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Estimating Thermophysical Parameters from *in-situ* Tests in Borehole Heat Exchangers

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ABSTRACT

We monitored the underground thermal recovery in a pilot geothermal plant, after modifying the equilibrium temperature-depth profile with the injection of a known heat flow for obtaining the thermal properties of the underground. The temperature-time series, recorded at 20 m depth intervals with a precise thermal logging device, were analyzed with inverse techniques based on the line-source and the cylindrical source models. The latter was approached as a best-fitting problem between the measured and computed fluid temperatures. By fitting the recorded temperature data with a least square approach, we obtained the underground thermal diffusivity and volumetric heat capacity, together with the borehole thermal resistance at several depth intervals. The results were then compared to data obtained from laboratory analysis on rock samples and from conventional thermal response tests.

1. INTRODUCTION

Ground-source heat pumps (GSHPs) take advantage of the constant ground temperature, to obtain higher efficiencies than conventional systems (Borinaga-Treviño et al., 2013). Ground is used as an infinite sink (cooling mode) or source (heating mode) of thermal energy (Desmedt et al., 2012), and thus the performance of GSHPs depends on the heat transfer between a borehole heat exchanger (BHE) and the surrounding rock (Luo et al., 2013). Besides the type of thermal regime, the efficiency of BHEs depends on the overall thermal resistance of the borehole. This can be strongly affected by the thermal conductivity of the underground (accounting for most of the heat that can be extracted) and of the grouting materials, which should ensure the stability of well sides but also optimal heat transfer from the carrier fluid circulating in the borehole pipes to the ground and vice versa.

The knowledge of thermophysical parameters is thus of crucial importance to reduce the overall thermal resistance of borehole heat exchangers and thus is one of the major tasks in designing GSHPs. An *in-situ* test of thermal response (TRT) (see Stauffer et al., 2014, for an historical review on the development of this technique) is customarily used to characterise the underground thermal properties and the borehole resistance. The interpretation of TRTs is generally based on the solution of analytical models of the heat diffusion equation, like the line and the cylindrical heat-source model. These solutions produce results of ground thermal conductivity integrated over the borehole length, as well as the borehole thermal resistance. However, in non-homogenous, stratified media, vertical variations of such parameters are likely to occur.

In this paper, we describe the results of a series of experiments, part of which still in progress, carried out in a pilot geothermal plant, consisting of two BHEs coupled with a GSHP and a Solid Oxide Fuel Cell (SOFC). The overall system is being used for heating some buildings of the University of Camerino, central Italy (Fig. 1). SOFC produces simultaneously electricity, partially used to start the GSHP, and domestic hot water using natural gas. Several parameters are being measured such as indoor and outdoor temperature, total energy consume, daily energy consume of SOFC as well as total and instant heat flow, inlet and outlet temperature, instant temperature difference and power, SOFC thermal storage, gas consumption, etc.

The test area is located within the geological frame of the Apennine mountain chain (Fig. 1). From the Upper Trias to Neogene, this area experienced a continuous marine sedimentation, which produced the so-called Umbria-Marche (U-M) sedimentary succession (Pierantoni et al., 2013).

The lower part of the U-M succession is a carbonate sequence cropping out in the inner part of the study area, while the outer part is covered by younger marine siliciclastic formations, unconformably deposed between Late Miocene and Lower Pleistocene (Centamore et al., 1991) and recording the stages of the Apennine compression. In particular, our pilot plant is located within the Camerino Basin, an Upper Miocene intermountain syncline (Cantalamessa et al., 1986). This basin is filled by an alternation of finely layered pelitic to pelitic-arenaceous and locally arenaceous pelitic deposits (Camerino Formation), unconformably resting on the marly Schlier Formation.

Two boreholes (B1 and B2) were drilled 9 m apart in the test area and equipped with two 95 m deep single U-shaped pipes. Figure 2 shows the stratigraphic reconstruction derived from the borehole cuttings. There was no substantial difference in the lithological sequence found in the two wells. The boreholes cut the pelitic and pelitic-arenaceous lithofacies of the Camerino Formation, with an arenaceous level, about 3 m thick, at about 60 m depth. Some slightly bituminous layers were recognized from cuttings. In the uppermost 5 m, coarse, landslide materials (MUSa1 - Holocene) were found, while the well bottom consisted of cemented pelitic lithofacies, clay-silty marls and marl-silty clay.

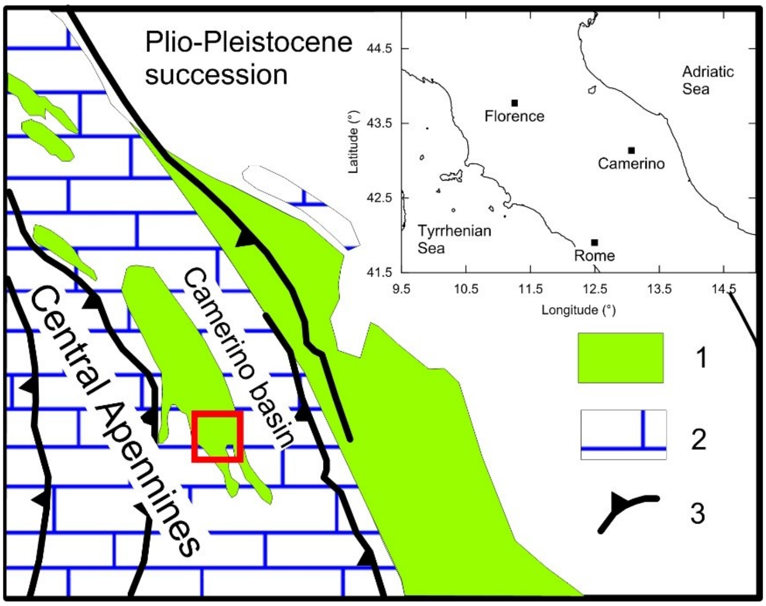

Figure 1: Location of the study area (red square) and geological sketch of the central Apennines: (1) siliciclastic Miocene turbidites and (2) calcareous, marly-calcareous, marly deposits of the Umbria-Marche sedimentary succession; (3) main thrust fronts.

Investigations of underground thermal properties of the pilot plant were initially carried out by means of the classical approach of the thermal response test (TRT). The estimation of thermal conductivity from TRTs is based on a number of assumptions and on the fact that, in particular, the underground thermally behaves as homogeneous medium. However, in lithologically complex realms, vertical variation of thermal conductivity is to be expected. An alternative approach, based on the underground temperature change (thermal recovery) after TRTs can yield information on the thermal conductivity distribution with depth. In this paper, we test the use of thermal recovery data with two different models, the line-source and the cylindrical heat source, and compare the thermal properties results with the parameters inferred from laboratory measurements.

2. HEAT TRANSFER MODELS

In a classical work, Lachenbruch and Brewer (1959) suggested a technique to remove the temperature disturbances due to the drilling fluid circulation and thus infer the undisturbed (equilibrium) underground temperature from borehole temperature data. By considering a drilled borehole like a linear heat source in a purely conductive medium, at a given depth the variation of the drilling fluid temperature, T_{df}, with time, t, is

$$T_{df}(t) = T_e + \left(\frac{q}{4\pi k}\right)\ln\left(1+\left(\frac{t_c}{t}\right)\right), \tag{1}$$

where T_e is the undisturbed temperature at that depth, q (W m^{-1}) the heat rate, assumed to be constant, which the circulating fluid is supplying to the well, k the bulk thermal conductivity, t_c the fluid circulation time and t the time since cessation of fluid circulation (shut-in time). Equation (1) is customarily applied for inferring T_e by plotting T_{df} against $\ln(1+(t_c/t))$. A straight line of best fit through all points from the same depth yields T_e for that depth at the T-axis intercept ($t=\infty$). The fluid circulation time and the shut-in time are usually known from drilling reports, whereas q and k, of course, unspecified.

Equation (1) can also be used to infer thermal conductivity in a BHE (see Verdoya et al., 2018). By considering q as the heat rate injected during a TRT and T_{df} equivalent to the temperature T_f of the fluid circulating in the BHE, putting $a = q/4\pi k$ and $b = \ln(1+(t_c/t))$, one has

$$T_f(t) = T_e + ab, \tag{2}$$

i.e. the fluid temperature can be expressed as a linear function of the logarithm of time, from which thermal conductivity can be easily inferred from the slope a. Notice that the method neglects the borehole thermal resistance, which therefore cannot be calculated.

In principle, the cylindrical heat-source model is also suitable for retrieving thermal parameter information. This model can well represent the heat transfer between the ground and the BHE, in absence of significant groundwater flow and for short-term evaluation. It assumes that heat is transferred only horizontally, the medium where the propagation occurs is infinite and with a thermal conductivity much lower than that of the cylinder. Moreover, a contact resistance R (m K W^{-1}) between the cylinder and the surrounding medium is taken into account. In its complete formulation, the model describes the temperature in the underground, but in most problems the interest is focused on the temperature of the material within the cylinder. Thus, we refer to the formula for the cylinder temperature as cylindrical model. By using the cylindrical coordinates, with the BHE placed at $r = 0$, the spatial domain is described by $r > a$, where a is the borehole radius, while the time domain is $t > 0$, where $t = 0$ corresponds to the starting of the fluid circulation. The problem formulation is based on the heat conduction equation:

$$\frac{\partial u}{\partial t}(r,t)-\alpha\frac{\partial^2 u}{\partial r^2}(r,t)-\alpha\frac{1}{r}\frac{\partial u}{\partial r}(r,t)=0, \tag{3}$$

where u is the underground temperature, α is the thermal diffusivity. The boundary condition in $r = a$ must describe the contact of the ground with the well stirred fluid within the cylinder (Carslaw and Jeager, 1959) The solution of Eq (3) endowed with proper boundary and initial conditions is then (Carslaw and Jeager, 1959; Gunzel and Wilhelm, 2000)

$$T_f(t)=T_e+\frac{8q\rho c}{\pi^3\alpha\rho_f^2c_f^2}\int_0^{\infty}\frac{e^{-\alpha(t-t_c)p^2/a^2}(1-e^{-\alpha t_c p^2/a^2})}{p^3 g(p)}dp, \tag{4}$$

where ρ_f and c_f are the density and the specific heat of the fluid, respectively, ρ and c are the density and the specific heat of the underground, respectively, q is the heat rate, t_c is the prescribed duration of the thermal stimulation prior to the thermal recovery, and

$$g(p)=\left(pJ_0(p)-\left(\frac{2\rho c}{\rho_f c_f}-hp^2\right)J_1(p)\right)^2+\left(pY_0(p)-\left(\frac{2\rho c}{\rho_f c_f}-hp^2\right)Y_1(p)\right)^2,$$

where $h = 2\pi Rk$ is the dimensionless thermal resistance parameter, k is the thermal conductivity, J_0; J_1 are the Bessel functions of the first kind and Y_0; Y_1 of the second kind.

The estimation of the soil parameters can be then formulated as a least square problem, that is

$$\min_{\alpha,\rho c,h}\sum_{n=1}^{N}\left(T^M(t_n)-T_f(t_n;\alpha,\rho c,h)\right)^2, \tag{5}$$

where T^M is the fluid temperature measured in situ during the recovery, T_f is the explicit solution (Eq 4), and N is the number of temperature readings registered during the recovery.

3. IN-SITU MEASUREMENTS

Figure 2 shows temperature-depth profiles recorded in the two boreholes B1 and B2. The temperature log for undisturbed underground temperature was recorded one month after the borehole completion, i.e. when conditions of thermal equilibrium were likely restored. A precision temperature acquisition system with a Pt-resistance sensor was used. Temperatures were recorded at regular depth intervals every 5 m until 20 m depth (i.e. the maximum depth at which the underground was expected to be influenced by seasonal variations), and then at 2.5-m-depth intervals.

The average temperature measured is 12.57 °C for B1 and 12.56 °C for B2. The occurrence of possible advective heat transfer was carried out by applying the moving line source theory, but the contribution of groundwater was evaluated negligible (see Verdoya and Chiozzi, 2018 and Verdoya et al., 2018 for details).

A TRT was performed by injecting a constant heat rate per unit length (the average amount of heat injected was q = 40 W m^{-1}) into the boreholes for a period of more than 60 hours. After the heat injection tests, the TRT apparatus was switched off and water circulation within the pipes stopped. The temperature variation with time was measured in both BHEs along inlet pipes. Measurements were carried out at 20 m depth intervals by means of the same apparatus used for thermal logging. The uppermost 20 m were not monitored because affected by daily and seasonal variations. The first record was performed within one hour after shut-in, and four measurements were carried out within 24 hours. Then, the record frequency was reduced and temperatures had been surveyed for 420 hours since shut-in.

Figure 3 shows the observed temperature variation with time after heat injection stopped. Because of heat diffusion, the temperature drop-off has occurred initially at a faster rate. After 160 hours, temperatures were on average only 0.46 K greater than the equilibrium (pre-TRT) temperatures. Records after 420 hours (in B2) indicate that thermal equilibrium was nearly attained as the differences with the undisturbed temperatures profile range from 0.06 to 0.17 K. Albeit the thermal recovery in both BHEs is similar, it also appears that the lower section of B1 (80 m depth) has cooled more slowly than B2.

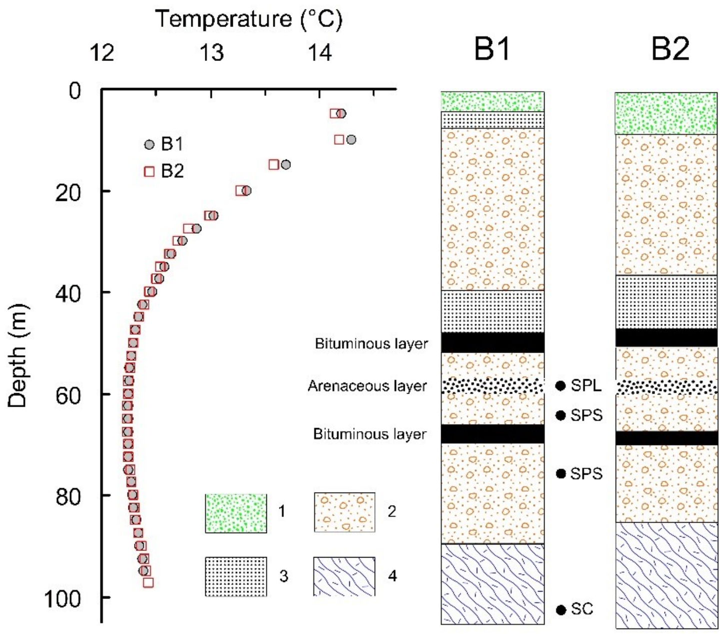

Figure 2: Undisturbed temperatures and stratigraphy of the boreholes B1 and B2 drilled at the Camerino University. 1) colluvial deposits; Camerino Formation: 2) pelitic-arenaceous layer consisting of grey-yellowish sand and clayey-silty marls; 3) pelitic layer with clay-silty marls and marl-silty clay, in lamina strata sometimes bioturbated; 4) marly, sterile layers above Schlier Formation. Stratigraphic position of rock samples analyzed in the laboratory (SPL, SPS and SC) is also shown.

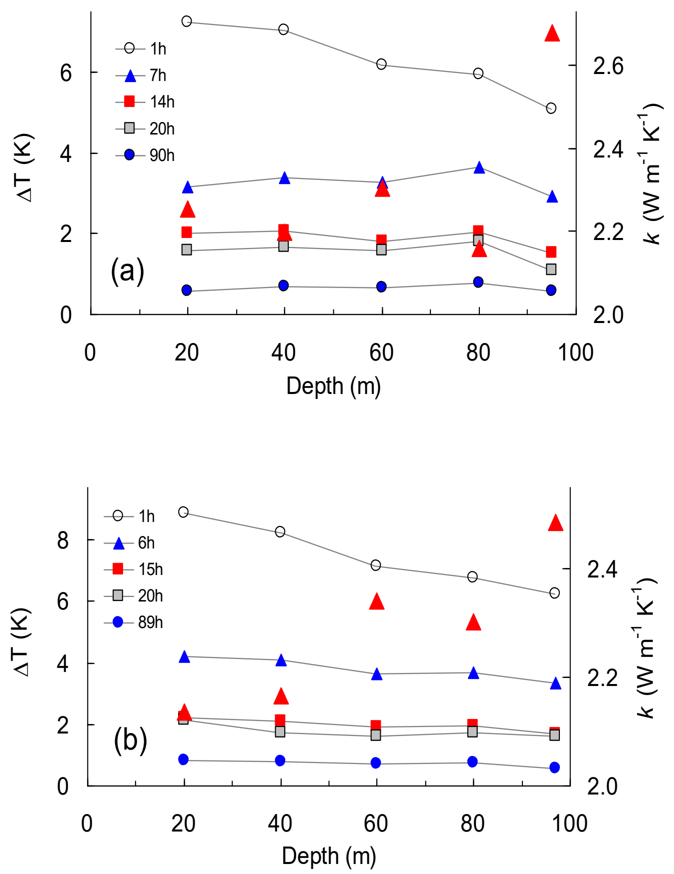

Figure 3: Temperature variation ΔT=T_f-T_e (Eq 2) as function of time (in hours) since the end of TRT in BHE B1 (a) and B2 (b). Temperatures are expressed as departures from the equilibrium temperatures (cfr. Fig. 2). The inferred thermal conductivity k at 20, 40, 60, 80 and 95 m (B1) and 97 m (B2) depth is also shown (full triangles).

4. ANALYSIS OF THERMAL RECOVERY DATA

The repeated measurements of temperature in the BHEs after heat injection stopped make it possible to study the variation of thermal conductivity with depth. First, we tested the linear source model (Eq 2) and then the cylindrical model (Eq 4).

In our experiments, T_e was known from equilibrium thermal logs (Fig. 2), q and t_c are assumed as the average heat rate per unit length and the fluid circulation time during the TRT, respectively, and the time since the end of TRT is known. Thermal conductivity is the only unknown of the problem.

Equation (2) was applied to the recorded temperature-time series recorded at 20, 40, 60 m depth and at the hole bottom. From 20 to 80 m depth, thermal conductivity is little variable (Fig. 3), as it ranges from 2.16 to 2.31 W m^{-1} K^{-1} in B1 and from 2.14 to 2.34 W m^{-1} K^{-1} in B2. Within this depth range, the maximum values are observed at 60 m depth. In both holes one can notice an increase at the hole bottom (2.68 and 2.49 W m^{-1} K^{-1} in B1 and B2, respectively). The average thermal conductivity values for the two BHEs are quite similar (2.32 ±0.21 W m^{-1} K^{-1} for B1 and 2.29 ±0.14 W m^{-1} K^{-1} for B2) and are consistent with the values obtained with the moving line source method.

The cylindrical model was applied to three time-series of measured fluid temperatures from B2, corresponding to 60, 80 and 97 m depth (Fig. 3), since they appeared more continuous and with no vacancy in data. Equation (4) was numerically approximated by applying the mid-point rule as quadrature scheme. In addition the integral domain was truncated in such a way to neglect the values of the variable p giving exponential values smaller than $exp(-1/5)$. The solution of least square problem (Eq 5) was computed by using the Nelder-Mead method (Lagarias et al., 1998). Calculation was based on the whole time series of recovery temperatures.

Table 1: Comparison between thermal conductivity *k* (W m^{-1} K^{-1}), diffusivity α (μm^2 s^{-1}) and volumetric heat capacity ρc (MJ m^{-3} K^{-1}) inferred by means of the linear heat source model (LSM), the cylindrical model (CSM) and laboratory analyses.

	LSM			CSM			Laboratory*		
Depth (m)	k	α	ρc	k	α	ρc	k	α	ρc
60	2.34	-	-	3.50	0.75	4.68	2.66	-	
80	2.30	-	-	3.16	0.83	3.79	1.84	0.68	2.68
97	2.49	-	-	3.86	0.70	5.55	2.34	-	

*Values after Verdoya et al. (2018)

Table 1 shows a comparison between values of thermal parameters obtained with the line-source and the cylindrical source models in borehole B2 and those measured on rock samples. Since percussion drilling was used, no core sample was available from the boreholes. However, surface samples and cores from other exploration drillings were collected in the vicinity of the BHE site. For the consolidated lithotype (sandstone samples SPL and SC, Fig. 2) the transient divided bar apparatus was used (see Pasquale et al. 2015 for details on the method). A needle probe was used to measure thermal properties of unconsolidated pelitic and pelitic-arenaceous lithotypes (SPS, Fig. 2).

Laboratory values for ground thermal conductivity range between 2.7 W m^{-1} K^{-1} and 2.3 W m^{-1} K^{-1}, with an average of 2.6 W m^{-1} K^{-1}. The largest thermal conductivities were observed in denser, hard rocks (sandstones, and marls), whereas pelitic lithotypes denotes lower values. The volume heat capacity is slightly variable (on the average about 2.7 MJ m^{-3} K^{-1}). Thermal diffusivity is on average about 0.7 μm^2 s^{-1}.

There is a good agreement between the LSM and the laboratory results, whereas the CSM model tends to overestimate them. The discrepancy might be smoothed by using a model that describes more properly the heat transfer occurring between the underground and the fluid within the exchanger. In particular, it should couple the soil thermal response with the exchanger, which consists in considering the mutual influence between the warming of the soil and the cooling of the exchanger. Such a coupling is not trivial, since it is related to complex fluid dynamics processes inside the exchanger and it is based on proper boundary conditions and source terms.

LSM and laboratory results of thermal conductivity are also consistent with those estimated through the moving line-source model by Verdoya et al. (2018), who found slightly different values in the two boreholes (2.48 W m^{-1} K^{-1} in B1 and 2.09 W m^{-1} K^{-1} in B2).

The CSM also yields an estimate of the borehole thermal resistance R at several depths. A comparison can be made with the value of R calculated from the interpretation of the TRT data (see Verdoya et al., 2018) and those obtained with CSM. Values of 0.191 in B1 and 0.187 m K W^{-1} in B2 were found by means of TRT, whereas CSM gave an average value of 0.095 m K W^{-1} in B2. This again indicates that the proposed model tends to underestimate the thermal resistance, which is reasonably due to the overestimation of the thermal conductivity.

5. CONCLUSIONS

We presented approaches to infer thermal parameters of the underground (thermal conductivity, diffusivity, heat capacity) and borehole resistance from in situ experiments based on the temperature record during the recovery phase of the thermal response test. We analysed experimental data from two adjacent borehole heat exchangers. In other word, we exploited these borehole exchangers as tools for relevant geological analyses. The inferred values were also compared with the values obtained from direct analyses on ground samples.

Thermophysical properties from laboratory measurements agree substantially with the effective thermal conductivity inferred from the *in-situ* tests even if slightly lower values of thermal conductivity were observed in the laboratory samples (<10%). This is partly ascribable to the difficulty of performing lab measurements especially on weak rocks and to heterogeneity in lithological composition. On the other hand, this may also explain the minor differences in effective thermal conductivity observed in the two boreholes.

For conduction-dominated thermal regime, the approach based on the thermal recovery and the line-source model is applicable and can yield relatively rapid and precise determinations of thermal conductivity and details of its variation with depth. At the present stage of development, the cylindrical source model tends to overestimate the thermal parameters (especially thermal conductivity and diffusivity). Nevertheless, being the underground thermal parameters and the borehole resistance subtle features to be determined via an indirect analysis, these preliminary results are promising, albeit could be refined either modifying the numerical approximation of the problem or even the analytical model behind the computation of the fluid temperature.

In summary, the experiment demonstrated that it is possible to infer stratigraphic information of the underground in case samples are not available for analyses and that these approaches can avoid long and expensive laboratory experiments.

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