Thermal response test with variable heat injection rates

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ABSTRACT
The design of commercial ground-coupled heat pump systems requires measuring the subsurface thermal properties with an in situ thermal response test. The variable heat injection rate test is presented here and treated as analogous to a pumping test. The analysis method using the line-source equation is modified with the superposition principle to account for variable heat injection and temperature recovery. The results of a test conducted in waste rock are given. Temperature recovery helped in that case to estimate the subsurface thermal conductivity independently from the borehole thermal resistance.

RÉSUMÉ
La conception des systèmes commerciaux de pompes à chaleur couplées au sol nécessite la mesure des propriétés thermiques du sous-sol avec un test de réponse thermique in situ. L'essai à taux d'injection de chaleur variable est présenté ici et traité de façon analogue à l'essai de pompage. La méthode d'analyse utilisant l'équation de la ligne-source est modifiée selon le principe de superposition afin de considérer les variations d'injection de chaleur et le retour à la température initiale. Les résultats d'un essai effectué dans une halde à stérile sont détaillés. La période de retour à la température initiale a permis dans ce cas d'estimer la conductivité thermique du sous-sol indépendamment de la résistance thermique du forage.

1 INTRODUCTION

Thermal response tests (TRT), also named borehole thermal conductivity tests, are conducted for in situ measurements of the subsurface and the borehole thermal properties considered in geothermal heat pump system design. The test is typically performed before drilling a complete borefield. The properties accounted for are the thermal conductivity and heat capacity of the subsurface and the thermal resistance of the borehole. These properties are used to calculate the required length of ground heat exchangers, which is commonly the main expense associated with a ground-coupled heat pump system. The test therefore has a direct impact on the economics of the heat pump system that is designed to save energy.

The standard testing method (Gehlin 2002) consists in injecting heat in a vertical ground heat exchanger by pumping water heated with an electric element in a closed loop. Water temperature at the inlet and the outlet of the ground heat exchanger and the flow rate are measured during the test. The mean water temperature increments measured are then generally fitted to computed temperature increments using Kelvin's line-source equation (Carslaw 1945; Ingersoll et al. 1954) to estimate the desired thermal parameters.

TRTs are somehow analogous to pumping tests performed to evaluate hydraulic properties of the subsurface. Theis (1935) in fact used the line-source equation that was adapted to predict transient drawdown in a pumped aquifer. The first development of TRTs (Austin III 1998; Gehlin 1998) is however much more recent than the development of pumping tests. Knowledge gained during more than 7 decades of aquifer testing could help enhance thermal conductivity testing methods. For example, the superposition principle, commonly used to analyze pumping test with variable discharge (Streltsova 1988), can be used to analyze TRTs with variable heat injection rates. Stepwise adjustment of heat injection can account for external heat transfer due to the mechanical work of the pump or fluctuations in solar radiations and atmospheric air temperature. Recovery tests, where heat injection is intentionally stopped but water is kept flowing in the ground heat exchanger to measure temperature, can also be analyzed by considering step heat injection rates.

This manuscript aims to transfer pumping test knowledge to TRTs and focuses on the application of the superposition principle used for analysis with the line-source equation. Beier and Smith (2005) and Beier (2008) used the superposition principle with the line-source equation to analyze interrupted tests. They did not, however, consider the analysis of temperature recovery tests which is treated here. TRT methodology and analysis are first reviewed and updated to account for variable heat injection rates. Parameter sensitivities are then evaluated with a factorial analysis. A test conducted at the South Dump of the Doyon Mine, Québec, is finally analyzed to highlight the benefits of step heat injection analysis.

2 TEST METHODOLOGY

The testing units used for TRTs are of various sizes, ranging from a suitcase to a trailer. Detailed descriptions of TRT units can be found in Austin III (1998) and Gehlin and Spitler (2002). Several studies describing TRT experiences are also reported throughout the literature (Austin III et al. 2000; Bozdağ et al. 2008; Cruickshanks et al. 2000; Gehlin and Hellström 2000; Katzenbach et al. 2007; Lim et al. 2007; Roth et al. 2004; Sanner et al. 2000; Sanner et al. 2005; Sharqawy et al. 2009; Spitler et al. 2000; Witte et al. 2002). A testing unit (Figure 1) typically consists of a pump, purge valves, an electric heating element, temperature sensors, a flow meter and a data logger. Some units enclose a heat pump for testing in cooling mode but they are not widely used.

Recent guidelines for test procedures can be found in ASHRAE (2007) and Sanner et al (2005). The undisturbed subsurface temperature is first measured before starting the test. It can be determined by measuring a temperature profile in the ground heat exchanger or by flowing water in the close loop and recording temperature with the TRT unit for 10 to 20 min before starting the heating element to begin the test. The first method appears more reliable because, for the second method, heat produce by mechanical work of the pump can be transferred to the fluid and introduce bias in the measurements (Gehlin and Nordell 2003). The ground heat exchanger should be purged before starting the test to make sure that air, which reduces heat transfer, is not trapped in the system. Pipe flow during testing must be turbulent as it would be during the heat pump system operation.

Another common practice is to isolate piping lying at the ground surface to minimize heat transfer from the system external environment, such as the pump motor, sun and atmospheric air. External heat transfers are however difficult to avoid, even if pipes and components inside and outside the unit are well insulated. It is consequently helpful to measure air temperature inside and outside the unit to quantify temperature changes. A steady power supply is advisable to minimize fluctuations of heat injection but it can be challenging to achieve. Sanner et al. (2005) recommend to measure heat injection from the temperature differential and the water flow rate to account for power fluctuations and external heat transfer. The heat injection rate Q [ML^2t^{-3}] can be calculated using:

$$Q(t) = V_w(t)\left(T_{w,in}(t) - T_{w,out}(t)\right)\rho_w c_w \qquad [1]$$

and can be averaged during the entire test period or during determined time intervals if a stepwise analysis is considered. The recommended heat injection for a constant rate test is in the range of 30 to 80 W/m of borehole. The water volumetric heat capacity $\rho_w c_w$ [$ML^{-1}t^{-2}T^{-1}$] in equation 1 can be assumed constant. Water temperature is measured at the inlet $T_{w,in}$ and the outlet $T_{w,out}$ of the ground heat exchanger with an accuracy of 0.9 °C for a temperature differential of 11 to 22 °C according to ASHRAE (2007) guidelines. A smaller

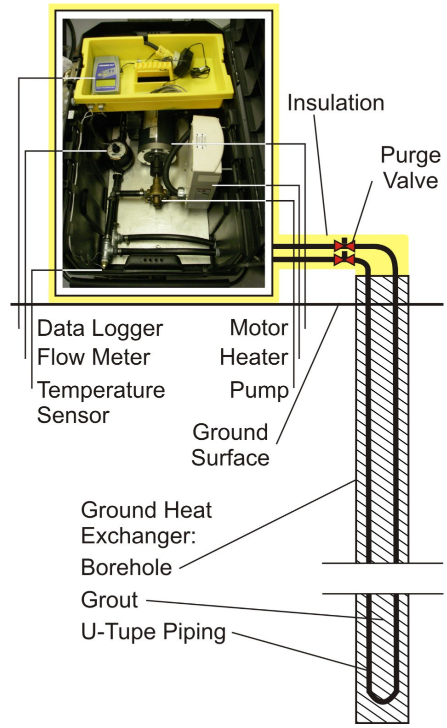

Figure 1. TRT unit constructed at Université Laval.

accuracy (0.5 to 0.1 °C) is advisable for smaller temperature differentials. The water volumetric flow rate V_w [L^3t^{-1}] is measured with a flow meter inside the unit. The flow meter precision has a direct impact on the precise measurement of the heat injection rate. Sharqawy et al. (2009) propose to conduct energy, exergy and uncertainty analyses of the TRT unit to better constrain heat injection rates. Data recording intervals during the entire test must be equal or less than 10 minutes.

There is no general agreement for the duration of a constant heat injection rate test. The only consensus is that the longer the test, the better the results. Recommendations for the test duration are 50 h (Austin et al., 2000); 60 h (Gehlin, 1998); 36 to 48 h (ASHRAE, 2007) and 50 h (Sanner et al., 2005). Long tests are however expensive and contractors therefore tend to conduct shorter tests that typically underestimate the subsurface thermal conductivity and lead to a conservative design estimate, which can unfortunately oversize the length of ground heat exchanger required for a ground-coupled heat pump system. Beier and Smith (2003) pointed out that the minimum test duration can vary by more than a factor of 100 among boreholes and sites. They developed a method to estimate the minimum test duration to obtain a subsurface thermal conductivity estimate that is within 10% of the measurement obtain with late time data.

The minimum duration for temperature recovery test has not been extensively studied. The authors experience showed that the time required for the borehole to return to its initial temperature can be longer than the heating period. Temperature changes near the end of the cooling period are however subtle and the test should be run until temperature changes are within the precision of the temperature sensors.

The authors built their own testing unit (Figure 1) within a larger research project that aims to evaluate the geothermal potential of mine waste dumps (Raymond et al. 2008). The equipment is contained in a 0.32 m^3 tool box. Water flows under the action of a gear pump entrained with an electric motor where rotations are controlled from a drive. A 9500 kW tank less water heater (commonly called booster) heats the water. Resistance temperature detectors (RTD) measure temperature and a displacement meter measures the flow rate recorded on a data logger with a respective precision of ± 0.1 °C and ± 1%. The piping is equipped with valves allowing connections to a reservoir for purging.

3 TEST ANALYSIS

Water temperature increments recorded at the pipe inlet and outlet during the test period are fitted to computed temperature increments to estimate the subsurface and the borehole thermal properties using various analytical and numerical models. The commonly used cylindrical- and line-source models are based on analytical solutions presented by Carslaw (1945) and Ingersoll et al. (1954). Both describe transient heat conduction from a source embedded in an infinite medium. Transient numerical models that simulate conduction, or both conduction and advection, in one (Gehlin and Hellström 2003; Shonder and Beck 1999; Shonder and Beck 2000), two (Austin III et al. 2000; Yavuzturk et al. 1999) or three (Marcotte and Pasquier 2008; Signorelli et al. 2007) dimensions are also considered. Among all models, the line-source, which is reported below, is preferred because it fits the observed data well and is simple to implement (Gehlin and Hellström 2003).

3.1 The line-source model

The analytical solution used with the line-source model is derived from the general equation of conductive heat transfer in radial coordinates:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{\rho c}{\lambda}\frac{\partial T}{\partial t} \qquad [2]$$

where r [L] is a radial distance and λ [$MLt^{-3}T^{-1}$] is the thermal conductivity. The system is initially at a constant temperature ($T(r,t=0)$ = T_0) and boundaries are located at infinite distances and are of a constant temperature ($T(r=\infty,t)$ = T_0). The surrounding medium is assumed to be homogeneous and isotropic. Equation 2 is solved for the above initial and boundary conditions for an infinite line-source having a constant heat flux per unit length. The solution describes the resulting temperature increment ($\Delta T(r,t)=T(r,t)-T_0$) at a distance r from the source and a time t:

$$\Delta T(r,t)=\frac{q}{4\pi\lambda_{ss}}\int_u^\infty \frac{e^{-u}}{u}du \quad \text{where} \quad u=\frac{r^2}{4a_{ss}t}$$
$$\text{and} \quad a_{ss}=\frac{\lambda_{ss}}{\rho_{ss}c_{ss}} \qquad [3]$$

In equation 3, q [MLt^{-3}] is the rate of heat transfer per unit length of borehole, a [L^2t^{-1}] is the thermal diffusivity and the subscript ss is for the subsurface which is the surrounding medium. The exponential integral, denoted *W(u) below*, can be approximated from infinite Taylor series:

$$W(u)=\left[-0.5772...-\ln u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}+...\right] \qquad [4]$$

where -0.5772… is the Euler constant. The first two terms on the right hand side of equation 4 are often used to approximate the exponential integral when t ≥ $5r^2/a_{ss}$ (Gehlin 2002), which is equivalent to Jacob's approximation used in pumping tests (Cooper and Jacob 1946). We, however, use the first six terms of the Taylor series to improve the precision of calculations during early test time.

The temperature increment at the borehole wall ($r=r_{bh}$) can be expressed as:

$$\Delta T(r_{bh},t)=\frac{q}{4\pi\lambda_{ss}}W(u) \quad \text{where} \quad u=\frac{r_{bh}^2}{4a_{ss}t} \qquad [5]$$

but another equation to calculate water temperature inside the ground heat exchanger is however desired to analyze a TRT. Equation 5 is therefore combined with the equivalent borehole thermal resistance R_{bh} [$T^1t^3M^{-1}L^{-1}$] to determine the mean water temperature increment along the borehole:

$$\overline{\Delta T_w}(t)=\Delta T(r_{bh},t)+qR_{bh} \qquad [6]$$

The resistance value assumes steady-state heat transfer across the borehole, which may not be valid early during the test when temperature changes are important. A fitting relationship is used to compare equation 6 to temperatures measured at the entrance $T_{w,in}$ and the exit $T_{w,out}$ of the ground heat exchanger. The average temperature increment ($\Delta(T_{w,in}+T_{w,out})/2$) has first been used (Austin III 1998; Gehlin 2002). Marcotte and Pasquier (2008), however, pointed out that this fitting relationship tends to overestimate R_{bh} because it assumes a constant heat flux along the entire borehole (Incropera et al. 2007; Zeng et al. 2003). Numerical modeling was used to simulate heat flux distribution along the borehole and determined that the "p-linear" average is a better fitting relationship. This average corresponds to (Marcotte and Pasquier 2008):

$$\overline{\Delta T_{\mathrm{w}}}(t) \approx \left|\Delta T_{\mathrm{p}}\right| = \frac{p\left(\left|\Delta T_{\mathrm{w,in}}\right|^{p+1} - \left|\Delta T_{\mathrm{w,out}}\right|^{p+1}\right)}{(1+p)\left(\left|\Delta T_{\mathrm{w,in}}\right|^{p} - \left|\Delta T_{\mathrm{w,out}}\right|^{p}\right)} \qquad [7]$$

where p is a fitting parameter whose value tends to -1. The standard TRT analysis procedure consists of fitting a plot of equation 6 to observed mean temperature increments by adjusting λ_{ss}, $\rho_{ss}c_{ss}$, and R_{bh}. The late time data are considered more reliable because of the steady-state nature of the borehole thermal resistance. The volumetric heat capacity has less influence on the plot position (Wagner and Clauser 2005) and fitting therefore consists in estimating the two other unknowns. Identical temperature curves can be generated with different combinations of subsurface and borehole parameters. The borehole thermal resistance can however be estimated from the first hour temperature measurements (Beier and Smith 2002) or from the ground heat exchanger configuration (Bernier 2001; Paul 1996; Remund 1999; Sharqawy et al. In Press) to better constrain unknowns. It is additionally shown below that a temperature recovery test can provide data to independently estimate subsurface and borehole parameters. Knowledge of geological settings can also help constrain λ_{ss}.

3.2 Step heat injection

The line-source equation can account for varying heat injection rates using the superposition principle (Eskilson 1987; Lee 1999; Streltsova 1988). The mean water temperature increment along the borehole is described by the sum of the contributions of step heat injection and becomes:

$$\overline{\Delta T_{\mathrm{w}}}(t) = q_{\mathrm{i}}R_{\mathrm{bh}} + \sum_{\mathrm{i}=1}^{\mathrm{n}}\left(q_{\mathrm{i}} - q_{\mathrm{i}-1}\right)\frac{W(u)}{4\pi\lambda_{\mathrm{ss}}} \qquad \text{where}$$

$$u = \frac{r_{\mathrm{bh}}^{2}}{4a_{\mathrm{ss}}(t - t_{\mathrm{i-1}})} \quad \text{for} \quad q_0 = 0 \quad \text{and} \quad t_0 = 0 \qquad [8]$$

The above equation provides a solution for a TRT with fluctuations in heat injection rate or to analyse a temperature recovery test. Departure from steady-state conditions across the borehole between steps must be negligible when using equation 8 because of the steady-state nature of R_{bh}. Good correlations with measured temperature increments suggest that this assumption is valid for small changes in heat injection rate that can be due to external heat transfer. The assumption does not, however, apply to early time following large changes in heat injection rate such as the beginning of the heating and the recovery periods.

4 PARAMETER SENTIVITIES

A factorial analysis (Box et al. 1978) with three parameters having two levels of variance is conducted to evaluate the influence of λ_{ss}, $\rho_{ss}c_{ss}$, and R_{bh} on the mean water temperature increment. These three parameters are increased and then decreased by 10% compared to a base case scenario and the mean water temperature increments are computed with hourly timesteps for all possible combinations of parameters (i.e. 2^3 combinations). The main effect of each parameter is successively evaluated from the change in temperature between two scenarios where the varying parameter has a low and a high value. Each parameter main effect is therefore calculated 4 times at each timestep. The main effect is finally averaged for each timestep to determine the influence of λ_{ss}, $\rho_{ss}c_{ss}$, and R_{bh} with time.

All parameters used to compute the mean water temperature increment with equation 8 in the base case scenario are presetend in Table 1. Temperatures are computed for a heat injection and a recovery period both equal to 48 hours, with 1 hour timesteps. A small heat injection rate is specified during the recovery period even if the electric element has been turned off because heat can be transferred to the fluid from the pump mechanical work. Heat injection rate is varied every 12 hours during the heating and the cooling period by 100 W and 60 W, respectively, to include the possible effects of external heat transfer.

Temperature increments at the borehole wall and in the U-pipe for the base case scenario are plotted in Figure 2a. The temperature differential across the borehole wall and the U-pipe, also plotted in Figure 2a, varied during the heating and the recovery period by 0.1 ℃ and 0.06 ℃, respectively. These small variations suggest that departure from steady-state conditions across the borehole can be neglected in a stepwise analysis considering external heat transfer. Transient conditions are however expected during the first hour of the heating and the recovery period because the differential changed by about 10 ℃.

The factorial analysis results (Figure 2) show the influence of a ±10% change in the value of each parameter. The main effect of λ_{ss} increases with time, which confirms that a better subsurface thermal conductivity estimate can be obtained with a longer test. The main effect of $\rho_{ss}c_{ss}$ and R_{bh} are negligible during the recovery period which shows that a recovery test provides an estimate of λ_{ss} that is almost independent of the borehole thermal properties. R_{bh} would in fact cancel in equation 8 if the heat injection rate was zero (i.e. no external heat transfer) during the recovery period. The uncertainty in TRT analysis is minimized when adjusting λ_{ss} to fit the recovery curve and then adjusting R_{bh} to fit the heating curve. Other factorial analyses were conducted with different data sets having good and poor heat transfer properties and showed similar results.

Table 1. Base case parameters for the factorial analysis

Parameter	Value	Units
λ_{ss}	2.5	$Wm^{-1}K^{-1}$
$\rho_{ss}c_{ss}$	2.0	$MJm^{-3}K^{-3}$
R_{bh}	0.15	mKW^{-1}
L_{bh}	150	m
r_{bh}	0.075	m
Heat injection rate		
t (h)		Q(W)
0-12		10,050
12-24		9,950
24-36		10,050
36-48		9,950
48-60		130
60-72		70
72-84		130
84-96		70

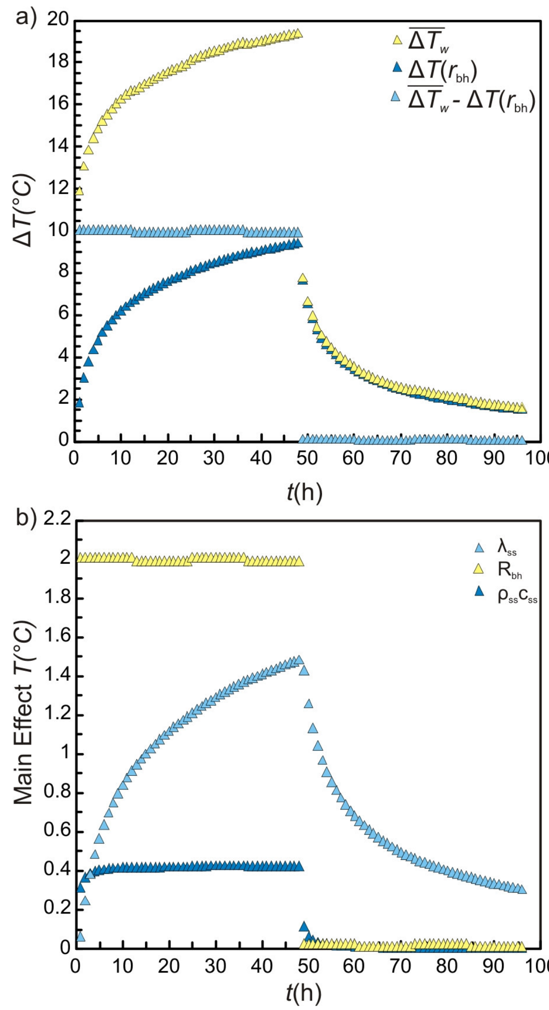

Figure 2. a) Base case temperature increments calculated with the line-source model using the parameters shown in Table 1. b) Results of the factorial analysis conducted to determine parameter sensitivities. The main effect on temperature for each parameter account by the line-source model is plotted as function of time.

5 ILLUSTRATIVE EXAMPLE

A TRT was conducted at the South Dump of the Doyon Mine, Québec, to evaluate the thermal properties of the waste rock. The dump is predominantly constituted of heterogeneously sized sericite schist fragments deposited on a silty overburden. The fragments contains iron sulfides that oxidize in the presence of water and oxygen (Gélinas et al. 1994; Lefebvre et al. 2001a; Lefebvre et al. 2001b; Molson et al. 2005). This exothermic process releases heat that is partly stored in the waste rock. Recent measurements indicate that the South Dump internal temperature ranges from 13 to 44 °C (Raymond et al. 2008). The TRT was conducted at a previously drilled borehole, BH-4, which is a 0.038 m diameter PVC pipe screened at the bottom and installed in a 0.15 m diameter borehole filled with sand pack (Lefebvre 1994). A flexible liner manufactured by FLUTe™ was used to block the well screen and to fill the PVC pipe with water. The liner was installed in the unsaturated dump material over a length of 33 m. A smaller HDPE pipe, having a 0.013 m diameter, was inserted in the PVC pipe to convert the observation well into a concentric ground heat exchanger (Figure 3). The resulting borehole has a high thermal resistance and is not optimal for geothermal energy exchange, but it is however adequate for a TRT.

The average undisturbed ground temperature near BH-4 is estimated at 18.8 °C from a temperature profile (Raymond et al. 2008). Heat was injected during the TRT for a 50.5 h period and temperature recovery was measured during the following 45.3 h. A fluctuating

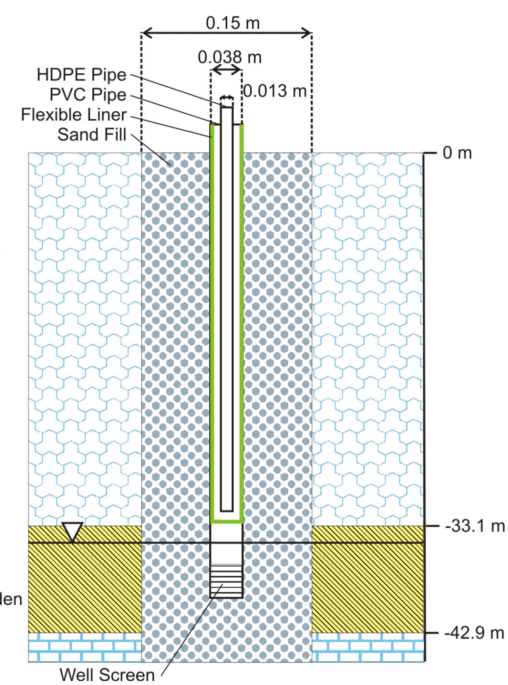

Figure 3. Ground heat exchanger configuration for TRT at well BH-4, South Dump, Doyon Mine. The figure aspect ratio is not proportional.

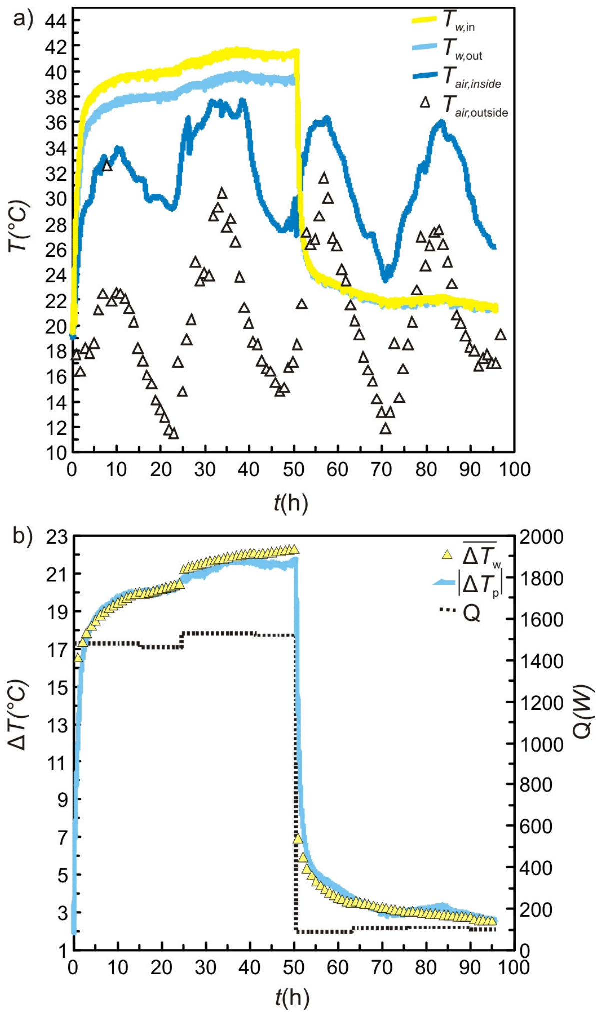

Figure 4. a) TRT data and b) analysis at well BH-4, South Dump, Doyon Mine.

temperature signal suggested significant external heat transfer. It was in fact difficult to minimize external heat transfer because the test was conducted on a waste dump without a vegetation cover, during a clear sky period and during the month of July at a latitude of 48°15'N where we measured more than 20 °C changes in atmospheric temperature between days and nights. Water temperature entering and leaving the ground heat exchanger and air temperature measured inside and outside the TRT unit are shown in Figure 4a. The step heat injection rates used for the analysis are calculated with equation 1 for time periods determined from the water temperature signals. Equation 8 is used to compute the mean water temperature increment for hourly timesteps (Figure 4b).

The line-source model best fitted our observations for λ_{ss} equal to 2.5 $Wm^{-1}K^{-1}$, $\rho_{ss}c_{ss}$ equal to 1.95 $MJm^{-3}K^{-3}$ and R_{bh} equal to 0.34 mKW^{-1}. Waste dump thermal properties are similar to those given by Lefebvre et al. (2001a) measured with near-surface cyclic temperature variations and calculated with mineralogy. The Beier and Smith (2002) method used to calculate R_{bh} from the first hour temperature measurements suggests a borehole thermal resistance of 0.31 mKW^{-1}. The value of 0.34 mKW^{-1} obtained from the line-source model is preferred because it is based on measurements taken during the entire heating period since λ_{ss} was first determined using data from the recovery period.

6 DISCUSSION

The line-source model can be used with superposition to analyse a TRT affected by significant external heat transfer from surface processes. The strength of this analysis procedure is its simplicity allowing to compute the solution in a spread sheet when approximating the exponential integral with Taylor series. The composite line-source model of Beier and Smith (2003), which also uses the superposition principle, provides an alternative to analyse TRT with varying heat injection rates. Their model gave a very good fit to an experimental interrupted test (Beier and Smith 2005; Beier 2008). Calculation of the composite line-source model is however performed in the Laplace domain and a numerical inversion algorithm is used to convert the results, increasing the amount of computations. Numerical models can also be used to account for varying heat injection rates but the amount of computations required for the test analysis is increased compared to an analytical solution (Gehlin and Hellström 2003). Physical processes involved in a TRT are however best represented by detailed three-dimensional numerical models (Signorelli et al. 2007). The line-source model, accounting for step heat injection rates, is therefore useful for preliminary screening and verifies if additional investigations are necessary.

Recovery analysis, although commonly performed for hydraulic conductivity testing (Streltsova 1988), is considered here for the first time with thermal conductivity testing. The influence of the borehole thermal resistance during the test recovery period is negligible, providing data to independently estimate the subsurface thermal conductivity and reducing uncertainty. Monitoring of temperature recovery however increases the test length, but it is believed that recovery analysis can still be performed for commercial ground-coupled heat pump systems because parameter uncertainties can have an important economic impact. A design example of a 8X8 borehole system, given by Marcotte and Pasquier (2008), showed a 15 % increase in a ground heat exchanger length caused by a 50% overestimation of the borehole thermal resistance. The cost associated with larger bore length exceeded the cost of a recovery test in this situation. Additional expenses to better estimate design parameters are easily justified when the system is large enough.

7 CONCLUSIONS

TRT procedures have been adapted to consider varying heat injection rates caused by external heat transfer from surface processes or a recovery test. The line-source model was reviewed from a hydrogeological perspective in a very similar way that hydraulic conductivity testing has been treated. Taylor series can approximate the line-source exponential integral to easily compute temperature increments caused by step heat injection accounted with the superposition principle. The resulting stepwise method can be used to increase the line-source fit to a TRT data set, a significant advantage in conditions where external heat transfers are difficult to control.

The analysis of temperature recovery has also been presented. The parametric sensitivity analysis indicated the advantage of constraining the subsurface thermal conductivity with recovery data and the borehole thermal resistance with heating data. The method has shown good correlations with a TRT performed at the South Dump of the Doyon Mine. Recovery test could gain popularity in commercial design practices since system cost can be optimized by reducing uncertainty in parameter estimates.

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