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Ten Years of Thermal Response Tests with Heating Cables

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ABSTRACT

The use of heating cables was proposed at the World Geothermal Congress in 2010 to conduct thermal response tests in ground heat exchangers without water circulating in the pipes of the exchangers. Heating water with a constant rate at surface during a test in the field can be difficult due to varying temperature at surface, the need to insulate the unit components, the establishment of a significant temperature difference between the pipe inlet and outlet, potential pipe leaks, air trapped in the circulating water, and parasitic heat losses. Circulating the water in a ground heat exchanger during a test additionally brings analytical challenges because the heat injection rate along the borehole likely varies with depth. Ten years of research have therefore been conducted since this original development, providing an alternative thermal response test method to avoid problems due to water circulation. The objective of the research was to evaluate the in situ subsurface thermal conductivity to design ground-coupled heat pump systems with a simplified field method using a low power source, typically less than 1 to 2 kW. Thermal response tests with a heating cable assembly have been conducted in various types of ground heat exchangers using three main cable configurations: 1) continuous heating cable in a 30 m deep heat exchanger installed for a direct expansion heat pump, 2) ten short 1.2 m length heating cable sections deployed in 100 to 140 m deep heat exchangers and 3), more recently, a continuous heating cable in a 100 m deep heat exchanger. This last test with a long and continuous heating cable was successfully conducted with a heat injection rate of less than 10 W m^{-1} to minimize the power requirement and has been possible due to the improvement of submersible data loggers, having a temperature accuracy and resolution of ±0.1 and ±0.05 °C, respectively. Field tests that combined a heating cable and fiber optic distributed temperature sensing were also conducted to better understand heat transfer mechanisms during such tests. A method to infer groundwater flow direction and magnitude during the test with temperature sensors surrounding the heating cable has additionally been proposed. This paper reviews recent developments for thermal response tests with heating cables and highlights novelty in this field.

1. INTRODUCTION

The design of a geothermal heating and cooling system, more specifically a ground-coupled heat pump (GCHP) with ground heat exchangers (GHE) installed in boreholes, requires knowledge on the thermal state and properties of the subsurface (Raymond et al., 2018). To gain this knowledge, practitioners commonly rely on the drilling of an exploration borehole, the measurement of the undisturbed ground temperature and a thermal response test (TRT) performed at the project pre-feasibility stage (ANSI/CSA, 2016). The TRT is an active field experiment to evaluate the *in situ* thermal conductivity of the subsurface by disturbing the subsurface thermal equilibrium and analyzing the subsequent transient temperature response. The conventional TRT is carried out by circulating heated water in a GHE, injecting heat from the surface to the underground at a constant rate (Raymond et al., 2011; Vieira et al., 2017). Temperature at the GHE inlet and outlet is recorded during the test and often analyzed with the infinite line-source equation to infer the subsurface thermal conductivity (Luo et al., 2016; Rainieri et al., 2011; Zhang et al., 2014). The method was first envisioned to reproduce heat transfer from GHE and infer the subsurface thermal conductivity from conditions at which a GCHP system can operate (Mogensen, 1983). While the conventional TRT has gained in popularity over the last four decades (Spitler and Gehlin, 2015), the method remains complex and can be difficult to implement in the field. The main difficulty is to maintain a constant heating rate for water circulating at the surface because of varying surface temperature or solar radiation, poor insulation of unit components, potential pipe leaks, air trapped in the circulating water, and parasitic heat losses of the circulating pump, which can affect the test analysis. In addition, a temperature difference between the GHE inlet and outlet of 3 to 7 °C has to be established

(Kavanaugh, 2001), such that tests are conducted with a heat injection rate of 30 to 80 W m^{-1}, representing 4.6 to 12.2 kW of power for a typical 152 m long GHE. Test analysis can be complex because the heat injection rate along the GHE decreases with depth and is therefore not uniform requiring various hypothesis to proceed with analysis (Marcotte and Pasquier, 2008; Beier, 2011; Beier et al., 2012, 2013; Koubikana Pambou et al., 2019).

When trying to solve the above issues related to water circulation, the first author conducted a TRT with heating cables standing in the GHE pipe water and reported results in a paper presented at the World Geothermal Congress (Raymond et al., 2010). The idea was adapted from heat tracing tests used for hydrogeological investigations (Pehme et al., 2007). The objective of TRTs conducted with a heating cable was to infer the subsurface thermal conductivity with a simplified field method, avoiding water circulation at surface and the requirement of a high power source. Tests with a low power source can be conducted since there is no need to create a temperature difference between the inlet and outlet of a GHE when using heating cables. Three main cable configurations were used for such TRT, which are: 1) continuous heating cable in a 30 m deep heat exchanger installed for a direct expansion heat pump system (Talaboulma, 2013), 2) ten short 1.2 m length heating cable sections deployed in 100 to 140 m deep heat exchangers (Raymond et al., 2015; Simon, 2016; Vélez Márquez, 2018) and, more recently, 3) a continuous heating cable in 100 m deep heat exchangers (Vélez Márquez, 2018). Additional research aimed to couple TRT with a heating cable and fiber-optic distributed temperature sensing (FO-DTS) to better understand heat transfer mechanisms taking place during such TRTs (Vélez Márquez, 2018). A method to infer groundwater flow direction and magnitude with a heating cable TRT conducted in a single borehole using temperature sensors surrounding the cable was further developed (Rouleau, 2015). This paper reviews the recent improvements associated with heating cable TRTs, emphasizing results found in four theses, two of them that remained unpublished. The use of heating cable appears to generate interest from the geothermal research community since it can be coupled with various ways of measuring GHE temperature, including FO-DTS, to evaluate a profile of the ground thermal conductivity with a high spatial resolution (Galgaro et al., 2018), while analysis is done confidently assuming a constant heat injection rate at depth.

2. METHOD

Heating cable TRTs are conducted with a cable assembly installed in at least one pipe of a GHE (Figure 1), commonly drilled for an exploration borehole and later integrated to a full GCHP system. The heating cable assembly can be made of alternating sections of heating and non-heating cable or a single continuous heating cable (Raymond et al., 2015). In the case of heating sections, care should be taken to install rubber discs at the interface between heating and non-heating cables to decrease the potential effects of free convection that can occur in the standing water column during the tests (Vélez Márquez et al., 2018). The cable is lowered under its weight in the GHE pipe and, unlike conventional TRT, there is no water circulation activated with a surface pump. A junction box allows to connect an electrical source to the cable dissipating heat underground. Various temperature sensors can be used to measure temperature at depth, including a chain of thermistors linked to the surface with wires and a central data logger, submersible temperature sensors commonly made with a semiconductor circuit sensitive to temperature and each linked to a miniature data logger, or a FO-DTS system. The latter provides the best spatial resolution, down to less than 1 m, but can be expensive due to the cost of the DTS unit. On the other hand, tests can be conducted with submersible temperature data loggers spaced at 5 to 15 m intervals along the GHE, which is cheaper than using FO-DTS. Submersible data loggers have become affordable over the last decade, while their accuracy and reliability have increased, making this option attractive for heating cable TRT. A power meter in the junction box is used to measure the current potential difference and intensity assigned to the heating cable. A potential difference regulator can be used to control the heat injection rate. An automated switch allows to program the start and the end of heat injection. Instruments in the junction box can be connected to a wireless router linked and the cellular network, which allows transferring data through the cloud and remote control of the unit.

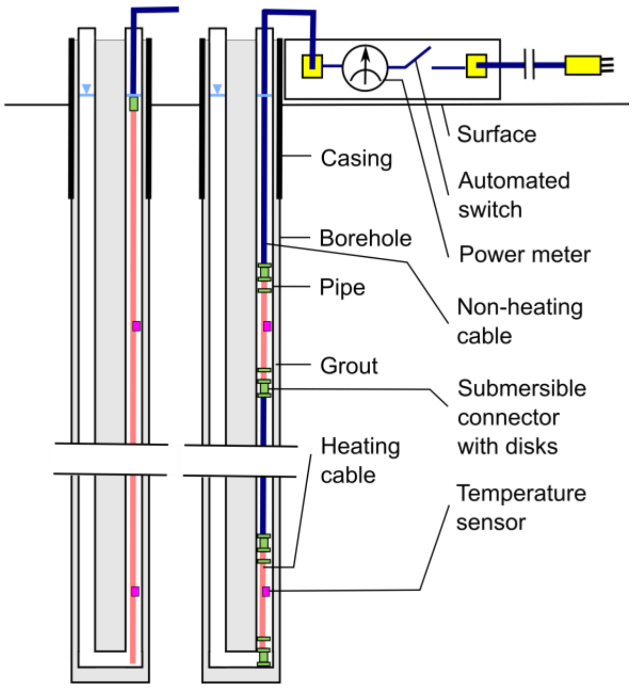

Figure 1. Unit components for TRTs with a continuous heating cable and alternating heating and non-heating cable sections installed in a GHE (modified from Raymond 2018).

The test starts with the measurement of the undisturbed ground temperature after the cable has been lowered in the GHE pipe. It is advisable to measure the undisturbed ground temperature for about 2-5 h to make sure the cable, which was previously at surface, reaches a thermal equilibrium with the ground. Electric current is flown in the cable assembly to start heat injection, which can last a minimum of 40 to 60 hours like conventional TRTs, (Austin III et al., 2000) or be carried out for a given duration to reach a radius of influence of at least ~1-2 m (Raymond et al., 2014). The following temperature recovery is monitored when heat injection stops for a duration at least equivalent to the heat injection period. The equipment is retrieved from the GHE and can be moved to another site for the following test. While doing various tests, the authors have tried to keep a low electric power requirement to facilitate field procedures. This can be possible with a heat injection rate of ~30-60 W m^{-1}, close to that of conventional TRT, over short GHE of ~30 m in length, which was achieved in the GHE of a direct expansion geothermal system presented as an example below. A similar heat injection rate can be used with short heating sections, for example 1.2 m in length and spaced by ~10 m, over conventional GHEs that are 100 to 150 m in length. Small-scale experimental tests with a single heating section and full-scale tests with ten heating sections conducted in GHE of 100 m length or more are presented in the second group of examples. Alternatively, tests can be made in GHE of 100 m in length or more with a continuous heating cable and a low heat injection rate below 10 W m^{-1}. The recent development of submersible temperature data loggers, having an accuracy and resolution of at least ±0.1 and ±0.05 °C, have made this option feasible. As long as the temperature sensors can detect subtle temperature changes, the heat injection rate can be low without affecting the test quality. The resolution of the temperature measurements is the sensor characteristic of importance since relative measurements of temperature increases are made during a TRT. A test conducted over a 100 m GHE with 14 temperature sensors is presented as a third example.

Temperatures measured during heating cable TRTs can be analyzed with the line-source equation (Raymond et al., 2010). Other approaches can also be used, such as the cylindrical-source equation or a numerical model solving conductive heat transfer from a 1D heat source representing the heating cable embedded in a 3D medium acting as the subsurface and GHE. The observed temperature increments can be reproduced with the analytical or numerical solution and the subsurface thermal conductivity is found by inversion with a solver to minimize the difference between observed and computed temperature (Raymond et al., 2015). A finite heat source equation is necessary for TRT conducted with heating cable sections (Raymond and Lamarche, 2014), while an infinite heat source equation is applicable for tests with a continuous heating cable. Alternatively, the test can be analyzed with the slope method, to calculate the thermal conductivity from the heat injection rate and the slope of the temperature increase with respect to logarithmic time, either for the heat injection or the recovery period when heat injection is stopped and the monitored temperature is analyzed considering the temporal superposition principle (Raymond, 2018). Unless the slope method is used, the temperature signal recorded during the heat injection depends on a borehole thermal resistance that is difficult to evaluate because it varies with the horizontal position of the cable inside the pipe. Small movements of the cable can result in temperature oscillations such that it is best to base the analysis on temperature recovery, where the horizontal temperature field inside the GHE tend to be independent of the cable or temperature sensor position (Raymond et al., 2011). The analysis is done independently for each temperature sensor. Neglecting vertical heat transfer allows determining the thermal conductivity of subsurface layers to profile ground heterogeneities. The error propagation theory can be used to evaluate uncertainty related to the thermal conductivity assessment, using an approach similar to conventional TRT (Witte, 2013).

The method used to find the equivalent subsurface thermal conductivity inferred at the depth of each sensor assumes that conduction is the dominant heat transfer mechanism in the subsurface. This approach is reliable when the groundwater flux is below 1×10^{-6} m s^{-1} to 1×10^{-8} m s^{-1}, the limit at which adjective heat transfer becomes significant to TRTs or GCHP operation (Signorelli et al., 2007; Dehkordi and Schincariol, 2014; Ferguson, 2015). In the case of significant groundwater flow, the magnitude and orientation of the flow can be detected by installing a minimum of three temperature sensors around the heating cable placed in an open borehole to conduct the TRT (Figure 2; Rouleau et al., 2016). An inversion method has been verified numerically to identify the subsurface thermal conductivity as well as the groundwater flow direction and magnitude from a TRT conducted in a single borehole (Rouleau and Gosselin, 2016), which is typical of GCHP prefeasibility studies. Recent numerical developments about this method are detailed below.

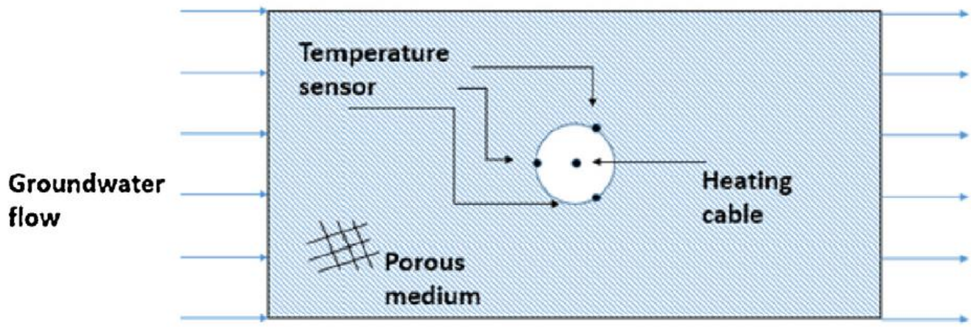

Figure 2. Installation of heating cable and surrounding temperature sensors in a borehole section to evaluate both the subsurface thermal conductivity and the groundwater flow magnitude and orientation (reproduced from Rouleau et al., 2016).

3. RESULTS

The examples below illustrate results for heating cable TRTs in GHEs of various lengths and configurations. In all cases, testing was with a compact equipment eliminating difficulties related to water circulation at surface and that uses a low electric power source with direct connection to the power grid.

3.1 TRTs WITH A CONTINUOUS HEATING CABLE IN A SHORT DIRECT EXPANSION GHE

Unlike conventional GCHP, direct expansion geothermal heat pump systems have no secondary loop with water circulating in the GHE. The heat pump refrigerant directly circulates in the GHE, which is commonly made of copper tubing installed in a short borehole with a length on the order of 30 m. The nominal diameter of the copper U-pipe is typically ¼ to ½ inch. Conventional TRT units with a water pump and an electric resistance heater made for secondary loop GHEs, having a high-density polyethylene (HDPE) pipe with a nominal diameter of ¾ to 1½ inch, are not adapted for TRT in GHEs of direct expansion systems, while a TRT unit with a heating cable can be easily adapted with a cable that fits inside the copper tube. Three TRTs were performed at École de technologie supérieure (ÉTS) in Montréal in such a direct expansion GHE, which had a length of 30 m and was drilled in unconsolidated Quaternary deposits and the underlying bedrock (Talaboulma, 2013). A chain of thermistors tied to the copper pipe was already installed along the GHE at depths of 7.5, 15.0, 18.8, 22.5 and 26.3 m and was used for temperature monitoring. A mineral insulated heating cable ensured thermal contact with the copper pipe that was filled with water. The average heat injection rate was 63 W m^{-1}, for a total power consumption of 1.89 kW. Heat injection tests lasted 50, 74 and 100 h (Figure 3), with the latter test including a power interruption of 8 h. Thermal recovery was monitored for an equivalent duration.

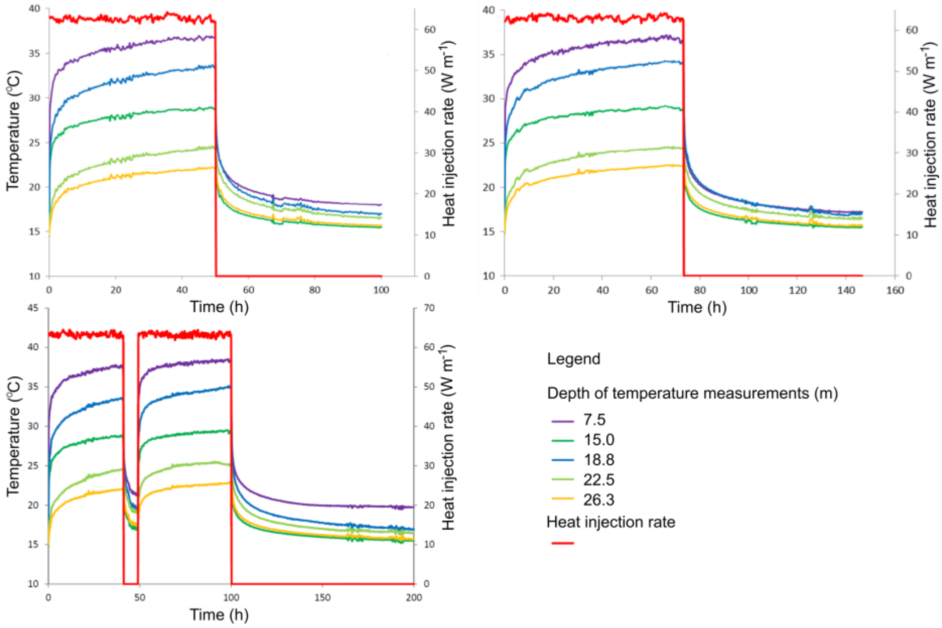

Figure 3. Data record for continuous heating cable TRTs conducted in Montréal in a direct expansion GHE of 30 m depth for a duration of 50 (top left), 74 (top right) and 100 (bottom left) h (modified from Talaboulma 2013).

The measured recovery temperatures were analyzed with the infinite line-source equation using the slope and the curve fitting methods, while the infinite cylindrical-source equation and a finite-element numerical model were also used for automated curve fitting. An example of curve fitting of recovery temperature measured at a depth of 26.3 m during the 100 h heat injection test is shown in Figure 4. The analyses of the three tests show that the subsurface thermal conductivity ranges from 2.5 to 4.2 W m^{-1} K^{-1} (Figure 5). The increasing thermal conductivity at depth suggests a contact with the bedrock between 18.8 and 22.5 m depth. The uncertainty of thermal conductivity estimates was on average ±2.5 % and the largest source of error was that associated to the measurement of the heat injection rate.

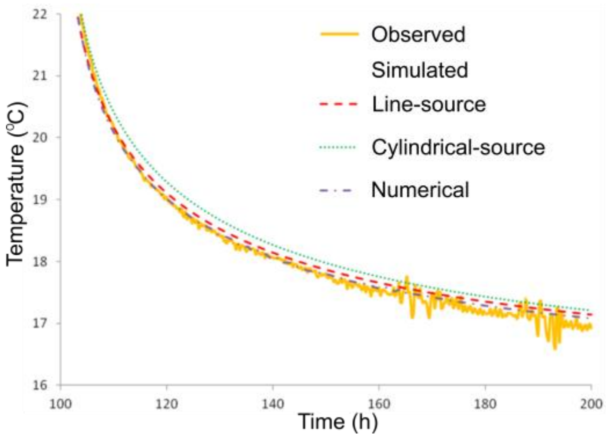

Figure 4. Reproduction of recovery temperature measured at 26.3 m depth to analyze the continuous heating cable TRT conduct in Montréal in a direct expansion GHE for the test with heat injection that lasted 100 h (modified from Talaboulma 2013).

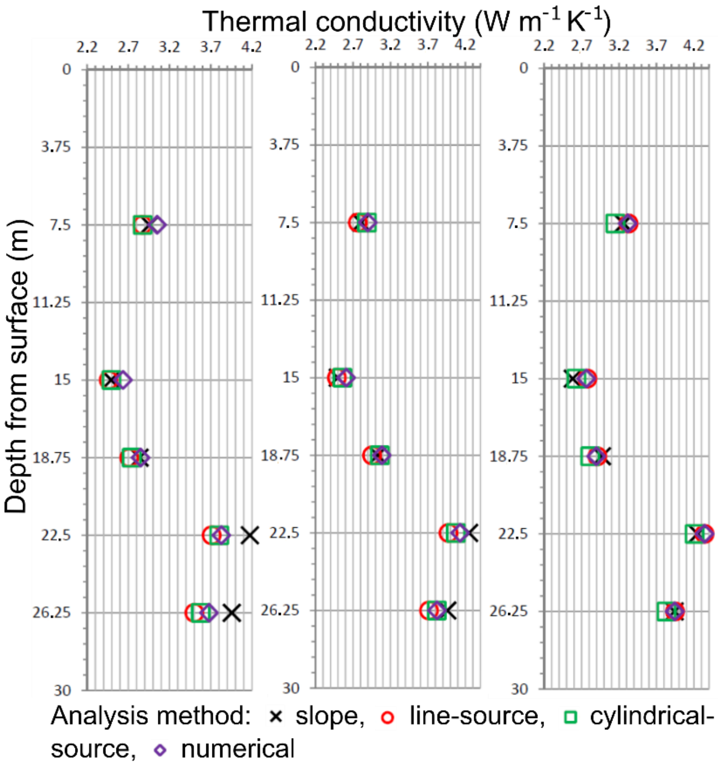

Figure 5. Thermal conductivity profiles determined for continuous heating cable TRTs conduct in a direct expansion GHE in Montréal for tests with heat injection that lasted 50 (left), 74 (middle) and 100 (center) h (modified from Talaboulma 2013).

3.2 TRTs WITH HEATING CABLE SECTIONS IN CONVENTIONAL GHEs

A cable assembly with alternating short heating (1.2 m) and long non-heating (8.8 m) sections was developed to conduct TRTs in conventional GHEs of 100 m in length or more, using a heat injection rate similar to that used for conventional TRT based on water circulation. The electric cables were made of copper wires of different diameters surrounded by a polymer jacket. The heating sections TRT offers an alternative to conduct tests with a low power source inside conventional GHE with regular length. However, water flow due to free convection can occur at the interface between heating and non-heating sections because of temperature contrasts caused by the change in heat injection rate, which can make the test analysis complex. Perforated rubber discs were installed at the edges of heating sections to reduce free convection effects (Figure 6). Tests were made at ÉTS in Montréal with a single heating section and an increased number of perforated rubber discs in GHEs with HDPE pipe of nominal diameter of 1¼, 2 and 4 inch to verify the discs ability to block free convection (Simon, 2016). The sandy material intercepted while drilling the pilot boreholes was sampled and its thermal conductivity, assessed with a needle probe, varied between 1.1 and 1.7 W m^{-1} K^{-1}. A total of eight TRTs were conducted in each borehole, starting with no rubber discs at the heating section edges and increasing their number up to four discs at the edges. The heat injection period was on average 72 h and the thermal recovery was monitored for a duration that was about twice that of the heat injection using a chain of thermistors with sensors at the middle of heating sections.

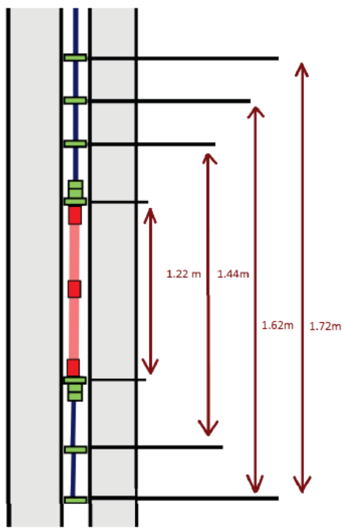

Figure 6. Distances between perforated rubber discs (green) installed at the edge of a heating section (red) to reduce free convection effects for TRTs in Montréal (reproduced from Simon, 2016).

The measured recovery temperatures were reproduced with the finite line-source equation using an automated curve matching procedure to invert the subsurface thermal conductivity. An example of test analysis for a temperature sensor located at the middle of a heating section for the GHE with the pipe nominal diameter of 1¼ inch, in the case of four rubber discs at the heating section edges, is provided below (Figure 7). A thermal conductivity of 1.38 W m^{-1} K^{-1} was evaluated with the needle probe for a sand sample collected at the location of the heating section. The analysis of the *in situ* tests indicate values ranging from 2.24 W m^{-1} K^{-1} for tests without discs to 1.51 W m^{-1} K^{-1} when using the four discs to partially block convection (Table 1). Higher *in situ* thermal conductivities suggest that free convection can play a role in heat transfer even with rubber discs that are designed to reduce its effect. Because it is not taken into account in the heat conduction solution used to analyze the test, free convection can affect the estimation of thermal conductivity from the test. One solution to eliminate this problem is to consider an active heating length, when computing temperature with the finite line-source solution, which is equal to the heating cable length plus that including the discs (Figure 6). This allowed an *in situ* estimate of the subsurface thermal conductivity within +9.4 to -16.4 % of the thermal conductivity determined with a needle probe in the laboratory (Table 1).

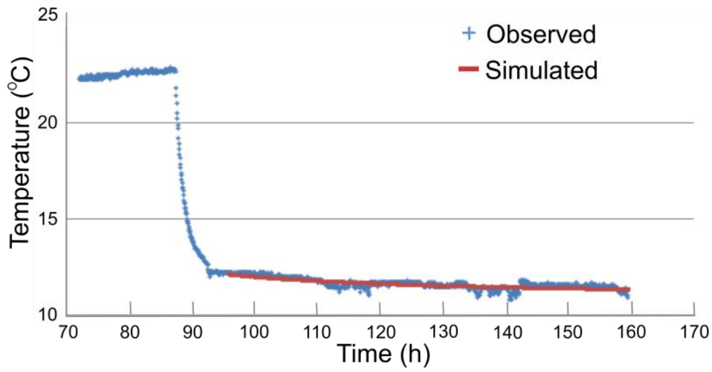

Figure 7. Reproduction of recovery temperature to analyze a small scale TRT conducted with a single heating section in Montréal to evaluate the effect of perforated rubber discs at the edge of the heating section to block free convection (Simon, 2016).

Table 1. Effect of active heating length considered for analysis of the heating sections TRT conducted in Montréal.

Sample thermal conductivity (W m^{-1} K^{-1})	1.38			
Active heating length (m)	1.22	1.42	1.62	1.82
In situ thermal conductivity (W m^{-1} K^{-1})	1.51	1.40	1.27	1.16
Difference (%)	+9.4	+1.2	-7.9	-16.4

Two full-scale tests in GHE of 140 and 100 m in length and including ten heating sections were additionally conducted (Raymond et al., 2015; Vélez Márquez et al., 2018). One TRT was in Saint-Lazare-de-Bellechasse, at the Versaprofiles plastic pipe factory in mudslate of the Appalachians, and the second was in Quebec City, at the environmental laboratories of the Institut national de la recherche scientifique in shale of the St. Lawrence Lowlands. The average heat injection rate of the heating sections for these tests was 32.0 and 42.5 W m^{-1}, respectively, for a total power consumption of 845 and 985 W, respectively. Temperature was measured with submersible temperature data loggers tied to the middle of the heating sections. Recovery temperature signals were matched to temperature computed with the finite line-source equation to determine the subsurface thermal conductivity, similarly to the approach used by Simon (2016) and provided as an example above (Figure 7). Thermal conductivity profiles of the subsurface were established at both sites (Figures 8 and 9) and compared to the bulk subsurface thermal conductivity inferred in the same GHE with a conventional TRT involving water circulation. The average thermal conductivity of the profiles inferred from the heating section TRT was within +12 to +15 % of the bulk thermal conductivity inferred with a conventional TRT.

Error analysis revealed an average uncertainty related to the thermal conductivity estimates of ±15 %. The largest source of error was that associated to the evaluation of the heat injection rate and the active heating length, which was 14 %. The heat injection rate dissipated by heating sections is evaluated indirectly, with electric potential difference and current intensity measurements for the full cable assembly and considering parasitic heat loss of non-heating sections, which has to be subtracted and increases uncertainty in addition to the active heating length that can be difficult to select accurately (Raymond and Lamarche, 2014). A FO-DTS system was installed for the second test to monitor temperature at 0.25 m intervals along the cable assembly in the standing water column and calculate Raleigh number, which indicated the presence of free convection slightly above the heating sections, although rubber discs were used at section edges. This can explain why the thermal conductivity of the profiles inferred with the heating sections is higher compared to the bulk value obtained with a conventional TRT, although the thermal conductivity estimate is within a reasonable range when considering sources of experimental errors.

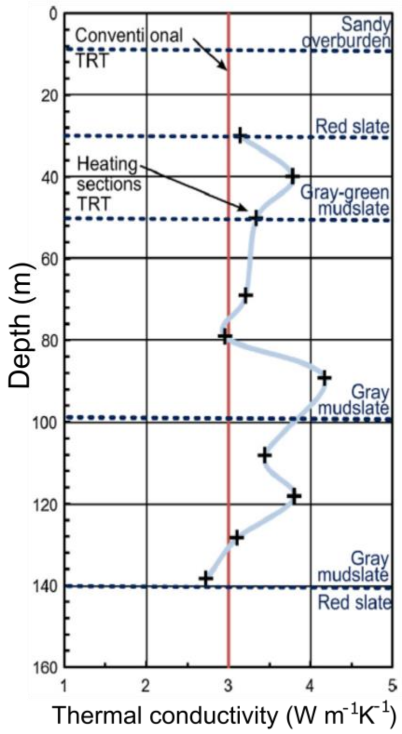

Figure 8. Thermal conductivity profile determined in Saint-Lazare-de-Bellechasse for a TRT conducted with ten heating sections in a conventional GHE of 140 m length (Raymond et al., 2015).

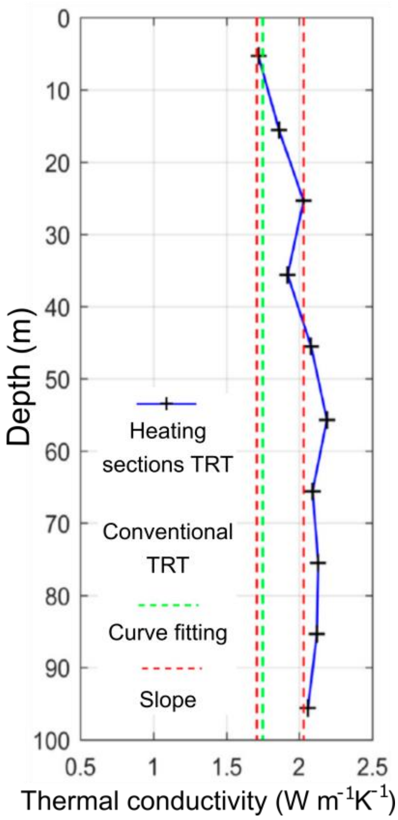

Figure 9. Thermal conductivity profile determined in Quebec City for a TRT conducted with ten heating sections in a conventional GHE of 100 m length (modified from Vélez Márquez et al., 2018).

3.3 TRT WITH A CONTINUOUS HEATING CABLE IN A CONVENTIONAL GHE

A continuous copper heating cable with a polymer jacket was used to perform a TRT in a conventional GHE of 100 m length. The GHE was installed in marly limestone of the Sologne basin below Orléans, France, at the experimental platform of the Bureau de la recherche géologique et minière (Vélez Márquez et al., 2018). A total of thirteen submersible temperature data loggers were installed at depth ranging from 12 to 85 m and the test was conducted with an average heat injection rate of 9.9 W m^{-1}, for a total power consumption of 990 W. The goal of this test was to verify if a very low heat injection rate can induce a temperature perturbation sufficiently high to be detected by the temperature sensors, to demonstrate the feasibility of continuous heating cable TRTs in conventional GHEs with a low power source. The accuracy and resolution of the submersible temperature data loggers were ±0.1 and ±0.05 °C, respectively. The heat injection period was 136 h and it was followed by monitoring of thermal recovery for 481 h.

Late recovery temperature measurements were analyzed with the infinite line-source equation using the slope method. The analysis for the temperature sensor at 53.6 m depth is provided as an example (Figure 10). The temperature of the recovery period varied from 16.0 to 14.6 °C and an accurate slope was calculated, although the temperature decrements were relatively small. The analysis allowed to determine a thermal conductivity profile with an average value of 1.47 W m^{-1} K^{-1} (Figure 11), which is exactly the same value as that inferred from a conventional TRT with water circulation conducted in the same GHE. The error associated to thermal conductivity estimates was ±2 % and was mainly due to the error related to the assessment of the heat injection rate computed from electric potential difference and current intensity measurements.

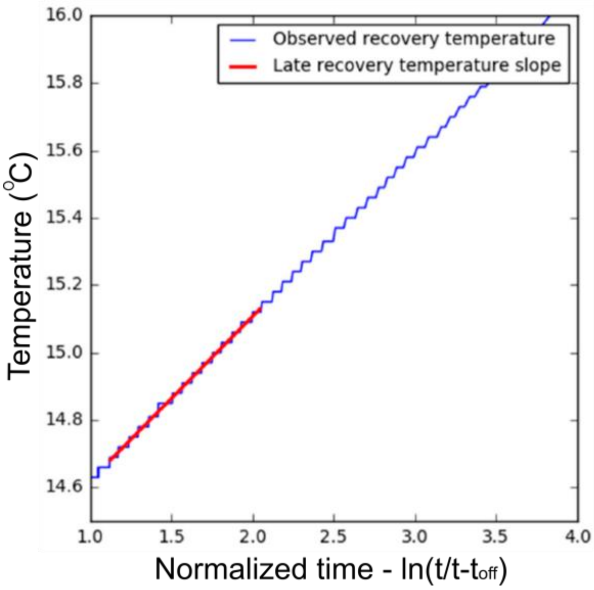

Figure 10. Analysis of recovery temperature measured at 53.6 m depth to analyze the continuous heating cable TRT conduct in Orélans in a conventional GHE of 100 m length with a very low heat injection rate (modified from Vélez Márquez et al., 2018).

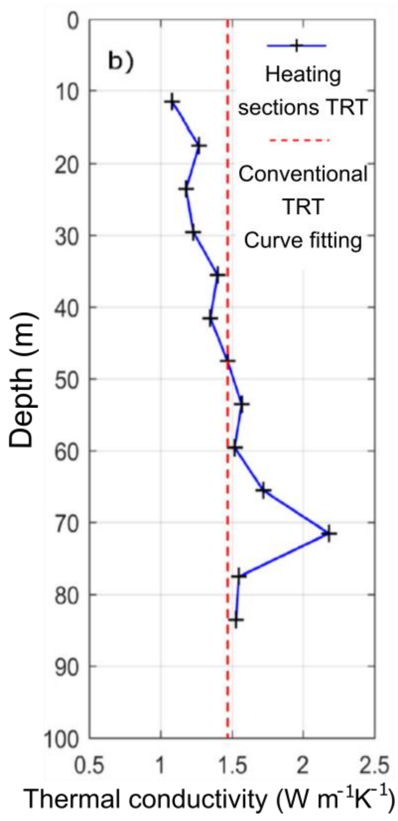

Figure 11. Thermal conductivity profile determine in Orléans for TRT conducted with a continuous heating cable in a conventional GHE of 100 m length (modified from Vélez Márquez et al., 2018).

3.4 POTENTIAL METHOD TO INFER GROUNDWATER FLOW MAGNITUDE AND DIRECTION

TRTs with a heating cable can be modified by adding temperature sensors around the heat source to evaluate the groundwater flow direction and magnitude, which can affect the operation of a GCHP system under significant flow conditions. The challenge here is to evaluate both the thermal conductivity and the groundwater flow direction and magnitude from a test conducted in a single exploration borehole. Numerical simulations were conducted to verify if this can be done by placing the heat source in an open borehole before installing the pipes of a GHE and adding three temperature sensors around the borehole wall at intervals of 120 ° (Rouleau et al., 2016). Typical TRTs with 50 h of heat injection followed by 50 h of thermal recovery with a heat injection rate of 40 W m^{-1} were simulated under varying groundwater flow conditions for which the Peclet number varies from 10^{-3} to 10^{-1}. The finite element method was used with Comsol Multiphysics to simulate heat transfer due to heat conduction and advection in a 2D model representing a slice of subsurface along which groundwater flow was imposed with constant head boundaries. The maximum temperature difference along the borehole perimeter was shown to be proportional to the flow velocity and its location was linked to the flow direction, such that a trigonometric calculation can be used to calculate the flow orientation and the maximum temperature difference along the borehole perimeter (ΔT_{max}; Figure 12). The Peclet number (Pe), characteristic of advective versus conductive heat transfer, was shown to vary linearly with this maximum temperature difference for different values of non-dimensional thermal conductivity ($\tilde{k}$; ratio of subsurface thermal conductivity divided by fluid thermal conductivity). An iterative procedure was then used to evaluate the subsurface thermal conductivity from the simulated recovery temperature measurements that were matched to temperature computed with an analytical solution, taking into account the groundwater flow velocity. An inversion procedure was further developed to determine the groundwater flow direction, magnitude and the thermal conductivity with analytical computations to reproduce temperature simulated numerically, which allowed to identify the groundwater flow velocity within -10 to + 22 %, considering a temperature sensor accuracy of 0.5 °C (Rouleau and Gosselin, 2016). A low heat injection rate was shown to affect the accuracy of the groundwater flow magnitude assessment such that is was suggested to use a heat injection rate on the order of 40 W m^{-1} to make sure the temperature sensors can properly detect groundwater flow.

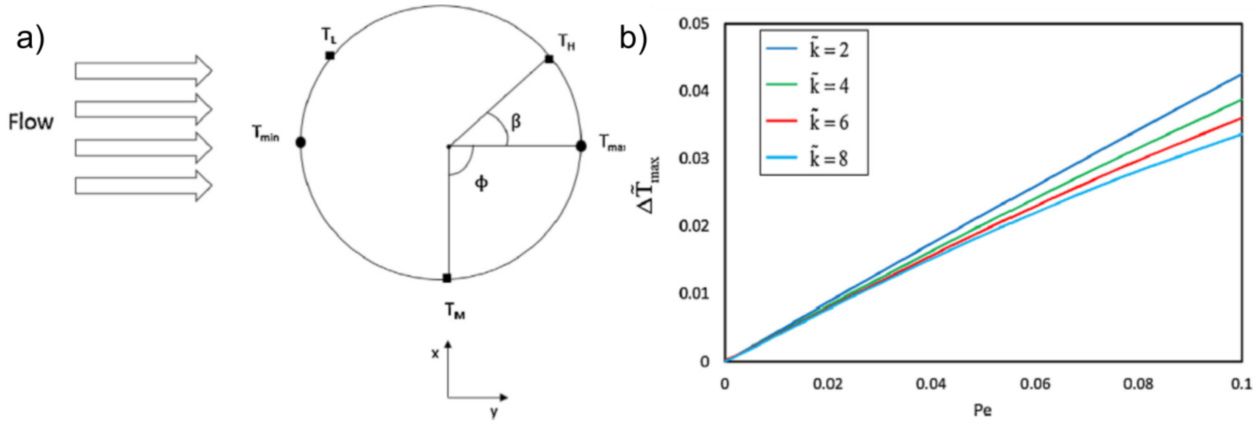

Figure 12. Concept of heating cable TRT with surrounding temperature sensors to infer a) the groundwater flow orientation with a trigonometric calculation and b) the groundwater flow velocity from the maximum temperature difference that affects the Peclet number (reproduced from Rouleau et al., 2016).

4. DISCUSSION

The different approaches developed to conduct heating cable TRTs in GHE of various lengths and configurations represent a set of alternatives to conventional TRT with water circulation. The error associated with thermal conductivity assessment of conventional TRTs is on the order of 5 to 10 % (Witte, 2013), while that of a heating section TRT can be above and that of a continuous heating cable TRT can be below this value (Vélez Márquez et al., 2018). In any TRT, the accuracy of the subsurface thermal conductivity assessment is strongly linked to the accuracy at which the heat injection rate is determined. Evaluating the heat injection rate with water flowing in the GHE requires an accurate flow meter, which can be expensive and difficult to maintain in hazardous field conditions, while the heat injection rate with a continuous heating cable is calculated from electrical potential difference and current intensity across the electric cable circuit, which are easily measured in the field. A TRT with a continuous heating cable performed properly can, therefore, be among the most accurate alternatives to assess *in situ* the subsurface thermal conductivity.

The first continuous heating cable TRTs were in short boreholes (~30 m), with a heat injection rate similar to that of a conventional TRT (Raymond et al., 2010; Talaboulma, 2013). Heating sections were then used to conduct tests in regular GHE of 100 to 140 m in length, keeping the same heat injection rate and a low power requirement (Raymond et al., 2015; Vélez Márquez et al., 2018). Over the past years, affordable submersible temperature data loggers (~100-200 US$ per logger) with improved accuracy have become available, allowing tests with a very low heat injection rate of less than 10 W m^{-1} (Vélez Márquez et al., 2018). These temperature data loggers, which are small enough to be located inside GHE pipes, are commonly made with a semiconductor circuit sensitive to temperature and connected to electrically erasable programmable read-only memory to record temperature. The logger can be encapsulated to sustain a pressure exceeding that of the water column at the base of a GHE. The last test performed in Orléans by Vélez Márquez et al. (2018) confirmed that such temperature loggers were sensitive enough to detect a small thermal perturbation and evaluate the subsurface thermal conductivity, providing detailed information about the variation of the subsurface thermal conductivity with depth, which is only possible for conventional TRTs coupled to FO-DTS and assuming variable heat injection rate at depth (Fujii et al., 2009; Acuña et al., 2011). Advantages of the continuous heating cable TRT rely on its simplicity, not only for field manipulations but also for analysis that can be done with the slope method, assuming a constant heat injection rate at depth, while providing a detailed subsurface assessment along the borehole to characterize ground heterogeneities.

The subsurface thermal conductivity assessments obtained from heating cable TRTs provide equivalent values, like in the case of conventional TRT, incorporating the effect of advective heat transfer due to groundwater flow. The method developed by Rouleau et al. (2016) and Rouleau and Gosselin (2016) to infer groundwater flow and magnitude with sensors surrounding the heat source is promising, but still has to be tested in the field and verified under varying groundwater flow conditions observed in natural environments. It will also be technically challenging to evaluate the position of the sensors at depth in a borehole.

5. CONCLUSIONS

Research has been carried out over the past ten years to fully develop heating cable TRTs and verify this method with successful comparison using thermal conductivity assessments on samples and conventional TRTs conducted in GHEs, always opting for a low power source. The simplicity of heating cable TRTs allow low-cost feasibility studies, potentially opening new markets for TRTs, for example in the residential sector where the subsurface of an urban district can be characterized with first GHE installations and where data is gained for subsequent installations by mapping the subsurface thermal conductivity (Raymond et al., 2017). While developments is sufficient for the method to be used by practitioners, further research can be envisioned to improve this alternative TRT concept. For example, TRT with a heating cable could be adapted through a constant temperature test to shorten its duration, like done for TRTs with a conventional unit where the constant temperature is maintained by water circulation (Aydin et al., 2017). Improving the current spatial limitation of TRTs, which have a radius of influence of ~1-2 m, is also worth further research efforts, either for conventional or heating cable TRTs. Temperature logs and other geophysical well logs methods can be combined with TRTs (Raymond, 2018), to laterally extrapolate the TRT assessment beyond the borehole where the heat injection test is conducted to characterize subsurface heterogeneities and the impact of groundwater flow. While various modeling approaches, such as the moving line-source equation (Molina-Giraldo et al., 2011; Wagner et al, 2013), have been developed to evaluate the impact of groundwater flow, field methods remain to be developed to properly evaluate groundwater flow direction and magnitude.

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