Finite-Element Evaluation of Thermal Response Tests Performed on U-Tube Borehole Heat Exchangers

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Abstract: The results of two thermal response tests recently performed on two vertical borehole heat exchangers (BHEs) are presented. The BHEs are located in North Italy; they have the same cross section and a depth of 100 m and 120 m respectively. The evaluation of the thermal properties of the ground and the grout is performed by a finite-element simulation method, developed through the software package COMSOL Multiphysics 3.4. The problem is sketched as two dimensional and the true geometry of the BHE cross section is considered. The convective thermal resistance is reproduced through an effective (reduced) conductivity of the tube walls. Water is considered as a solid in which a uniform heat generation occurs. The heat capacity of the water contained in the circuit is represented through a time dependent effective density of the water contained in the BHE. The method allows to reproduce accurately the time evolution of the mean temperature of water, even in the initial part of the heating process, and to obtain a reliable evaluation of the thermal properties of both ground and grout.

Keywords: borehole heat exchangers, thermal response tests, numerical evaluation

Nomenclature

a	borehole radius, [m]
c_p	specific heat capacity at constant pressure, [J/(kg K)]
k	thermal conductivity, [W/(mK)]
$\dot{m}$	mass flow rate, [kg/s]
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}_b$	power delivered to the borehole, [W]
$\dot{Q}_c$	calorimetric power, [W]
$\dot{Q}_{el}$	electric power, [W]
$\dot{Q}_r$	heat loss per unit time from the tank, [W]
$\dot{Q}_t$	heat loss per unit time from external tubes, [W]
q_g	heat generation per unit volume, [W/m^3]
R_b	borehole thermal resistance, [mK/W]
Re_D	Reynolds number referred to the diameter
r	radial coordinate, [m]
T	temperature, [°C]
T_g	undisturbed ground temperature, [°C]
T_{in}	inlet water temperature, [°C]
T_m	mean water temperature, [°C]
T_{out}	outlet water temperature, [°C]
t	time, [s]
U	Heaviside unit step function
U_t	global heat transfer coefficient , [W/K]
V_b	BHE water volume, [m^3]
V_{eff}	effective water volume, [m^3]
Greek symbols	
α	thermal diffusivity, [m^2/s]
ρ	density, [kg/m^3]
ρ_{eff}	effective water density, [kg/m^3]

1 Introduction

Borehole heat exchangers (BHEs) for ground coupled heat pumps are typically composed of one or two U-tubes, made of high density polyethylene, which are placed in a borehole and then grouted with a cement-bentonite mixture. In order to determine the total length of the BHEs needed for a plant, a thermal response test (TRT) is usually carried out following the procedure recommended by ASHRAE [1]. First, the undisturbed ground temperature is measured. Then, by means of electric resistances, a constant heat load is supplied to the heat carrier fluid, namely water, which flows in the pipes. The water inlet and outlet temperatures, T_{in} and T_{out}, with mean value T_m, as well as the mass flow rate $\dot{m}$ and the electric power $\dot{Q}_{el}$, are measured and recorded at regular time intervals.

The values of T_{in}, T_{out} and $\dot{m}$ allow to determine the *calorimetric* power, *i.e.*, the power measured by flow calorimetry,

$$\dot{Q}_c = \dot{m}\, c_p\, (T_{in} - T_{out}) \ , \qquad (1)$$

which, when steady state conditions are approached, is nearly equal to the thermal power exchanged between BHE and ground. In Eq. (1), c_p is the specific heat capacity at constant pressure of water at temperature T_m. Powers $\dot{Q}_{el}$ and $\dot{Q}_c$ are functions of time determined experimentally; while $\dot{Q}_{el}$ is almost constant, $\dot{Q}_c$ becomes almost constant only after several hours.

To determine the total length of the BHEs necessary for a plant one needs to find out, by means of a TRT, the values of the effective thermal conductivity k and of the effective thermal diffusivity α of the ground. In order to evaluate k and α, both analytical and numerical methods are employed.

The *line heat source* model, proposed by Mogensen [2], is both the simplest and the most widely used analytical method. It considers a BHE as a linear power source with a constant power per unit length, within a homogeneous and isotropic infinite medium with a uniform initial temperature. This method con be applied only after a sufficiently long time after the beginning of electric heating; typically 15 hours.

Another analytical method, called *cylindrical heat source*, approximates a BHE as an infinite cylindrical surface with radius a, within a homogeneous and infinite medium at initial temperature T_g, which supplies to the external medium a constant heat flux per unit area. Values of k and α are obtained by minimizing the difference between the measured values and the calculated values of $T_m(t)$. The cylindrical heat source method tends to overestimate the value of k, so that the line heat source method is both simpler and more reliable [3, 4].

Several numerical models for the evaluation of thermal response tests, with different complexities, have been proposed: 1-D finite difference models [4], 2-D finite volume models [5, 6], 3-D finite element models [7]. Even with 3-D models, it is difficult to reproduce with high accuracy the results of the first hour of the test, so that the comparison between experimental and numerical results is often reported starting from some hours after the initial instant. One of the difficulties is to account for the thermal inertia of the water contained in the circuit.

In this paper we present the key features and the results of a 2-D finite-element method for the numerical simulation of thermal response tests, developed by means of the software package COMSOL Multiphysics 3.4. Simulation results are compared with the experimental data of two thermal response tests carried out by the authors on U-pipe BHEs with a depth of 100 m and 120 m respectively, placed in North Italy. The method allows an accurate simulation even of the first hour of the heating process, and allows a reliable evaluation of the thermal properties of both soil and grout.

2 Thermal Response Tests

The TRTs hereby considered have been performed on two U-pipe BHEs, each composed of four polyethylene pipes, having inner radius 13 mm and thickness 3 mm, grouted by a mixture of cement (80%) and bentonite (20%). The first BHE considered is located in Fiesso D'Artico (VE), the second is located in Cesena (FC), both in the Padana flat (North Italy). The TRTs have been carried out implementing the apparatus recommended by ASHRAE [1], illustrated in Figure 1. Three 2 kW electric resistances and one 1 kW electric resistance are located inside a 100 litre tank. A 200 $\div$ 400 W centrifuge pump circulates the heat carrier fluid through the borehole. The water flow rate is measured by means of a G.P.I. device, G2A series, with range $0.228 \div 2.280\ \mathrm{m^3/h}$. Two type T thermocouples are positioned near the inlet and the outlet of the water tank (Figure 1) and 2 in air. The acquisition system is composed of a digital multimeter AGILENT 34970A, with LABVIEW software, and of a device Fluke 1735 Power Logger to measure and record the electric power. The estimated error in water flow rate measurements and in electric power measurements is less than 1.5%. The estimated error in temperature measurements (verified by an high precision calibration system) is 0.2 °C in temperature values and 0.05 °C in temperature differences.

The first TRT has been carried out for more than 111 hours, the second for more than 86 hours. The two BHEs have the same cross section and they are made with the same materials. The BHE section is illustrated in Figure 2. The same figure shows the stationary temperature field that one obtains when the inner wall of the pipe is at 30 °C and the external grout surface is at 20 °C, for the Fiesso D'Artico BHE. The most relevant geometrical data of the two BHEs are reported in Table 1.

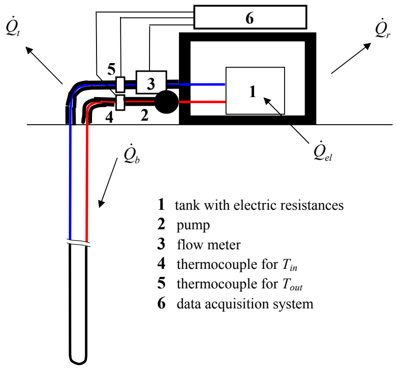

Figure 1: Scheme of the apparatus and of the energy balance.

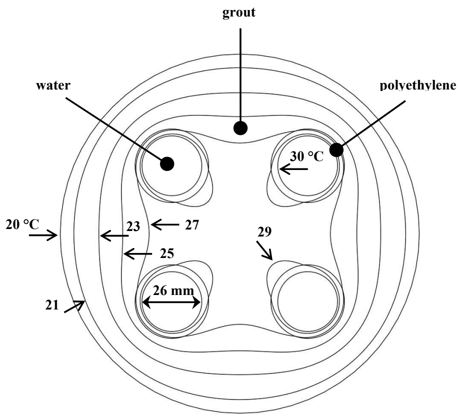

Figure 2: Cross section of the BHEs and isothermal lines for the Fiesso D'Artico BHE.

The convective heat transfer coefficient between water and the inner wall of the pipe has been calculated by means of the Dittus-Boelter correlation for circular tubes, with cooling down fluid [8],

$$Nu = 0.023\ Re_D^{0.8}\ Pr^{0.3} \quad . \tag{2}$$

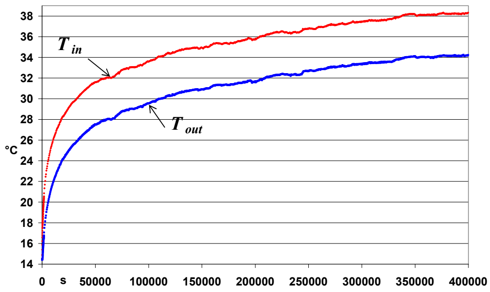

Figure 3: Plots of T_{in} and T_{out} versus time, Fiesso D'Artico BHE (time in seconds).

where Re_D is the Reynolds number referred to the inner diameter of the pipe. In the numerical simulation, the convective thermal resistance has been taken into account by considering an effective (lower) thermal conductivity of the polyethylene. The values of the thermal properties of water, at the mean water temperature, have been taken from [9]. As an example, plots of the temperatures T_{in} and T_{out} recorded at Fiesso D'Artico are reported in Figure 3. In this TRT, the mean value of the electric power during the whole test was 7679 W, with small fluctuations within 200 W. In the numerical simulations, the electric power has been considered constant. As regards the Cesena TRT, the mean electric power was 8200 W, with important fluctuations especially during the initial part of the test. In the numerical simulations the electric power data have been interpolated by means of a sinusoidal curve between 0 and 129000 s and by a constant value between 129000 s and the end of the test (310000 s).
The simulations are based on the power $\dot{Q}_b$ received by the water which flows in the BHE. As illustrated in Figure 1, one can write the energy balance equation

$$\dot{Q}_b = \dot{Q}_{el} - \dot{Q}_r - \dot{Q}_t \quad , \tag{3}$$

where $\dot{Q}_{el}$ is the electric power, $\dot{Q}_r$ is the heat loss per unit time from the tank and $\dot{Q}_t$ is the heat loss per unit time from the external tubes.

	B1	B2
Inner tube diameter, m	0.026	0.026
External tube diameter, m	0.032	0.032
Cross section pipe area, dm^2	0.5309	0.5309
Borehole diameter, m	0.156	0.156
Borehole depth, m	100	120
External pipe length, m	10	2
Borehole water volume, m^3	0.2124	0.2548
Tubes water volume, m^3	0.0212	0.0042
Tank water volume, m^3	0.098	0.098
Total water volume, m^3	0.3316	0.3570
Volume flow rate, l/min	26.51	26.99
Water mean velocity, m/s	0.4161	0.4236
Water mean temperature, °C	32.32	32.89
Reynolds number	14089	14516
Nusselt number	78.28	79.85
Thermal convection coefficient, $W/(m^2K)$	1864	1905
k polyethylene, W/(mK)	0.4	0.4
ρ polyethylene, kg/m^3	940	940
c_p polyethylene, J/(kgK)	2300	2300
Polyethylene effective k , W/(mK)	0.371	0.371

Table 1: Main geometrical data and test conditions; B1 = Fiesso D'Artico, B2 = Cesena

In the Cesena TRT, as is usual, the power $\dot{Q}_t$ was negligible because the linking pipes between the tank and the borehole were short and well insulated. In the Fiesso D'Artico TRT, on the contrary, the four pipes linking the tank to the borehole were 10 m long each and they couldn't be damaged by placing thermocouples. In this case, the power $\dot{Q}_t$ was calculated by determining the global heat transfer coefficient between the pipes and the external environment. The pipes, identical to those inside the BHE, were insulated with a 19 mm thick insulation with thermal conductivity 0.04 W/(mK). The global heat transfer coefficient was estimated as

$$U_t = 12.1\ W/K \ . \tag{4}$$

The difference between the mean temperature of the water flowing in the pipes and the external temperature was 29.57 °C, so that the mean thermal loss per unit time was

$$\dot{Q}_t = 358\ W \ . \tag{5}$$

The power $\dot{Q}_r$ is small and difficult to calculate. In order to estimate $\dot{Q}_r$ and to take into account the measurements of the calorimetric power $\dot{Q}_c$, the following method was adopted. In steady state regime one has

$$\dot{Q}_r = (\dot{Q}_{el} - \dot{Q}_c)_{st} \ , \tag{6}$$

where the subscript *st* means *steady state.* In all the TRTs carried out with the apparatus described above, the difference between $\dot{Q}_{el}$ and $\dot{Q}_c$ after 50000 s was positive and less than 2.7% of $\dot{Q}_{el}$, but higher that the estimated value of $\dot{Q}_r$. This result confirms the reliability of measurements, but suggests that a small systematic error affects the measurements of $\dot{Q}_c$. Therefore, 2/3 of the measured difference between $\dot{Q}_{el}$ and $\dot{Q}_c$ in quasi-steady conditions was considered as a systematic error and $\dot{Q}_r$ was evaluated by the equation

$$\dot{Q}_r = \frac{(\dot{Q}_{el} - \dot{Q}_c)_{st}}{3} \ . \tag{7}$$

In the Fiesso D'Artico TRT: $\dot{Q}_{el} = 7679$ W, $(\dot{Q}_{el} - \dot{Q}_c)_{st} = 162$ W, $\dot{Q}_t = 358$ W. From Eqs. (7) and (3) one has

$$\dot{Q}_b = 7267\ W \ . \tag{8}$$

Thus, the mean heat transfer rate per unit length of the borehole was 72.67 W/m.
In the Cesena TRT the power data were

$$\dot{Q}_{el} = 8250 + \{300\ sin[0.000075 \times (t - 12000)] - 163\} \times U(129500 - t) \ , \tag{9}$$

where U is Heaviside's unit step function, $(\dot{Q}_{el} - \dot{Q}_c)_{st}$= 216 W, $\dot{Q}_t \simeq 0$, thus

$$\dot{Q}_b = 8178 + \{300\ sin[0.000075 \times (t - 12000)] - 163\}U(129500 - t) \ . \tag{10}$$

The mean value of $\dot{Q}_b$ was 8200 W; the mean heat transfer rate per unit length of the BHE was 68.33 W/m.

3 Evaluation of the Undisturbed Ground Temperature

For the evaluation of the undisturbed ground temperature, T_g, the following method is recommended [10]. The BHE is filled with water some days before the test and reaches the thermal equilibrium with the ground. Then, water flow through the apparatus is produced by the pump, with electric resistances switched off; the water flow rate and the temperatures T_{in} and T_{out} are measured and recorded. The undisturbed ground temperature T_g is calculated by averaging T_{out} until all the fluid initially contained within the borehole has passed through. If the difference between the external temperature and the undisturbed ground temperature is large, the external condition can alter the results [10]. This phenomenon took place in the Fiesso D'Artico TRT, where the external temperature was much lower than the undisturbed ground temperature.

In order to estimate and reduce this error, in both TRTs considered in this paper the experimental determination of T_g has been matched with a numerical simulation of the measurement procedure, carried out by the method described in the next section. The injection in the borehole of water at a lower temperature, coming from the tank, has been simulated by a power subtraction during a time period which has been deduced by the plots of T_{in} and T_{out}; the electric power delivered by the pump has been considered too. At the end of the simulation, the mean fluid temperature T_m must coincide with the measured value. In the Fiesso D'Artico TRT, this procedure determined a + 0.2 °C correction of the value obtained experimentally. Figure 4 illustrates the time evolution of T_{in} and T_{out} during the measurement of T_g at Fiesso D'Artico. One can observe the temperature fluctuations due to the injection of colder water, for about 900 s, followed by a progressive rising of the mean water temperature due to the heat injected by the pump. The undisturbed ground temperature measured experimentally was 14.1 °C. The simulation by means of COMSOL Multiphysics 3.4 revealed that the effective undisturbed ground temperature was about 14.3 °C. Therefore we assumed, for the Fiesso D'Artico TRT

$$T_g = 14.3\ ^\circ\text{C} \quad . \tag{11}$$

For the Cesena TRT, the measured value of the undisturbed ground temperature was 14.6 °C and the numerical simulation was in perfect agreement with it. Therefore we assumed

$$T_g = 14.6\ ^\circ\text{C} \quad . \tag{12}$$

The numerical simulation of the measurement of the undisturbed ground temperature allowed us to determine the temperature distribution over the BHE and the ground to be used as initial condition for the simulation of the heating part of the test.

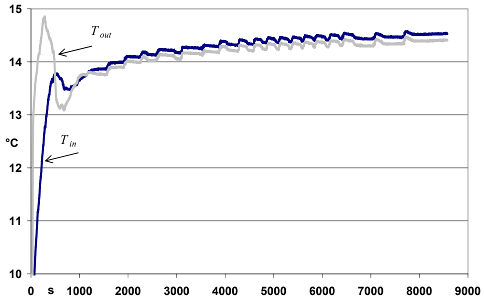

Figure 4: Plots of T_{in} and T_{out} versus time during the measurement of the undisturbed ground temperature, Fiesso D'Artico.

4 Simulation Method

In U-pipe BHEs, the mean fluid temperature is almost independent of the vertical coordinate. Moreover, for BHEs deeper than 100 m, the effects of the vertical changes in the ground temperature close to the surface are negligible. Therefore the problem has been considered as two-dimensional. The cross section of the BHEs has been represented in its true geometry. The convective thermal resistance between the water and the pipes has been taken into account by considering an effective thermal conductivity of the polyethylene. Water has been simulated as a solid with very high thermal conductivity ($k = 1000$ W/(mK)) where a uniform heat generation takes place. The heat generation per unit volume, q_g, has been calculated by dividing the power $\dot{Q}_b$ by the water volume within the borehole. Hence, by means of Eqs. (8) and (10), using data from Table 1, the following values of q_g have been obtained, for the Fiesso D'Artico BHE and for the Cesena BHE respectively:

$$q_g = 34218\ W/m^3 \quad , \tag{13}$$

$$q_g = 32090 + \{1177\ sin[0.000075 \times (t - 12000)] - 640\} \times U(129500 - t) \quad . \tag{14}$$

In order to simulate the thermal inertia of the water within the circuit, an effective water density has been considered. During the very initial part of the heating test, T_{out} does not change and the derivative with respect to time of $T_m = (T_{in}+T_{out})/2$ is equal to one half of the derivative of T_{in}; moreover, the time derivative of T_{in} is driven by the thermal inertia of the water in the tank. Therefore, the initial water volume to be considered in simulations is twice the tank volume. After a time interval determined experimentally, the time derivative of T_{in} becomes almost identical to that of T_{out}. After this time interval, it is reasonable to take into account the heat capacity of all the water within the circuit. Thus, the effective density of water has been calculated at the beginning and at the end of this interval, by the equation

$$\rho_{eff} = \rho \frac{V_{eff}}{V_b} \ , \tag{15}$$

where ρ is the water density, V_{eff} is the effective volume of water, evaluated as described above, V_b is the water volume within the borehole. To evaluate the thermal properties of water, the mean water temperature between 0 and 50000 s has been considered. By this method, the data reported in Table 2 have been obtained.

	B1	**B2**
Water T_m between 0 and 50000 s, °C	23.82	26.62
Water c_p, J/(kgK)	4179	4177
Water ρ, kg/m^3	997.4	996.6
V_{eff}/V_b at initial time	0.923	0.769
V_{eff}/V_b at final time	1.561	1.401
Water ρ_{eff} at initial time	920	767
Water ρ_{eff} at final time	1557	1397
Final time, s	570	740

Table 2: Evaluation of the effective density of water; B1 = Fiesso D'Artico, B2 = Cesena

The changes of the effective water density from the initial to the final value have been set using the "flc2hs" function of COMSOL Multiphysics, that generates a smoothed Heavyside function with continuous second derivative. Grout and soil have been represented in their true situation, but the movement of groundwater has not been considered. Indeed, the target of a TRT is to find *effective* values of the thermal diffusivity and conductivity of the ground that reproduce the real heat flows by pure conduction [4, 3]. The computational domain included the ground placed between the borehole radius, $a = 0.078$ m, and a 5 m external radius; the latter is large enough to make the results independent of the domain extension. The values of the thermal conductivity k and of the heat capacity per unit volume ρc_p of both grout and ground have been evaluated by attempts, by minimizing the standard deviation between measured and calculated values of T_m. Preliminary calculations have been carried out by a computational grid with 16032 triangular elements; the final calculations have been carried out by a computational grid with 64128 triangular elements.

The simulation time has been divided into intervals of variable duration: 50 s from 0 to 2000 s; 200 s from 2000 to 10000 s; 500 s from 10000 to 40000 s; 5000 s from 40000 to the end of the simulation. The differential equation to be solved, in the considered domain, is the Fourier equation for conduction with internal heat generation,

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + q_g \ . \tag{16}$$

For the simulation of the measurement of the undisturbed ground temperature, the initial condition is a uniform temperature distribution $T = T_g$. For the simulation of the heating part of the test, the initial condition is the final temperature field of the previous simulation. The continuity conditions have been imposed at the interfaces between different materials; the isothermal boundary condition $T = T_g$ has been set at the boundary of the computational domain (5 m radius circumference). The zero heat flux condition on this boundary gives the same results. The standard deviation between the values of T_m obtained by the final grid and those obtained by the preliminary grid was less than 6×10^{-5} °C.

5 Simulation Results

The values of the thermal properties of grout and soil that minimize the standard deviation between measured and calculated values of T_m are reported in Table 3, together with the values of the BHE thermal resistance per unit lenght, R_b. The latter has been evaluated by the numerical simulation of steady conduction in the BHE, by considering a 10°C difference between the internal and the external surface and the value of k

for grout reported in Table 3. The isothermal lines so obtained for the Fiesso D'Artico BHE are shown in Figure 2. A comparison between experimental and simulated values of T_m is shown in Figures 5 and 6. The figures reveal an excellent agreement between experimental results and simulations, even in the initial part of the heating process. The standard deviation between experimental and simulated values of T_m is 0.16 °C for the Fiesso D'Artico BHE and 0.12 °C for the Cesena BHE.

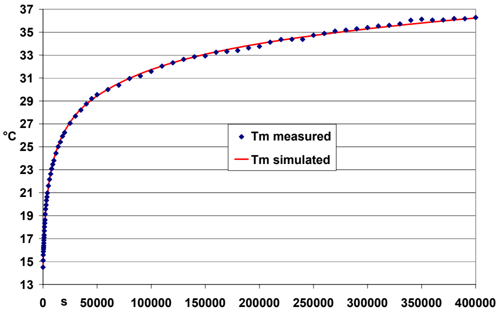

Figure 5: Simulation results for Fiesso D'Artico BHE.

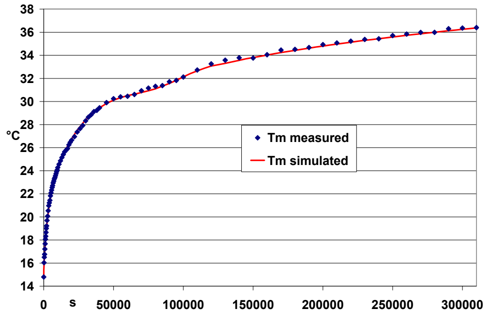

Figure 6: Simulation results for Cesena BHE.

	B1	**B2**
Grout k, W/(mK)	1.13	1.08
Grout ρc_p, MJ/(m^3K)	1.8	1.3
Soil k, W/(mK)	1.77	1.50
Soil ρc_p, MJ/(m^3K)	2.5	2.5
R_b, mK/W	0.0921	0.0950

Table 3: Simulation results; B1 = Fiesso D'Artico, B2 = Cesena

6 Conclusion

The simulation method proposed allowed us to reproduce with accuracy the time evolution of the mean temperature of the water contained in the BHEs, even during the initial part of the TRTs. The accuracy obtained allowed us to determine reliable values of the thermal properties of both ground and grout. Moreover, the method allowed us to verify and to correct the measured values of the undisturbed ground temperature.

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