Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Interpretation of Thermal Response Tests in Borehole Heat Exchangers Affected by Advection

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Keywords: Thermal conductivity, groundwater flow, subsurface temperature

ABSTRACT

We focus on the treatment of thermal response test data when both advection and short-period changes of surface temperature occur. We used a moving line source model to simulate temperature-time signals under an advective thermal regime. The subsurface thermal conductivity, the Darcy velocity and the borehole thermal resistance were inferred by means of an optimisation procedure. In case of Darcy velocity lower than 10^{-7} m s^{-1}, the underground thermal conductivity is comparable to that obtained by means of the infinite line source model, which assumes a purely conductive thermal regime. The optimisation analysis was finally applied to real thermal response test data. The temperature-time curves were filtered to remove the disturbing spectral components associated with a non-optimal thermostatic behaviour of the apparatus. This produced reliable estimates of thermal and hydraulic parameters. An independent method based on the analysis of temperature-depth logs was also used to validate the inferred groundwater flow.

1. INTRODUCTION

The thermal power that can be extracted with borehole heat exchangers (BHE) depends mainly on the thermal properties of the underground, and in particular, on thermal conductivity. Laboratory measurements of thermo-physical properties can be unfeasible, as core samples are often unavailable in boreholes. Thus, in-situ tests are routinely used to determine subsurface and borehole thermal properties. Tests record the underground temperature variation with time due to a constant heat that is injected (or extracted) by means of a carrier fluid into a borehole acting as a heat exchanger. The most commonly used model to analyse temperature-time curves obtained from these tests is the infinite line source (ILS). If some conditions are fulfilled, this model can give rapid and appropriate estimations of thermal parameters. On the other hand, several flaws can often affect the data interpretation. Some of them are related to the model assumptions, which imply a purely conductive heat transfer regime, a homogeneous medium, no vertical heat-flow and infinite length of the borehole. Others have to do with the difficulty in the proper thermal insulation of the test equipment, and consequently with the oscillations of the carrier fluid temperature due to surface air temperature changes, which generally produce a periodic offset in the recorded temperature-time curves. In this paper, we discuss the treatment of the thermal response test (TRT) data when both advection caused by groundwater flow and periodic changes of air surface temperature occur. An approach based on the moving line source (MLS) model is tested with simulations of temperature-time signals obtained under different hypothesis of thermal and hydraulic conditions. Then, the same procedure is applied to real TRT data to estimate thermal conductivity, borehole thermal resistance and Darcy velocity. The magnitude of the inferred groundwater flow is finally checked by means of an independent method based on the analysis of the undisturbed temperature-depth records.

2. THEORETICAL BACKGROUND AND MODEL COMPARISON

The underground thermal response to a constant heat injected or extracted from a BHE through the carrier fluid is generally modelled with the Kelvin's line source theory. By treating the borehole as an infinite line with constant radial heat flow, the underground temperature T at a distance r from the borehole with time t is given by the solution of the heat diffusion equation (Ingersol et al., 1954)

$$T(r,t) = T_o + \frac{q}{4\pi\lambda} \int_{r^2/4\kappa t}^{\infty} \frac{e^{-u}}{u} du \tag{1}$$

where T_o is the initial undisturbed underground temperature, q the heat flow per unit length, λ the bulk thermal conductivity of the saturated medium and κ the thermal diffusivity. In a BHE, the temperature of the carrier fluid T_f can be expressed as a combination of the temperature at the wall $T(r{=}r_{b}, t)$ and the thermal resistance R_b of the borehole. Thus, a good expression for T_f derived from the approximation of eq. (1), with a maximum error less than 10% for $t \geq 5\, r_b^2/\kappa$, takes the form (e.g. Wagner and Clauser, 2005, Signorelli et al., 2007; Wagner at al., 2013)

$$T_f(t) = T_o + \frac{q}{4\pi\lambda} ln(t) + \left\{ qR_b + \frac{q}{4\pi\lambda}\left[ln\left(\frac{4\kappa}{r_b^2}\right) - \gamma \right]\right\} \tag{2}$$

where γ is the Euler's constant. T_f is assumed to correspond to the average of the inlet and outlet temperature of the circulating fluid, while R_b depends on the thermal properties of the BHE and the carrier fluid as well as on the geometry of the pipes in the borehole (Marcotte and Pasquier, 2008). Equation (2) can be rewritten as a linear function of the logarithm of time

$$T_f(t) = a\,ln(t) + b \tag{3}$$

The ground thermal conductivity can be thus derived from the slope of eq. (3)

$$a = \frac{T_f(t_2) - T_f(t_1)}{ln(t_2) - ln(t_1)} = \frac{q}{4\pi\lambda} \tag{4}$$

By considering random and systematic experimental errors and the assumptions implied in the ILS model, the interpretation of the thermal test with eq. (4) leads to the estimation of the ground thermal conductivity with an error of about 10% (Witte et al., 2002; Gehlin and Spitler, 2002). However, the results of this approach may be biased by several shortcomings that have to do with the assumption of an infinite line shape, homogeneous thermal conductivity and no vertical temperature change in the subsurface (see e.g. Wagner et al., 2013). Moreover, a purely conductive thermal regime can often be unrealistic, especially in permeable formations, which can often be affected by groundwater flow.

In order to take into account the advective processes a different approach should be used. An analytical solution of the heat advection equation, derived by Carlslaw and Jaeger (1959) for a constant, infinite line source moving in a homogeneous and infinite medium (MLS), can be adapted to infer the temperature distribution in the underground affected by horizontal groundwater flow, like e.g. far from recharge/discharge areas (Zubair and Chaudhry, 1996; Sutton et al., 2003)

$$T(r,t) = T_o + \frac{q}{4\pi\lambda} exp\left(\frac{\rho c v_x r}{2\lambda}\right) \int_0^{\frac{(\rho_w c_w v_x)^2 t}{4\rho c\lambda}} exp\left[-\phi - \frac{(\rho_w c_w v_x)^2 r^2}{16\lambda^2\phi}\right]\frac{d\phi}{\phi} \tag{5}$$

where ρ, c, ρ_w and c_w are density and specific heat of the ground and water, respectively, v_x is the Darcy velocity in the x-axis direction and ϕ the integration parameter. When heat is transported by groundwater flow, differential advection can occur due to the different flow paths. This process, which is often neglected in heat transfer modelling, is called thermal dispersion (see e.g. Molina-Giraldo et al., 2011, for a wide discussion). When the Darcy velocity is large, thermal dispersion is dominant. For heat transport in two dimensions (in the x-y plane), thermal dispersion caused by groundwater flow can be taken into account by introducing the longitudinal λ_x and transverse λ_y thermal conductivity components given by (Sauty et al., 1982; Smith and Chapman, 1983; Molson et al., 1992)

$$\begin{aligned} \lambda_x &= \lambda + \delta_x \rho_w c_w v_x \\ \lambda_y &= \lambda + \delta_y \rho_w c_w v_x \end{aligned} \tag{6}$$

where λ is the bulk thermal conductivity, δ_x and δ_y the thermal dispersion coefficients.

Dispersion coefficients vary over a wide range because of heterogeneities and appear to be scale-dependent (e.g. Xu and Eckstein, 1995). A compilation of different empirical equations describing the dependence of longitudinal dispersivity in relation to the field scale is reported by Molina-Giraldo et al. (2011). The relation δ_y=0.1 δ_x, commonly assumed for solute transport (e.g. Domenico and Schwartz, 1998), is often extended to heat transfer (Smith and Chapman, 1983; Su et al., 2004).

By taking into account advection and hydrodynamic dispersion, eq. (5) becomes (Metzger et al., 2004)

$$T(x,y,t) = T_o + \frac{q}{4\pi\sqrt{\lambda_x\lambda_y}} exp\left(\frac{\rho c v_x x}{2\lambda_x}\right) \int_0^{\frac{(\rho_w c_w v_x)^2 t}{4\rho c\lambda_x}} exp\left[-\phi - \left(\frac{x^2}{\lambda_x} + \frac{y^2}{\lambda_y}\right)\frac{(\rho_w c_w v_x)^2}{16\lambda_x\phi}\right]\frac{d\phi}{\phi} \tag{7}$$

Figure 1 shows the two-dimensional underground temperature distribution calculated for ILS (eq. 1) and MLS models (eq. 7) under different hypotheses of Darcy velocity v_x. We assumed a horizontal groundwater flow parallel to the x-axis and a heat extraction q of 30 W m^{-1} for a period of 300 days. Groundwater flow produces an asymmetrical temperature distribution around the heat source only parallel to the flow direction. At large Darcy velocity (v_x of the order of 10^{-7} m s^{-1}) the differences between ILS and MLS become remarkable.

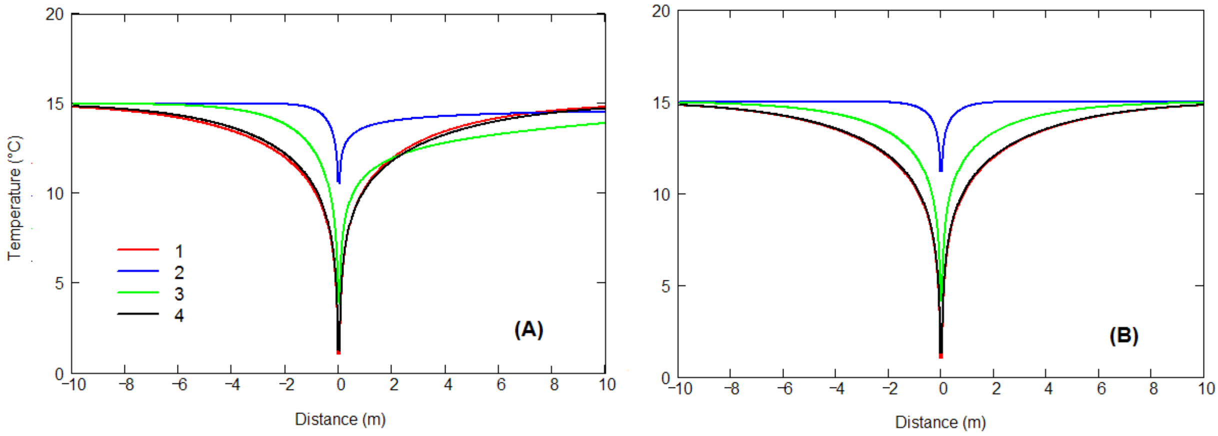

Figure 1: Underground temperature for ILS (1) and for MLS for under different hypotheses of Darcy velocity (2, v_x = 3.0x10^{-6} m s^{-1}; 3, v_x = 3.0x10^{-7} m s^{-1}; 4, v_x = 3.0x10^{-8} m s^{-1}) parallel (A) and normal to the groundwater flow direction (B). The adopted parameters are: 2.0 W m^{-1} K^{-1} for the bulk thermal conductivity, 2.4x10^{6} J m^{-3} K^{-1} for the ground volume heat capacity, 1000 kg m^{-3} for the water density and 4186 J kg^{-1} K^{-1} for the water specific heat. Thermal dispersivity δ_x is 0.5 m and T$_o$=15 °C.

The temperature of the circulation fluid in a vertical heat exchanger can be modelled by introducing the thermal resistance R_b between the fluid and the borehole wall and setting the thermal dispersion coefficients equal to zero (λ_x=λ_y=λ) in eq. (7). Therefore, one obtains the relation (Diao et al., 2004; Molina-Giraldo et al., 2011; Wagner et al., 2013)

$$T_f(x,y,t) = T_o + \frac{q}{4\pi\lambda} exp\left(\frac{\rho c v_x x}{2\lambda}\right) \int_0^{\frac{(\rho_w c_w v_x)^2 t}{4\rho c\lambda}} exp\left[-\phi - \frac{(\rho_w c_w v_x)^2 r_b^2}{16\lambda^2\phi}\right]\frac{d\phi}{\phi} + qR_b \tag{8}$$

where coordinates fulfil the condition $r_b^2 = x^2 + y^2$.

3. SYNTHETIC DATASET AND PARAMETER ESTIMATION PROCEDURE

Simulations of temperature-time signals acquired during TRTs in boreholes affected by groundwater flow were carried out by means of the MLS model (eq. 8). A random noise of amplitude 0.05 K was added to the signal in order to mimic high-frequency disturbances due to equipment operating conditions. Moreover, sinusoidal perturbations of amplitudes 0.1 and 0.05 K and period 24 and 12 hours, respectively, were superimposed in order to take account of influence of surface temperature oscillations due to possible non-optimal insulation of the equipment. The adopted thermal parameters are representative of a water-saturated ground with ρc= 2.4x10^{6} J m^{-3} K^{-1} and thermal conductivity of 2.0 W m^{-1} K^{-1}. The synthetic signal was generated with a constant heat flow of 30 W m^{-1}. Figure 2 presents the obtained synthetic signals for a slow (3.0x10^{-9} m s^{-1}) and a fast (3.0x10^{-6} m s^{-1}) groundwater flow. Notice that the first 12 hours of the temperature-time signal were removed, in agreement with the standard procedures of data processing.

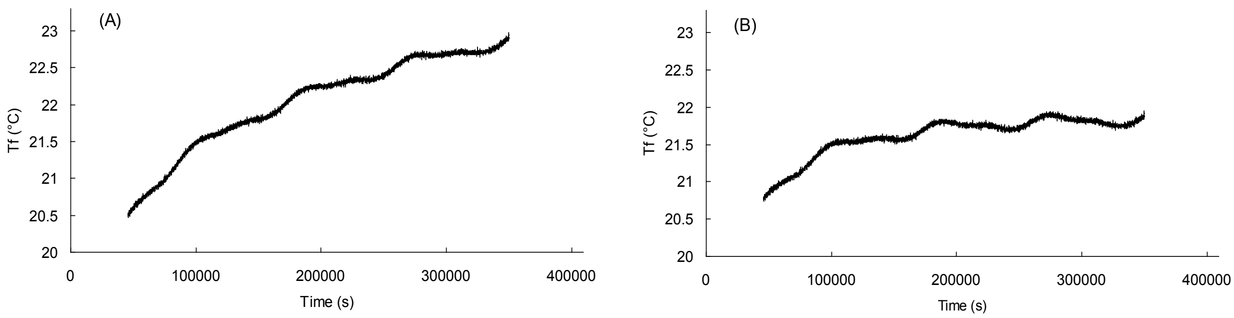

Figure 2. Synthetic TRT data obtained for the MLS model with Darcy velocity 3.0x10^{-9} (A) and 3.0x10^{-6} m s^{-1} (B). The assumed parameters are: T_o= 15 °C, R_b= 0.1 m K W^{-1}, ρ_w= 1000 kg m^{-3}, c_w= 4186 J kg^{-1} K^{-1} and r_b=0.075 m.

Figure 3 presents the interpretation of the overall synthetic signal with the ILS approach, i.e. by means of eq. (3) and (4). From the slope of the linear function of the logarithm of time, for the synthetic signal obtained with a Darcy velocity of the order of 10^{-9} m s^{-1} (Fig. 3A), the inferred thermal conductivity is 2.05 W m^{-1} K^{-1}, i.e. in good agreement with the "a priori" value. At large Darcy velocity (Fig. 3B), thermal conductivity is however largely overestimated (more than 5 W m^{-1} K^{-1}).

The synthetic temperature-time curves were then interpreted with the MLS model. In this case, the parameter estimation involved minimising the differences between the synthetic signal and the analytical model. Some input data, which in principle can be measured or assumed during the experiment (such as q, T_o, R_b, ρc), were kept constant, whereas the ground thermal conductivity λ, the Darcy velocity v_x and the borehole thermal resistance R_b were allowed to vary. The best estimate of the variables was found by minimising the root mean square error RMSE between the synthetic dataset and the theoretical model;

$$RMSE = \sqrt{\sum_{i=1}^{i=n} \frac{\left(T_{f_m} - T_{f_o}\right)^2}{n}} \tag{9}$$

where T_{fm} is the modelled carrier fluid temperature, T_{fo} is the "observed" (synthetic) temperature datum and n the number of data.

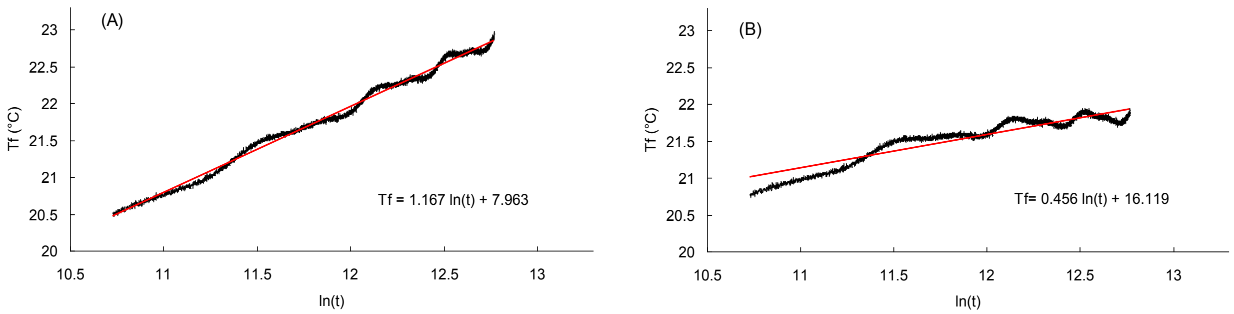

Figure 3. Synthetic TRT data (black curve) as a function of the logarithm of time and linear regression (red curve). A – v_x = 3.0x10^{-9}; B – v_x=3.0x10^{-6} m s^{-1}. The linear regression equation is also shown.

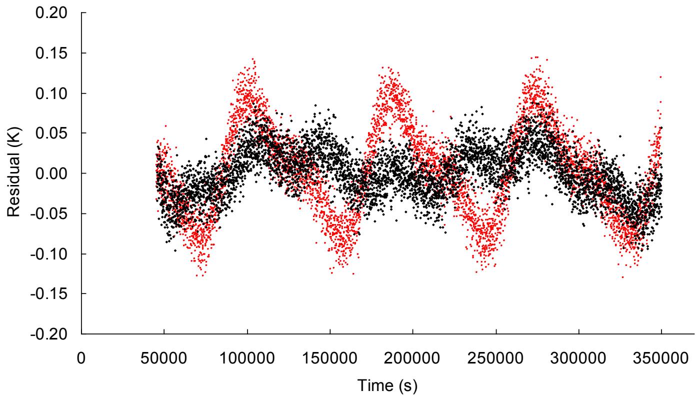

Figure 4. Residuals of the optimised temperature-time curve and the synthetic TRT data obtained for a Darcy velocity of 3.0x10^{-6} m s^{-1}. Red dots: residuals calculated from the raw data; black dots: residuals after filtering the TRT curve to remove periodic oscillations (see text).

Optimisation was carried out with a non-linear procedure based on the Nelder and Mead (1965) algorithm, and thermal and hydraulic properties were determined by iterative reprocessing.

Figure 4 shows a plot of the differences between the calculated temperature-time curve and the synthetic signal obtained by simulating a TRT curve in a BHE affected by strong groundwater flow (see Fig. 2B). We applied the optimisation technique both to the raw data and after treating the signal for removing the periodic oscillations. A polynomial trend was subtracted from the signal and a Butterworth high-pass filter was applied in order to remove the 12-24 h periodic oscillations. After filtering, the residuals decrease and appear more regularly distributed along the zero line. However, the RMSEs are small (0.030-0.057 K) in any case, and the optimisation give similar results in terms of λ, v_x and R_b, in perfect agreement with the "a priori" values (Table 1).

4. BOREHOLE DATA ANALYSIS

A real temperature-time record from a grouted, double-U-shaped BHE was tested with the optimisation procedure described in the previous section. Figure 5 presents the undisturbed temperature-depth profile of the BHE, which was drilled in a sedimentary formation. The undisturbed temperatures were measured with a precision logging apparatus (thermal resistance Pt-100) with uncertainty of 0.02 °C. The borehole is 15 cm in diameter and reaches a depth of 100 m. It encountered a homogenous formation consisting of sand and silt successions. The water table is at 0.80 m below surface, thus indicating the presence of a shallow aquifer. The non-linearity of the temperature depth profile may be evidence of possible advective processes in the selected test site.

Table 1. Thermal and hydraulic parameters obtained with the optimisation procedure from synthetic TRT data.

TRT Signal	λ (W m^{-1} K^{-1})	v_x (m s^{-1})	R_b (m K W^{-1})	RMSE
Filtered	2.00	3.0x10^{-6}	0.10	0.030
Raw	2.01	3.1x10^{-6}	0.11	0.057

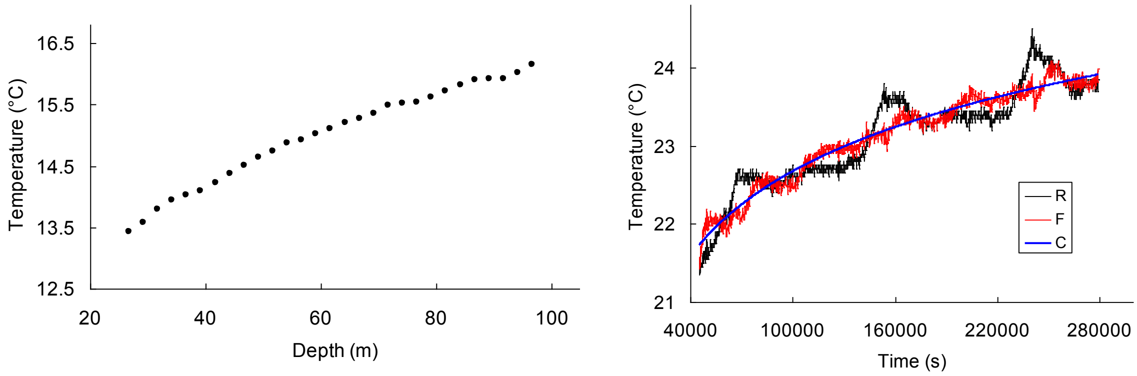

Figure 5. Undisturbed temperature-depth profile (left) and TRT data (right) recorded in the investigated BHE. R- raw data; F- filtered data; C- best fitting curve obtained with the optimisation procedure (see text).

Table 2. Analytical models of temperature *T* versus depth *z* incorporating advective heat transfer. Models were obtained from the mass and energy balance under the assumption of a steady-state thermal regime in permeable horizons with uniform thermal and hydraulic properties. Non-dimensional parameters $\beta=\rho_w c_w v_z L/\lambda$ and $\alpha=\rho_w c_w v_x L/\lambda$, where L is the investigated depth range of the aquifer. Models are rewritten as simplified equations suitable to the best fitting procedure. The meaning of coefficients a_n, b_n, c_n and d_n, used for inferring Darcy velocity horizontal (v_x) and vertical (v_z) components, are made explicit. Γ_z and Γ_x are the vertical and horizontal temperature gradients

Model	Equation	Coefficients
A) $T(z)=T_o+(T_L-T_o)\left[\frac{\exp(\beta z/L)-1}{\exp(\beta)-1}\right]+\frac{v_x}{v_z}L\Gamma_x\left[\frac{\exp(\beta z/L)-1}{\exp(\beta)-1}-\frac{z}{L}\right]$	$T=a_1+b_1\exp(c_1 z)-d_1 z$	$c_1=v_z\rho_w c_w/\lambda$ $d_1=v_x\Gamma_x/v_z$
B) $T(z)=T_o+(T_L-T_o)\left[\frac{\exp(\beta z/L)-1}{\exp(\beta)-1}\right]$	$T=a_2+b_2\exp(c_2 z)$	$c_2=v_z\rho_w c_w/\lambda$
C) $T(z)=T_L-\frac{L}{2}(\alpha\Gamma_x+2\Gamma_z)+\Gamma_z z+\frac{\alpha}{2L}\Gamma_x z^2$	$T=a_3 z^2+b_3 z+c_3$	$a_3=v_x\rho_w c_w\Gamma_x/2\lambda$
D) $T(z)=\left[T_L-L\Gamma_z-\alpha\Gamma_x\left(\frac{L}{2}+\frac{L^2 D}{6}\right)\right]+\Gamma_z z+\frac{\alpha}{2L}\Gamma_x z^2+\frac{\alpha}{6L}\Gamma_x D z^3$	$T=a_4 z^3+b_4 z^2+c_4 z+d_4$	$b_4=v_x\rho_w c_w\Gamma_x/2\lambda$

Figure 5 also shows the fluid temperature recorded in the boreholes at 60 seconds intervals during a TRT over a period of about 80 hours. The test was carried out by injecting heat into the BHE with an average heat flux per unit length of about 30 W m^{-1}.

Chiasson et al. (2000) showed that, as a first approximation, when there is considerable groundwater movement, the values computed on the basis of the ILS seem to be more reliable when the data is measured during short tests (50 h). However, if significant groundwater flow occurs, the subsurface thermal conductivity cannot be correctly evaluated from the data of a TRT without incorporating the effect of advection. Therefore, we interpreted our real dataset by means of the optimisation procedure based on the MLS model. The obtained best fitting curve is shown in Fig. 5. We performed a spectral analysis of the recorded TRT data which denotes a superposition of periodic components, whose origin may be only partly ascribed to a non-optimal thermostatic behaviour of the apparatus, resulting in a periodic noise that cannot be considered of minor importance. Therefore, the same denoising procedure applied to synthetic data was used to attempt to improve the signal quality. By assuming a volume heat capacity of 2.4x10^{6} J m^{-3} K^{-1}, the optimisation technique led to values of 2.09 W m^{-1} K^{-1} for the thermal conductivity, 4.12x10^{-7} m s^{-1} for the Darcy velocity and 0.11 m K W^{-1} for the borehole thermal resistance.

The estimated thermal conductivity appears to be consistent with literature data reporting values of thermal parameters of lithotypes similar to those observed in the investigated borehole (see Pasquale et al., 2011). The reliability of the obtained groundwater flow can be tested by means of an independent method based on the analysis of the temperature-depth logs carried out under thermal equilibrium conditions (prior to the thermal test). The method consists of matching temperature-depth data with analytical models that incorporate the effect of horizontal and/or vertical heat and water flow (Table 2). A detailed description of the theoretical bases of the method and the analysis procedure is given by Verdoya et al. (2008). The horizontal v_x and vertical v_z components of the Darcy velocity were calculated by using the value of thermal conductivity λ as inferred from the optimisation of TRT data. A horizontal temperature gradient Γ_x of 5 mK m^{-1} was assumed for calculations.

Figure 6 shows the residuals of the best fitting procedure while Table 3 lists the calculated values of Darcy velocity and the statistical parameters describing the goodness of fit. It turns out that model D exhibits the lowest summed square of residuals and root mean square error, and therefore it seems the most reliable. The corresponding Darcy velocity is of the order of 10^{-7} m s^{-1}, thus in good agreement with that inferred from the TRT data. This result, on the other hand, is also evidence of the reliability of the inferred thermal conductivity.

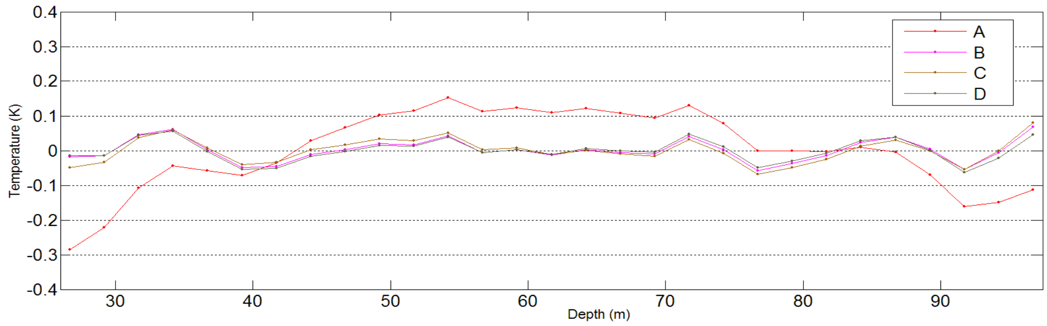

Figure 6. Differences between observed and modelled temperature values as a function of depth in the investigated BHE, for the theoretical models A-D of Table 2.

Table 3. Statistics of the models A–D used to match thermal data from the investigated borehole. SSE is the summed square of residuals, R-square the correlation coefficient.

Model	v_z (m s^{-1})	v_x (m s^{-1})	SSE	R-square	RMSE
A	-1.59x10^{-6}	1.16x10^{-5}	0.130	0.993	0.072
B	-7.67x10^{-9}		0.037	0.998	0.038
C		-5.45x10^{-8}	0.036	0.998	0.037
D		-1.39x10^{-7}	0.028	0.998	0.028

5. CONCLUDING REMARKS

Sizing borehole heat exchangers implies, as a preliminary step, in-situ thermal tests consisting of the heat injection (or extraction) to infer the subsurface thermal conductivity and the borehole thermal resistance. The most common model to analyse temperature-time curves obtained from these tests is the infinite line source. This model gives appropriate estimations of underground thermal parameters only if particular hydro-geological conditions are fulfilled. When groundwater flows at Darcy velocity larger than 10^{-7} m s^{-1}, the infinite line source model yields unreliable estimates of thermal conductivity.

The optimisation technique implemented in this study appears to be a suitable procedure to analyse thermal response test data both under a purely conductive thermal regime and in presence of groundwater flow. The application of the moving line source model seems to improve the results obtained with the infinite line source approach. Despite of the strong assumptions (e.g. homogenous medium, no vertical temperature gradient and only horizontal groundwater flow), the proposed approach seems to yield reliable results both in term of thermal (λ and R_b) and hydraulic (Darcy velocity) parameters. The reliability of the inferred Darcy velocity can be validated by an independent approach based on the analysis of temperature-depth logs recorded under conditions of thermal equilibrium.

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