Insights from field experiments to conduct thermal response tests with a low power source

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Abstract: The assessment of the subsurface thermal conductivity with a conventional thermal response test is a costly procedure that has to be paid at the forefront of a geothermal heating and cooling project. Prohibitive cost, which is a drawback to geothermal technologies, can be avoided by reducing the power needed to conduct such tests. The conventional test method with flow of heated water in the ground heat exchanger is however not suited for low power. An alternative method using interchanging sections of heating cable to inject heat underground with a 120 V and 10 A power source is described in this study. Preliminary field tests, conducted to understand heat transfer phenomena, showed that recovery temperatures can be analyzed with a heat conduction solution when disks are placed at the extremities of the heating sections to reduce free-convection in the standing water column of the ground heat exchanger. The proposed method is expected to provide a subsurface thermal conductivity profile using less than 10 % of the energy required for a conventional thermal response test.

Key Words: geothermal, thermal response test, heating cable, heat exchanger, thermal conductivity

Nomenclature

[M L T t] are used to denote units of mass, length, temperature and time, respectively

H	length of heat source [L]
Fo	Fourier number [-]
g	finite heat source function [-]
q	heat transfer rate per unit length [M L t^{-3}]
r	radius [L]

Greek symbols

α	thermal diffusivity [L t^{-2}]
λ	thermal conductivity [M L T-1 t^{-3}]

Subscripts

off	interruption time
s	subsurface

1 INTRODUCTION

Field assessment of the subsurface thermal conductivity is commonly performed to design ground-coupled heat pump (GCHP) systems in the commercial, institutional and industrial sector of the building industry. Often referred as thermal response test (TRT), the assessment is carried out at the prefeasibility stage to evaluate the subsurface properties for calculation of the length of ground heat exchangers (GHEs) required to fulfill the building energy needs. The subsurface thermal conductivity significantly impacts the required GHE length and therefore affects the system installation cost, evidencing the importance of such a test.

The conventional testing method used by the geothermal industry aims to reproduce heat transfer taking place at a GHE (Mogensen 1983). Water circulating in a GHE is heated at surface to inject heat underground and disturb the thermal equilibrium to infer the subsurface thermal conductivity (Raymond et al. 2011b). Heavy mobile apparatus enclosing a pump, heating elements and measurement devices were developed more than fifteen years ago to conduct the tests (Gehlin 1998; Austin III 1998). A heat injection rate of 50 to 80 W m^{-1} is recommended by the North American industry guidelines to create a temperature difference of about 3 to 7 °C between the inlet and outlet of the GHE (Kavanaugh 2001). The total heating power needed to conduct a TRT in a GHE that is 150 m long is therefore between 7.5 and 12 kW, which requires an electric current intensity of 31 to 50 A for a potential difference of 240 V. The power is supplied by a fuel-fired generator or by connecting the TRT unit to the electric grid. The mobilization of heavy equipment and the supply of power are important sources of cost and the TRT is generally considered expensive by the industry stakeholders. According to the authors experience, the cost associated to the use of a generator for a conventional TRT, including mobilization and fuel, is approximately 30 % of the total TRT cost. This can in fact be a drawback to GCHP systems since TRT expenses has to be paid at the forefront of a project before the economic viability of the system has been demonstrated.

Alternative and cost competitive approaches for carrying out TRTs could facilitate prefeasibility studies for GCHP systems and contribute to increased market share. Improving TRT economics is possible by decreasing power requirements to avoid the use of a heavy generator, which can be achieved by injecting heat at specific depths of the subsurface rather than through the entire GHE. A new method was therefore developed to conduct TRTs with a low power source, where heat is injected along interchanging sections of heating and no-heating cables installed in a single pipe of the GHE (Raymond and Lamarche 2013, Submitted). Numerical simulations of the proposed TRT were initially achieved to validate the analysis methodology (Raymond and Lamarche 2014, Accepted). Field experiments have then been conducted with a first prototype apparatus to demonstrate potential use of the technology. Preliminary results obtained from temperature measurements recorded along a heating section during those experiments are described in this manuscript after reviewing the proposed apparatus and method to conduct TRTs with a low power source.

2 APPARATUS DESCRIPTION AND FIELD METHOD

A cable assembly is lowered in a single pipe of the GHE to conduct the proposed thermal response test (Figure 1a and b). The cable assembly encloses interchanging sections of heating and non-heating cables joined with submersible connectors (Figure 1c). The heating cable sections are used to inject heat at different depths in the subsurface and the interchanging assembly allows a reduction of the power requirements when compared to a continuous heating cable. Perforated rubber disks are located at the extremities of each cable section to prevent convective water movements in the standing column of water. Perforations are necessary to reduce friction when the cable is being inserted into the GHE pipe. The size of the perforations has to be small enough to block convective water movements. Two circular holes with a 5 mm diameter were made in the disks for the tests reported in this study. Experience gained with the initial field experiments showed that friction due to the disks actually helps lowering the cable assembly that gently sinks in the pipe of the GHE. Without disk, the cable sinks rapidly under its weight and has to be slowed down to avoid potential failure. The disks are, therefore, not only helpful to reduce heat transfer by free-convection, but also beneficial to field installation. A temperature sensor is positioned at the middle height of each heating cable section to monitor temperature at depth during the TRT. Temperature sensors with electrically-erasable programmable read-only memory enclosed in a submersible capsule were used in this study to measure and record temperature. The accuracy provided by the manufacturer for the temperature sensor was ± 0.125 °C.

A junction box at surface is attached to the GHE casing and provides the link between the power supply and the heating cable assembly (Figure 1b). A power meter with a data logger to measure and record the electric potential difference and current intensity induced to the heating cable is enclosed in the junction box, which also contains a breaker panel for the different electric circuits. An automated switch controls the electric circuit supplying power to the cable assembly to automatically start and stop heat injection. The accuracy for the power measurements recorded during this study was approximately ± 3 %.

The test begins with a measurement of the undisturbed subsurface temperature at the depth of each temperature sensor before heat injection starts. The electric current is then induced to the cable assembly and power is monitored during the heat injection period to disturb the subsurface temperature. Heat injection is stopped afterward and temperature inside the GHE returns to equilibrium during the thermal recovery period. Temperature can be monitored during both the heat injection and the recovery period but only recovery temperatures are

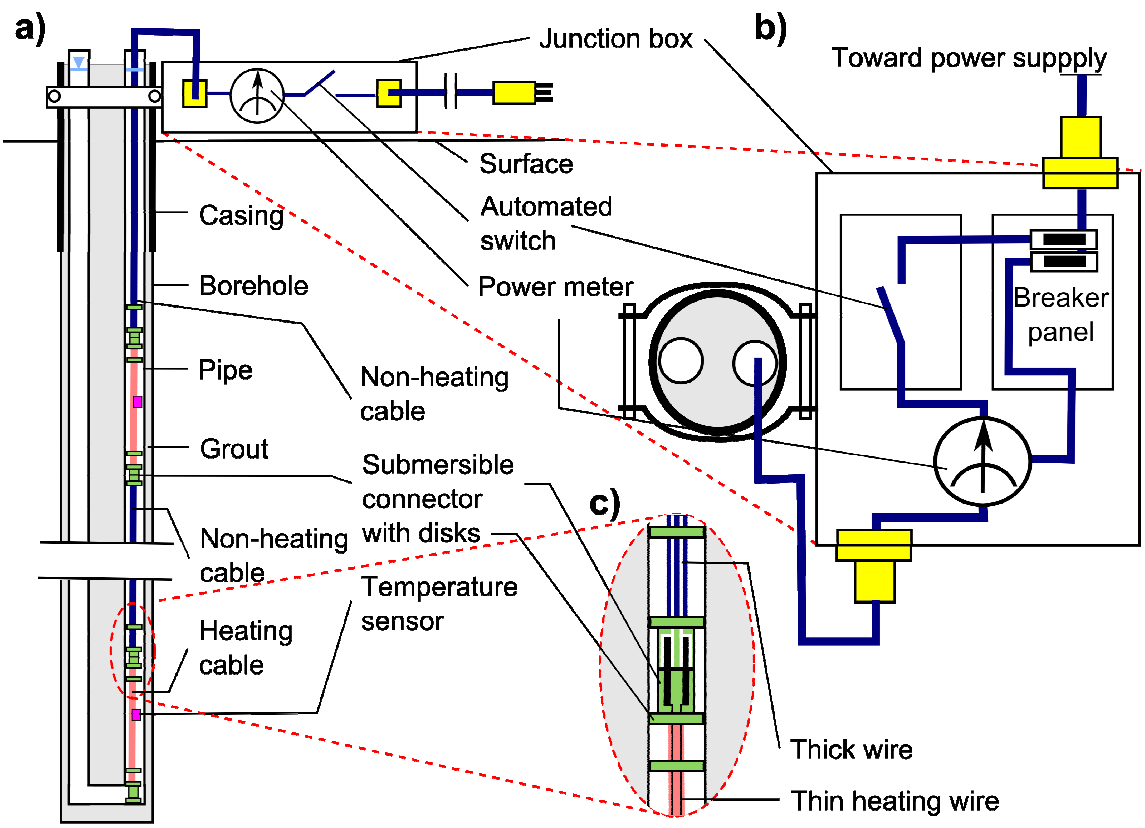

Figure 1: a) Vertical cross-section and b) plan surface view of the apparatus to conduct TRTs with heating cable sections joined with c) submersible connectors enclosing perforated disks.

used to evaluate the subsurface thermal conductivity. The cable assembly is finally removed from the GHE pipe to retrieve the temperature sensors after the thermal recovery, which can be monitored for a duration equivalent to that of the heat injection period.

The proposed TRT differs in many aspects from the conventional TRT. Firstly, heat is injected underground along heating cable sections inside the GHE in replacement of heating water at surface with an electric element. Secondly, water is standing in the pipe of the GHE instead of flowing in and out of the GHE. Thirdly, temperature measurements are conducted at distinct depths rather than at the pipe inlet and outlet of the GHE, although temperature measurements inside the GHE during conventional TRTs can be achieved (Fujii et al. 2009). The injection of heat with heating cable sections in a single pipe of the GHE is an improvement of previous research, where the use of continuous heating cables installed in each pipe of the GHE was investigated (Raymond et al. 2011a; 2010). A continuous heating cable can be used to perform TRTs with a low power source in a short borehole, for example in GHEs used with direct exchange geothermal systems where the length is on the order of 30 m (Talaboulma 2013), but would require a higher power source for GHEs used with GCHP systems where the length is commonly more than 100 m.

3 TEST ANALYSIS

The subsurface thermal conductivity at the depth of each temperature sensor can be inferred from recovery temperatures. During the heat injection period, the temperature depends on the radial position of the sensor making the analysis difficult. The temperature in the vicinity of the heating cable in a horizontal slice of the GHE tends to become uniform during the recovery period, which allows estimation of the subsurface thermal conductivity without knowing the exact position of the temperature sensor (Raymond and Lamarche 2014, Accepted).

A dimensionless g [-] function, approximating the temperature increments ($\Delta T = T - T_0$) at the middle height (z = 0) of a finite linear heat source surrounded by a homogenous conductive medium is used for analysis:

$$\Delta T_z = \frac{q}{2\pi\lambda_s} g\left(Fo, \frac{r}{H}\right) \tag{1}$$

and $$Fo = \frac{\alpha_s t}{H^2} \tag{2}$$

In equations 1 and 2, q [M L t^{-3}] is the heat injection rate per unit length, r [L] is the radial distance from the heat source, H [L] is the height of the heat source and λ_s [M L T^{-1} t^{-3}] and α_s [L^2 t^{-1}] are the thermal conductivity and diffusivity of the medium representing the subsurface. To analyze a TRT, the temperature near the heating cable during the recovery is found by calculation of the function g at a small distance from the heat source (r = 0.01 m) with the superposition principle to account for the interruption of the heat injection:

$$\Delta T_{z,r} = \frac{q}{2\pi\lambda_s}\left[g(Fo) - g(Fo')\right] \tag{3}$$

and $$Fo' = \frac{\alpha_s (t - t_{\text{off}})}{H^2} \tag{4}$$

where t_{off} is the time when heat injection stopped. Calculations of Fourier numbers *Fo* [-] implies an assumption of the subsurface heat capacity, which can be constrained by identification of geological materials from drill cuttings where the GHE has been installed. The variability of the heat capacity for geological materials is low (Waples and Waples 2004) and it is, therefore, assumed that a visual description performed on site or on collected samples is sufficient to estimate the heat capacity without further laboratory analysis. Temperatures computed to reproduce the TRT with equation 3 are adjusted to fit the observed temperatures by optimization of the subsurface thermal conductivity. This has been done with a generalized reduced gradient solver for non-linear problems (Lasdon et al., 1978) to minimize the sum of the squared residuals calculated from the difference between computed and observed temperature increments.

Equation 3 used to analyze the tests suppose that heat transfer during the recovery period of the proposed TRT is dominantly conductive. Heat transfer due to free-convection can however occur in the standing water column and initial field experiments with a prototype apparatus were conducted to verify the extent by which the disks reduce free-convection.

4 FIELD EXPIREMENTS

Three field tests were performed from May to November 2013 at Versaprofiles factory in Saint-Lazare-de-Bellechasse, Quebec, Canada, located in the Appalachian geological province. This site hosts two GHE pilots that were installed to evaluate the performance of thermally enhanced pipes (Pasquier and Groleau 2009). Two boreholes were drilled to a depth of 150 m through about 10 m of sandy overburden followed by Cambro-Ordovician mudslate of the Armagh Formation (Lebel and Hubert 1995). The groundwater level was measured at 0.72 m below the ground surface. A single U-pipe was installed in each borehole until a depth of 139 m since blocks collapsed from the borehole wall and blocked the lower end. The boreholes were backfilled with silica sand and space clips were used to separate the tubes of the U-pipe. Three tests of the proposed TRT apparatus (Figure 1) were carried out on one of the GHEs, where a conventional TRT performed in January 2009 revealed a bulk subsurface thermal conductivity equal to 3.0 W m^{-1} K^{-1} (Raymond et al. 2011b).

The cable assembly of the prototype apparatus used for each of the three field tests contained ten heating sections of 1.12 m length and which were enclosed between non-heating sections of 8.94 m length or greater. The number of perforated disks at the interface of the heating sections was increased between each test to evaluate the effect of the disks on free-convection. No disk, three disks above and below and four disks above and three disks below were installed at the heating cable interfaces during the first, second and third tests (Table 1). The three first disks above and below the heating cable interfaces for the second and third tests were spaced by distances of 0.10 and 0.15 m. The fourth disk added above the heating cable sections for the third test was installed at a distance of 0.2 m above the third upper disk. The distance separating the third upper and lower disks above and below the heating sections, 1.36 m, was considered as the active heating length for test analysis. Thick electric conductors in the connectors, a preferred path for heat transfer, and convective water movements between the disks are assumed to extend the active heating length beyond the actual heating cable section . Total heat injection along each active heating length was carried out at an average rate of 40.61 to 43.52 W during 72 h for the three tests and thermal recovery was monitored during the following 48 h.

Temperature at the middle height of the heating sections was measured during the three tests, which corresponds to elevation z = 0 m in the analytical an numerical models used for comparisons. Additional temperature sensors were placed 1 m above the heating section interfaces during the second and third tests to further document the temperature evolution along the cable assembly as the first test revealed significant heat transfer due to free-

Table 1: TRTs conducted with the pilot apparatus

Test number	1	2	3
Starting date	05/30/2013	09/06/2013	11/15/2013
Number of disks above heating sections	0	3	4
Number of disks below heating sections	0	3	3
Average heat injection rate along heating sections (W)	40.61	42.85	43.52
Heat injection duration (h)	72	72	72
Recovery duration (h)	48	48	48

convective water movements. Comparison of results obtained for the three tests has been performed for a heating section located at a similar depth in the GHE.

5 NUMERICAL SIMULATIONS

Temperatures measured along the single heating section, located at approximately 130 m depth and enclosed between other heating sections, were compared to temperatures simulated with a finite element model to evaluate the impact of perforated disks on free-convection for the three tests. The numerical model was developed with the COMSOL Multiphysics program (COMSOL AB 2011) that can simulate convective heat transfer and laminar non-isothermal flow according to the Navier-Stokes equations. A single heating section overlain by a non-heating section whose length is 8.94 m and underlain by a non-heating section whose length is 2.24 m was represented in the model (Figure 2). The distance separating each heating section was shown to be sufficient for the temperature effect of one heating section on the others to be negligible (Raymond and Lamarche 2014, Accepted). The geometry of the model was simplified with a single pipe centered in the borehole surrounded by the subsurface for the simulations to be carried out in a radial coordinate system, speeding up flow simulations that require a large amount of the computer memory. The heating and non-heating cable sections were centered in the model single pipe containing water. Simulations were performed with increasing number of disks at the heating section interfaces according to the field tests. Thermal properties and dimensions of the model materials were selected to be representative of the field tests (Table 2). Default properties of water provided with the program were used for the thermal conductivity, heat capacity, viscosity and density to be temperature dependent.

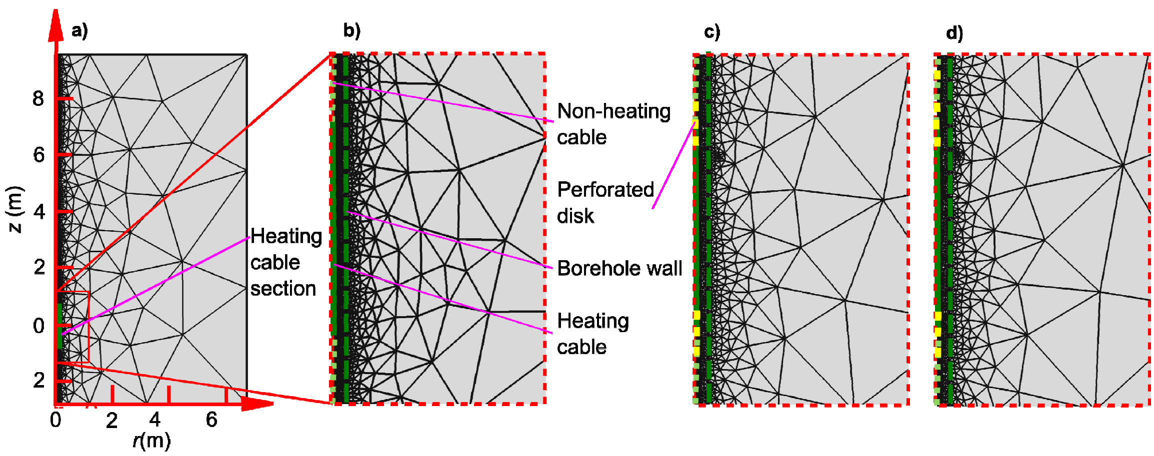

Figure 2: Mesh of a) the numerical model in radial coordinates used for simulation of heat transfer along a section of heating cable and enlargement of the mesh showing the disk configuration for the b) first, c) second and d) third simulation cases.

Table 2: Thermal properties and dimensions of the numerical model materials

Dimension/Property	Input value
Domain shape	Cylinder
Domain height	12.30 m
Subsurface radius	6.72 m
Borehole radius	0.076 m
Pipe outer radius	0.021 m
Pipe thickness	4×10^{-3} m
Cable outer radius	2.5×10^{-3} m
Cable jacket thickness	2.0×10^{-3} m
Subsurface thermal conductivity	3.2 $Wm^{-1}K^{-1}$
Filling thermal conductivity	2.7 $Wm^{-1}K^{-1}$
Pipe thermal conductivity	0.4 $Wm^{-1}K^{-1}$
Cable conductor thermal conductivity	100.0 $Wm^{-1}K^{-1}$
Cable jacket thermal conductivity	0.3 $Wm^{-1}K^{-1}$
Disk thermal conductivity	0.3 $Wm^{-1}K^{-1}$
Subsurface and filling volumetric heat capacity	2.5 $MJm^{-3}K^{-1}$
Cable and disks volumetric heat capacity	2.0 $MJm^{-3}K^{-1}$

The initial condition for the simulation of heat transfer was a uniform temperature. Heat transfer boundary conditions were adiabatic, except at the subsurface nodes parallel to the borehole elongation where a constant temperature equal to the initial temperature was imposed. No heat flow is assumed at the upper and lower boundaries as the distance separating those boundaries from the other heating sections and the ground surface is significantly long. A constant heat source, whose magnitude is equal to that measured during the field tests, was imposed to the domain forming the heating cable section. Parasitic heat losses of the non-heating cable sections were similarly represented. The cable and pipe inner boundaries were treated as thin resistive layers, where the temperature difference across the interface is proportional to the ratio of the thickness and the thermal conductivity.

The initial water pressure for flow simulation was calculated according to the water density. Flow boundary conditions were formed by the solid lateral walls of the pipe enclosing water and symmetry planes at the top and bottom of the pipe, whose effect is to gradually decrease flow velocity as the upper and lower boundaries are approached. Time steps of 1 h or less were automatically adjusted by the solver whose relative tolerance was set equal to 1×10^{-3} to ensure that the numerical solution remains realistic.

Simulations of heat transfer by free-convection were performed according to the disk configurations and heat injection rate of the three field cases (Table 1). Addition simulations of the three cases were conducted assuming a static water column and heat transfer by conduction only. The purpose of those simulations was to predict the temperature curves that could be observed if heat was transferred by conduction only and to determine if the disks adequately restricted free-convective heat transfer, which is not taken into account by equation 3 to analyze the TRT data.

6 TEMPERATURE EVOLUTION AND ANALYSIS

Temperatures measured at the middle height and 1 m above a single heating section for the three field tests, as well as those simulated with the numerical model, have been initially compared to evaluate the impact of the perforated disks (Figure 3a, b and c). Temperatures simulated with the numerical model were determined at an arbitrary radial distance of 0.01 m from the model symmetry axis. During the heat injection, the oscillating temperature signal was affected by the radial position, such that correlation between simulations and observations can difficultly be attempted. The exact radial position of the cable and its sensor that can potential move laterally is hardly controlled or determined during a field test. However, the effect of the radial position on temperature is negligible during the late recovery period since temperature in a slice of GHE becomes uniform after heat injection stopped. Recovery temperatures can consequently be compared or reproduced for analysis without knowing the exact position even when the match with heat injection temperatures is relatively poor.

The first test with no disk shows weak temperature increments during the heat injection and a rapid return to its initial temperature during the recovery (Figure 3a). Observed temperatures during the recovery better match with the simulated temperatures accounting for free-convective heat transfer rather than heat conduction only. Simulated temperatures with free-convection at the middle height and 1 m above the heating section are respectively weaker and stronger than the temperatures simulated by conductive heat transfer only, indicating significant convection when there is no disk. Interpretation of the temperature curves simulated during the heat injection, especially at the heating cable middle height, is difficult since their strength is extremely sensitive to the radial position. The effect of position on simulations of recovery temperature or temperature 1 m above the heating section during both the heat injection and the recovery are however less important.

The second test with three perforated disks above and below the heating section shows a better correlation of the recovery temperatures at the middle height of the heating section (Figure 3b). Convective cells moving heat upward appear responsible for the temperature buildup at the heating cable middle height and above, creating the difference in temperature increments shown between heat injection simulations with and without free-convection. Such interpretation is however tentative and difficult to confirm because of the position effect and the complexity of the convective cells shown on the model results. Simulated temperatures with free-convection determined 1 m above the heating section are stronger than the temperatures simulated by conductive heat transfer only. This suggests that convection was not significantly blocked above the heating cable section. Convective water movements allowed upward heat transfer in the pipe above the heating section.

The third test with four and three perforated disks respectively above and below the heating section still shows a good correlation of the recovery temperatures measured at the middle height of the heating section (Figure 3c). Simulated temperatures with free-convection determined 1 m above the heating section are similar to the temperature simulated by conductive heat transfer only. The disk configuration used for the third test case appeared sufficient to reduce convection effects above the heating cable interface for heat to be dominantly transferred by conduction.

Analysis of the temperature measured at the middle height of the single heating section during the recovery period for the three field tests was then performed. Computed recovery temperatures determined with equation 3 were matched with observed temperatures by optimization of the subsurface thermal conductivity (Figure 3d, e and f). The subsurface heat capacity was estimated equal to 2.5 MJ m^{-3} K^{-1} from a description of the drill cuttings and no attempt was made to optimize this parameter. The first ten hours of recovery measurements were not used for the test analysis to allow sufficient time for the temperature to become

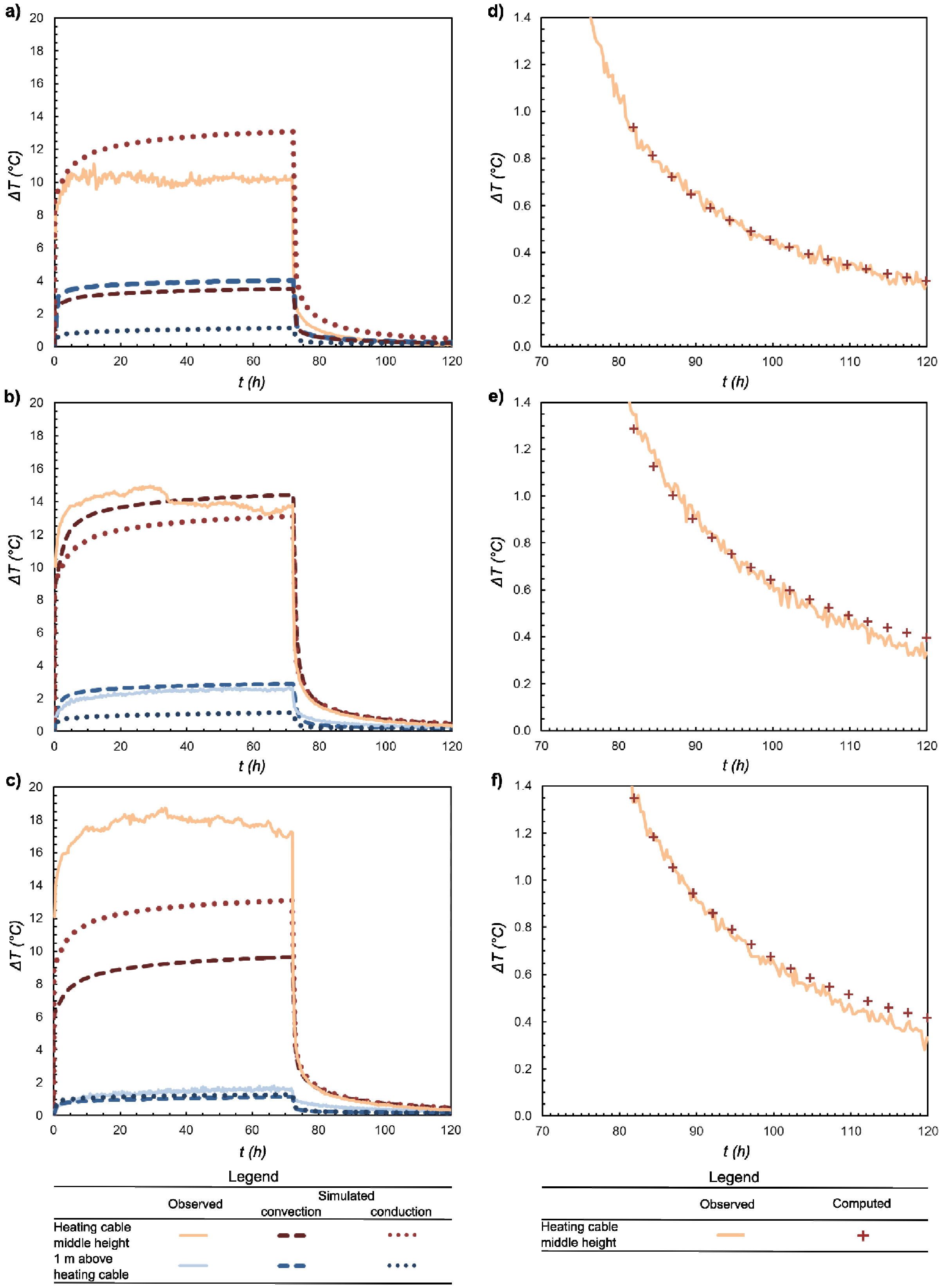

Figure 3: Comparison a), b) and c) of observed and simulated temperatures during the three thermal response tests and analysis d), e) and f) of recovery temperatures record at the middle height of the heating section.

uniform inside a horizontal slice of the GHE after heat injection stopped. The solver returned a subsurface thermal conductivity equal to 4.10, 3.29 and 3.20 W m^{-1} K^{-1}, from the first to the third field test. The match between observed and computed temperature increments near the end of the recovery period was sometimes difficult to achieve because the observed increments become weaker as time proceeds and the measured signal is affected by the accuracy of the temperature sensors.

Although the heating sections were not positioned at the exact same depth from one test to another, the decreasing thermal conductivity results suggest increasing efficiency of the disks to block convection. The last two analysis results are reasonably close to the bulk subsurface thermal conductivity measured previously with a conventional TRT (3.0 W m^{-1} K^{-1}). The conventional TRT result is thought to provide an estimate of the bulk subsurface thermal conductivity over the entire depth of U-pipe installed in the borehole, whereas results from the new TRT are representative of the subsurface thermal conductivity at the depth where the heating sections were installed.

7 POWER CONSUMPTION

The main advantage of the proposed TRT is to reduce power needed to conduct the tests. An average total power of 849 W was required to inject heat along the ten heating sections. The average potential difference, current intensity and total energy recorded during the 72 h of heat injection for the three tests was 105.5 V, 8.04 A and 61 KWh, respectively. The average heating power and total energy for the first 72 h of the conventional TRT performed on the same borehole was 9308 W and 670 KWh, respectively. The power and energy needed to conduct TRTs with sections of heating cable were 91 % smaller than those of the convectional TRT. This power reduction can decrease TRT cost since an electric grid connection with the high power required to conduct a conventional TRT is difficult to find on construction sites, so a heavy fuel-fired generator is usually needed. Low power can be easier to find on a construction site, avoiding the need for a generator when using the new TRT method.

8 CONCLUSIONS

Initial field experiments have been conducted to validate a new thermal response test method (TRT) using sections of heating cable and whose main advantage is to reduce power consumption. Ten sections with an active heating length of 1.36 m separated by non-heating sections of ≥ 8.94 m were installed in a 139 m deep ground heat exchanger (GHE) to conduct three tests. Preliminary analysis of temperature measured along a single heating section has been carried out to evaluate the effect of perforated disks positioned at the heating cable extremities to block free-convective water movements inside the pipe of the GHE filled with water. The amount of disks was increased from the first to the third test. Numerical simulations of free-convective and purely conductive heat transfer were conduct for comparison with the field test results. Observed and simulated temperatures suggested that the disk configuration used for the third test, four disks above and three disks below the heating section, was sufficient to restrict heat transfer by free-convection during the recovery period. Using that configuration, it was possible to analyze the test with a finite linear heat source solution taking into account heat transfer by conduction only. Analysis of the third test reveals a subsurface thermal conductivity at the depth of the heating section (3.20 W m^{-1} K^{-1}) within ~7 % of the bulk subsurface thermal conductivity measured over the entire GHE length with a conventional TRT (3.00 W m^{-1} K^{-1}).

Insights gained during the initial tests reported in this paper will be used to develop a revised program to simultaneously analyze temperature recorded at the ten heating sections during the proposed TRT. The new method generates more temperature data to analyze than the conventional TRT method and an efficient program has to be developed for the time spent doing data analysis to be similar. Results expected with the new method for analysis of the last and successful TRT described in this paper will be a thermal conductivity profile with ten distinct measurements over the GHE length. The subsurface thermal conductivity assessment will be compared to that provided by the conventional TRT conducted on the same GHE to validate the proposed TRT with field observations. Further research has to be performed to determine appropriate methods for evaluation of the bulk subsurface thermal conductivity over the drilling depth using values obtained with a single test. Averaging the thermal conductivity values from distinct depths with various methods, weighted according to the site stratigraphy inferred with a geological description of the drilled cuttings, is a potential option. Geophysical well logs could additionally be used to help determine the site stratigraphy or extent the measurements to other boreholes where no TRT has been performed.

Among differences with the conventional TRT are the temperature measurements recorded underground during the proposed TRT, which are therefore not affected by atmospheric temperature fluctuations and solar radiations. The time to conduct the proposed TRT with recovery measurements is longer than the time to conduct a conventional TRT with heat injection only. Time spent in the field for the proposed TRT can however be smaller since heat injection is automatized and there is no need to purge air trapped inside the pipe of the GHE. Those differences as well as the lower power requirements make the proposed TRT a potentially sound and lower cost alternative to the conventional TRT. Thick insultation added to the surface pipe to connect a conventional TRT unit, time needed to purge air from water in the piping before injecting heat and to follow-up operation of the mechanical unit, mobilization of a heavy generator with a large fuel tank to continuously inject heat are costly items avoided with the new TRT. The first author of this manuscript, which started performing conventional TRT by building its own unit in a Ph.D. project and then collaborated with industrials on commercial tests, found that installing the cable assembly for the new TRT was fairly straightforward compared to preparing the field site for a conventional TRT. Using a wired method inspired form geophysical surveys may be simpler than trying to reproduce the operation of a ground-coupled heat pump system.

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