$$

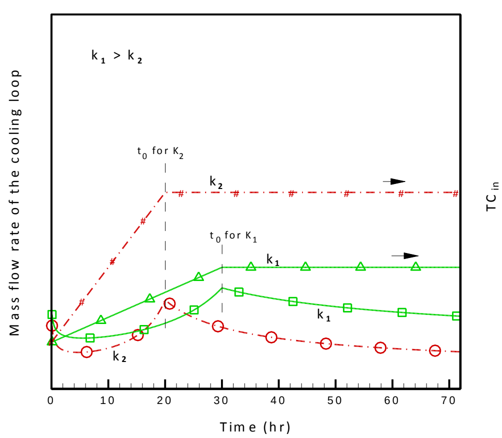


Figure 4: Qualitative change in $\dot{m}_c$ for scenario #3 under linear TC_{in} increase

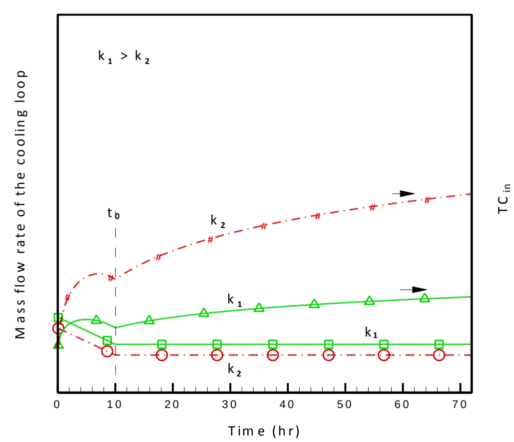


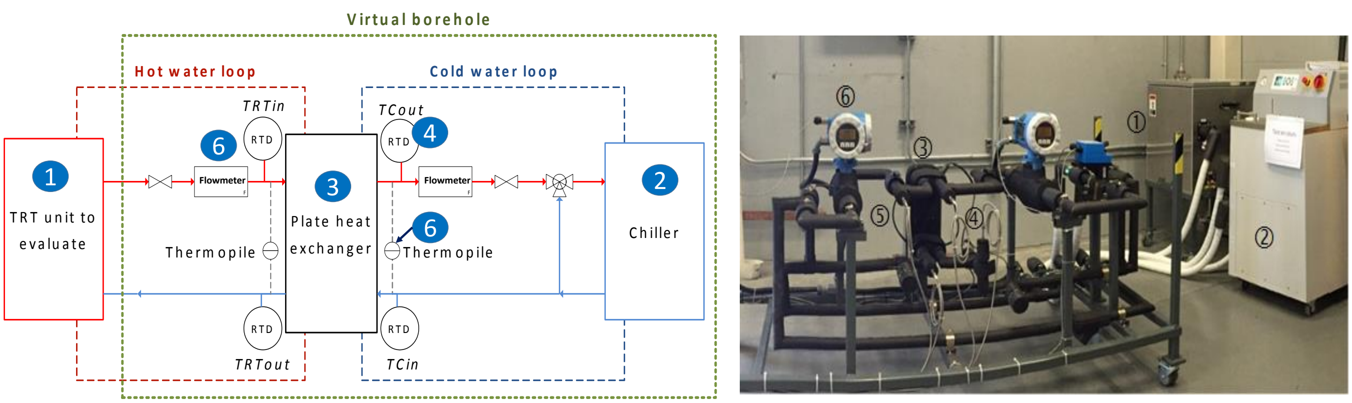
Figure 5: Qualitative change in TC_{in} for scenario #3 under linear $\dot{m}_c$ decrease

Similar to the other scenarios, the time evolution of $(\dot{m}_c \times c_p)$ and the time evolution of TC_{in} (Equation 7a and 7b) are given and reproduced by the chiller and the control unit. Figure 4 and Figure 5 present the qualitative time evolution of $\dot{m}_c$ and TC_{in} for two cases: Linear TC_{in} increase (Figure 4) and linear mass flow rate decrease (Figure 5). The change in the TC_{in} and $\dot{m}_c$ values at the beginning of the test is not as sharp as those presented in Figures 2 and 3, respectively. Therefore, as shown in Figures 4 and 5, scenario #3 results in lower range variations of parameters than scenario #1 and #2 which might facilitate the operation of the control unit.

EXPERIMENTAL SETUP AND TEST PROCEDURE

Experimental setup

A VB test bench was built at the CanmetENERGY-Varennes research laboratory. The complete system is presented schematically in Figure 6. The main components of this facility include: a commercially-available TRT unit (4 kW heating capacity), a plate heat exchanger (PHE) and a chiller unit. The test facility is fully equipped with different measuring devices including temperature sensors (RTDs and thermopiles) and flow meters. As shown in Figure 6, four RTD probes measure the inlet and outlet temperatures to the PHE (TRT_{in}, TRT_{out}, TC_{in} and TC_{out}). Two thermopiles are also used to measure the temperature differences for each water loop. Loop flow rates ($\dot{m}_h$ and $\dot{m}_c$) are measured using Coriolis mass flowmeters. Specifications of the devices and measuring instruments used on the test bench are listed in Table 1. Data are recorded using a conventional data acquisition system.



(a) (b)

Figure 6: Virtual borehole test bench

Test procedure

As indicated earlier, the test bench is operated based on Scenario #1. The VB sequences of operation are:

- Step 1: Use the TRC model to calculate TRT_{in} as a function of time for a given set of borehole dimensions, preset ground properties, heat injection rate and TRT mass flow rate.
- Step 2: Calculate the TC_{in} evolution (Equation 5) to be reproduced by the chiller and the control unit. In this step, TC_{in} is calculated beforehand according to the plate heat exchanger efficiency, the mass flow rate of the cooling loop and the calculated TRT_{in}.
- Step 3: Set the temperature in the cooling loop by controlling the chiller outlet water temperature to follow precisely the pre-calculated TC_{in}. This is accomplished using a control unit integrated within the chiller.
- Step 4: Start both the TRT unit and the chiller. Then, the TRT loop measures the mean temperature in the heating loop (TRT_m).
- Step 5: Compare the thermal conductivity value reported by the TRT with the one selected by the user on the VB unit.

Table 1. Devices and measuring instruments used in the VB test bench

Items	Numbers (Figure 6)	Function	Technical specification	Uncertainty
TRT unit	①	Heat injection and water pumping in the hot water loop	4 kW heating capacity	
Chiller	②	Heat extraction and water pumping in the cold water loop	5 kW cooling capacity at 0 °C	
PHE	③	Heat transfer area	0.74 m^2	
RTD	④	Temperature measurement	Pt100	±0.2
Thermopile	⑤	Temperature differential measurement		
Flowmeter	⑥	Mass flow measurement	Coriolis flowmeter	±0.2%

TRT UNIT CALIBRATION

In this section, a commercially available TRT unit is evaluated by the VB test bench. The VB is set to reproduce a ground thermal conductivity of 3.0 $Wm^{-1}K^{-1}$. The parameters used for the test are shown in Table 2. The heat exchanger efficiency was evaluated experimentally according to the TC_{in} temperature range of the test and the mass flow rates. A heat injection rate of 4 kW is used in the TRC model simulation since this value is used by the TRT unit.

The time evolution of the mean fluid temperatures on the TRT side and the chiller outlet water temperature (TC_{in}) are obtained from the TRC model and from the heat exchanger model, respectively. To start the test, the flowrates are set to 0.2 kg/s in both loops, the calculated TC_{in} profile (Figure 7) is set on the chiller and then the TRT unit heat injection (4 kW) is started.

Table 2. Parameters used for the TRT unit calibration

		Test
	Injected heat (W)	4000
Hypothetical borehole dimensions and ground and grout thermal properties	Borehole length (m)	80
	Borehole diameter (m)	0.089
	Pipe outer diameter (m)	0.0267
	Pipe inner diameter (m)	0.0218
	Shank spacing (m)	0.0137
	Ground thermal conductivity (W m^{-1} K^{-1})	3.0
	Ground thermal capacitance (kJ m^{-3} K^{-1})	2415
	Grout thermal conductivity (W m^{-1} K^{-1})	1.73
	Grout thermal capacitance (kJ m^{-3} K^{-1})	1500
	Pipe thermal conductivity (W m^{-1} K^{-1})	0.43
	Undisturbed ground temperature (°C)	10
	Experimentally calculated heat exchanger efficiency (-)	0.60
	Cooling and heating loops mass flow rates (kg/s)	0.2

Figure 7 presents the time evolution of the TC_{in} calculated using the plate heat exchanger model and the values reproduced using the chiller. It is shown that the chiller is able to reproduce TC_{in} with very good precision.

Figure 8 shows the time evolutions of the measured TRT_m on the VB and the corresponding value predicted by the TRC model for a ground thermal conductivity of 3.0 $Wm^{-1}K^{-1}$. As shown in Figure 8, the time evolution of TRT_m obtained on the virtual borehole is very similar to that given by the TRC model. The maximum deviation between the curves is 0.4°C and the mean deviation is 0.07°C. The maximum deviation occurs 6 minutes after the start of the test when the rate of change in the chiller outlet temperature is the highest. After that, the temperature of the hot water loop approaches the one predicted by the TRC model and the gap between the curves decreases.

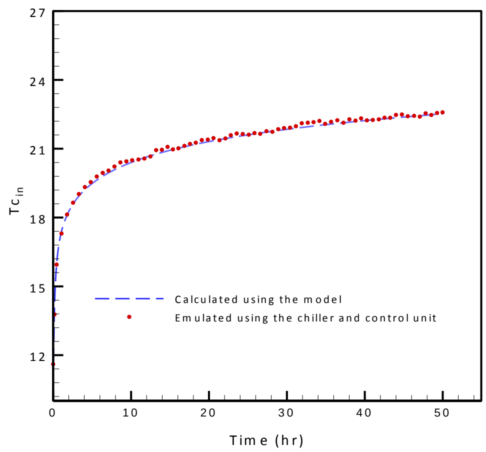


Figure 7: Calculated and measured TC_{in}

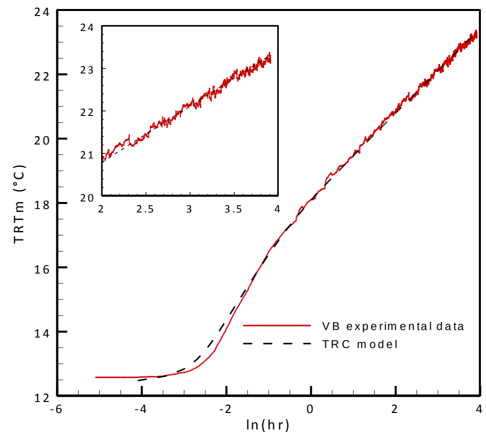


Figure 8: Comparison between the measured values of TRT_m and the ones predicted by the TRC model for k = 3.0 W m^{-1} K^{-1}

Based on this experiment, the VB is able to successfully reproduce the ground thermal behavior calculated by the TRC model for ground thermal conductivities of 3.0 W.m^{-1}.K^{-1}. An uncertainty analysis was also performed to quantify the uncertainty of the ground thermal conductivity simulated by the VB. For the test presented in this paper, the uncertainity is ±0.005 W.m^{-1}.K^{-1} This uncertainty corresponds to a relative error of ±0.2% confirming that the VB can accurately reproduce the ground thermal response.

The TRT unit connected to the virtual borehole includes measuring instruments and a data acquisition system that records temperature, flow, current and voltage measurements. The data recorded in the TRT unit is exported to an analysis software that uses the infinite line source method to calculate the ground thermal conductivity. For the tests performed on the virtual borehole, this software calculates a thermal conductivity of 3.18 W.m^{-1}.K^{-1} for the 3.0 W.m^{-1}.K^{-1} test. This corresponds to a difference of 6%.

CONCLUSION

In this paper, the concept of using a virtual borehole (VB) to calibrate TRT units is presented. The VB consists of a plate heat exchanger, a water loop cooled by a chiller and a control algorithm, which mimic the thermal behaviour of ground heat exchangers by using a TRC model. The TRT unit is connected to the VB as it would in a real geothermal borehole. In this paper, the VB is used to simulate a ground thermal conductivity of 3.0 W.m^{-1}.K^{-1}. For this test, there is a good agreement between the time evolution of TRT_m obtained using the VB and the one calculated by the TRC model of the borehole. A commercially-available TRT unit is then tested with the VB. The TRT unit reported a thermal conductivity of 3.18 Wm^{-1}K^{-1} while the VB had a preset value of 3.0 ± 0.005 Wm^{-1}K^{-1}. This corresponds to a 6% difference. The VB concept could be a valuable tool to calibrate TRT units for various groud conditions. However, additional work is necessary to characterize the heat exchanger for the complete range of flowrates that are likely to be used during tests.

ACKNOWLEDGMENTS

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