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

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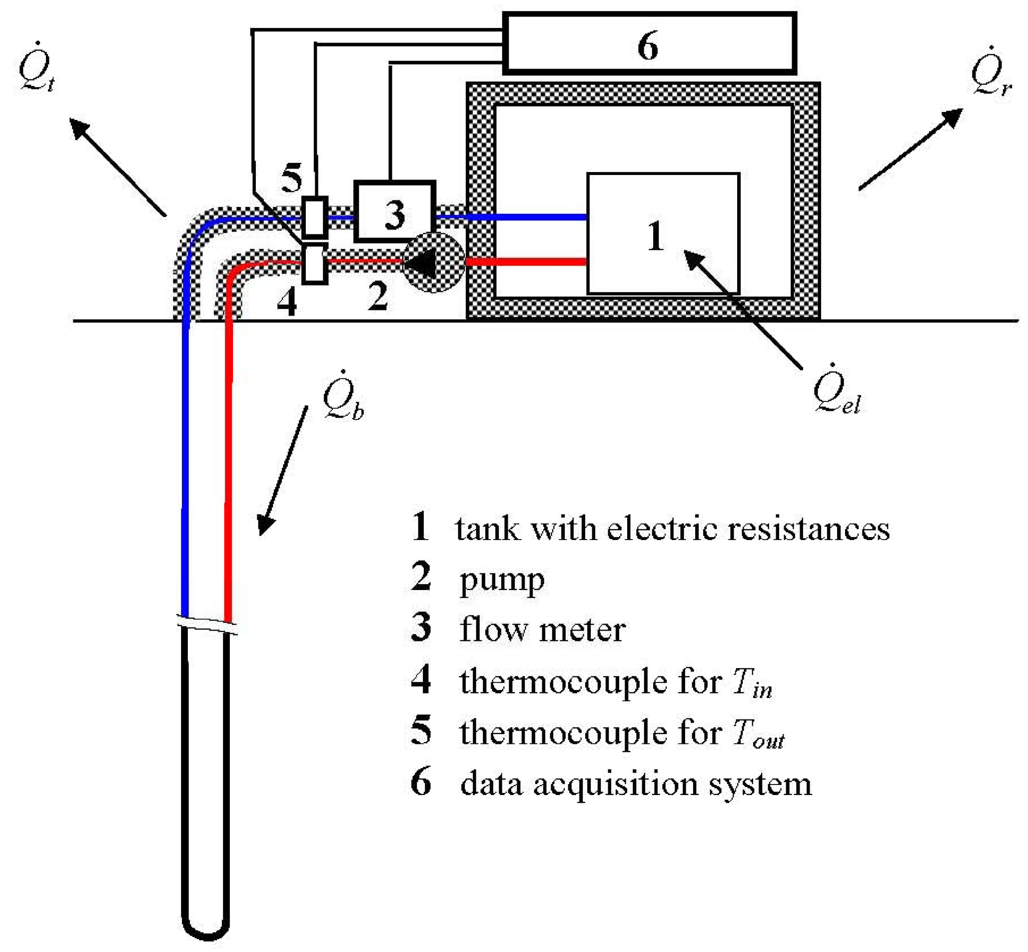
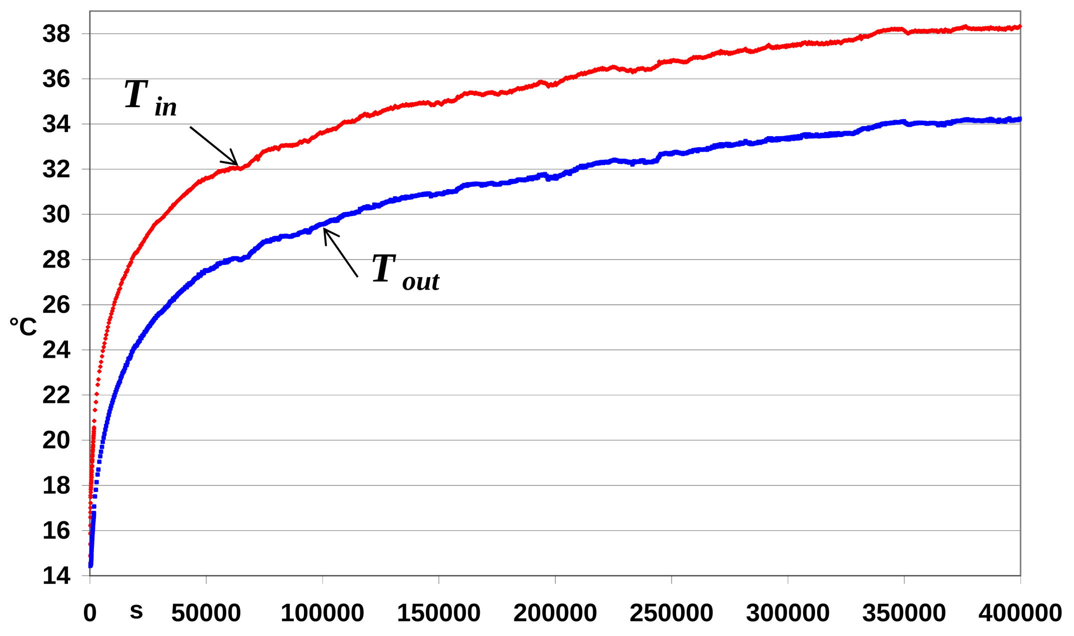
The Thermal Response Tests (TRTs) have been performed on two U-pipe Borehole Heat Exchangers (BHEs), each composed of four polyethylene pipes, having inner radius 13 mm and thickness 3 mm, grouted by a mixture of cement (80%) and bentonite (20%). The first BHE considered is located in Fiesso D'Artico (VE), the second is located in Cesena (FC), both in the Padana flat (North Italy).

Apparatus:

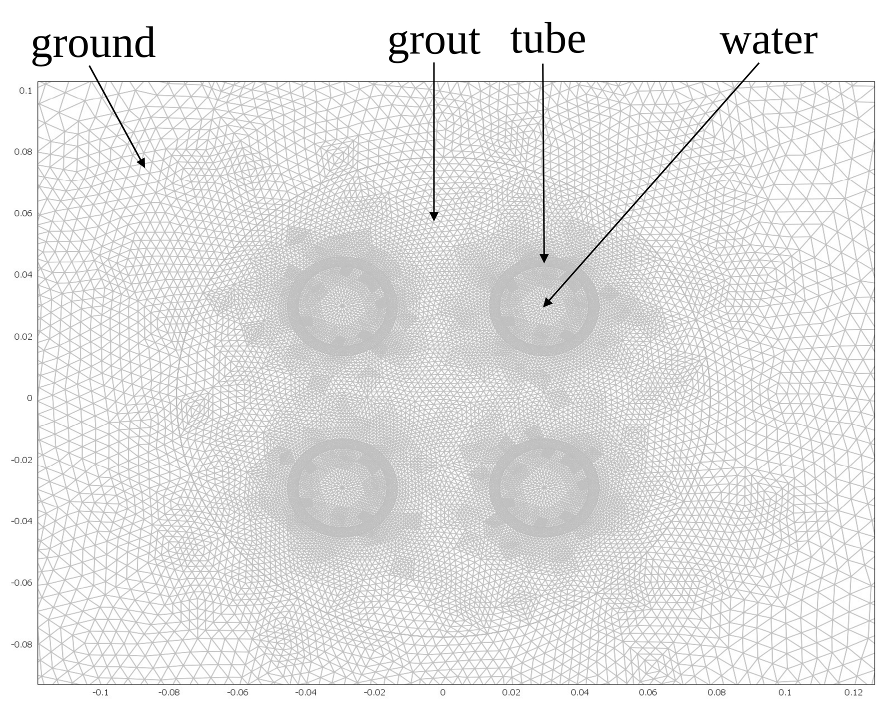
- **1 – 100 litre tank with three 2 kW electric resistances and one 1 kW electric resistance.**
- **2 – 200 ÷ 400 W centrifuge pump**
- **3 – water flow meter G.P.I., series G2A, with range 0,228 ÷ 2,280 m³/h.**
- **4 and 5 – type T thermocouples : two are positioned near the inlet (5) and the outlet (4) of the water tank; two in the air (not represented in the figure)**
- **6 – acquisition system: digital multimeter AGILENT 34970A and Fluke 1735 Power Logger**



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



Cross section of a BHE and particular of the final computational grid (central part of the domain)



Energy balance:

$$\dot{Q}_b = \dot{Q}_{el} - \dot{Q}_r - \dot{Q}_t$$

Cesena TRT: $\dot{Q}_t \approx 0$

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

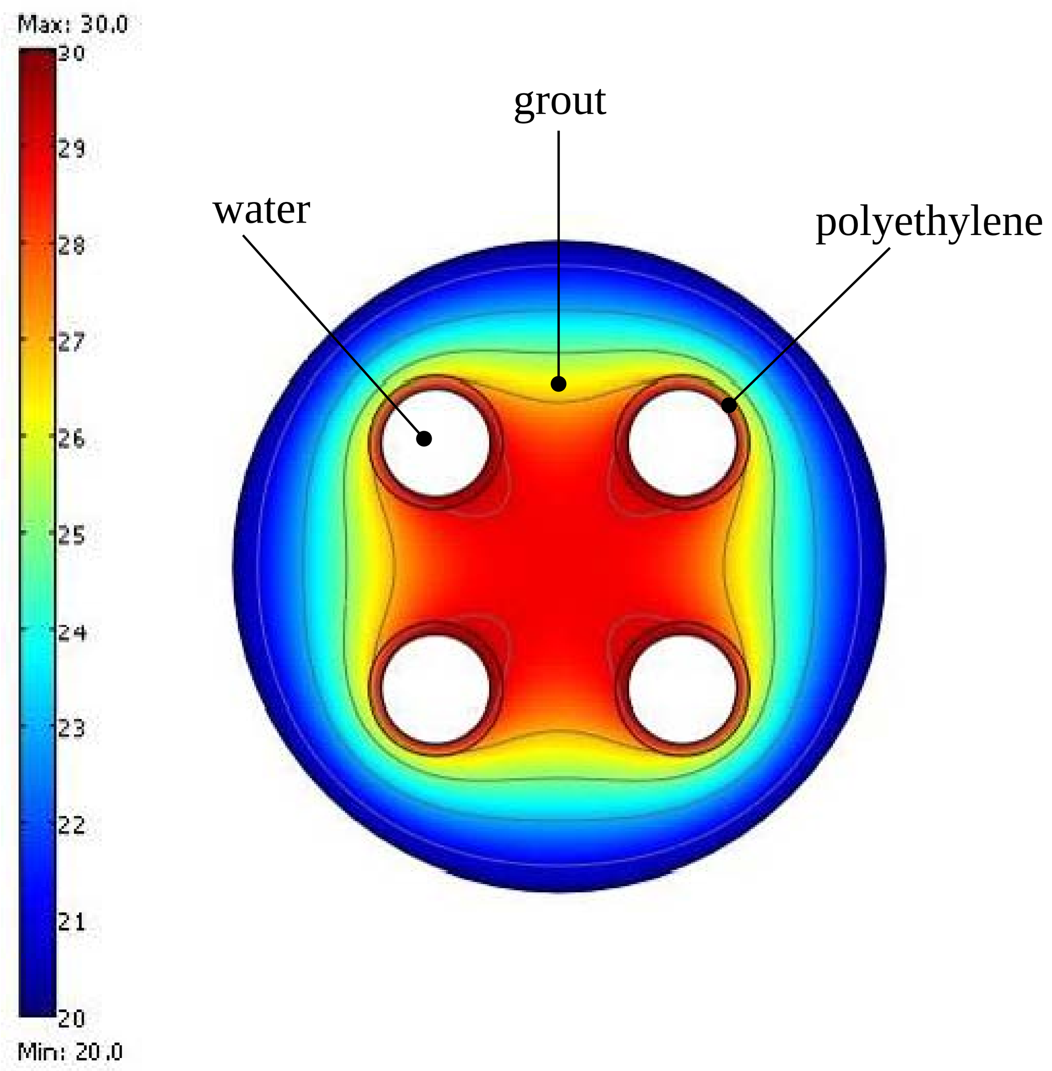
$$\dot{Q}_b = 8178 + \left\{300 \sin\left[0.000075\,(t - 12000)\right] - 163\right\} \times U\,(129500 - t)$$

Fiesso d'Artico TRT: $\dot{Q}_t = 358\,W$

$\dot{Q}_{el} = 7679\,W$ $\qquad$ $\dot{Q}_b = 7267\,W$

$\dot{Q}_b$ = power delivered to the borehole; $\dot{Q}_{el}$ = electric power
$\dot{Q}_r$ = heat loss rate from the tank
$\dot{Q}_t$ = heat loss rate from the external tubes
T_{in} = inlet water temperature
T_{out} = outlet water temperature
$T_m = (T_{in} + T_{out})\,/\,2$ = mean water temperature
T_g = undisturbed ground temperature

Cross section of the BHEs and isothermal lines for the Fiesso D'Artico BHE; inner surface at 30 °C, external surface at 20 °C.



SIMULATION METHOD

The problem as 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 a high thermal conductivity where a uniform heat generation takes place. The heat generation per unit volume has been obtained by dividing the power delivered to the borehole by the water volume within the borehole.

In order to simulate the thermal inertia of the water within the apparatus an effective water density has been considered (during the initial part of the heating test, the water volume considered was twice the tank volume; then all the water within the apparatus was taken into account).

The computational domain included the ground placed between the borehole radius and a 5 m external radius.
The values of the thermal conductivity k and of the heat capacity per unit volume $\rho\, c_p$ of both grout and ground were evaluated by attempts, by minimizing the standard deviation between measured and calculated values of $T_m = (T_{in} + T_{out})\,/\,2$.

The initial condition was determined by the simulation of the measurement of the undisturbed ground temperature.

Boundary condition: $T = T_g$ at the boundary of the computational domain.

The unsteady heat conduction problem was solved by means of the software package COMSOL Multiphysics 3.4.

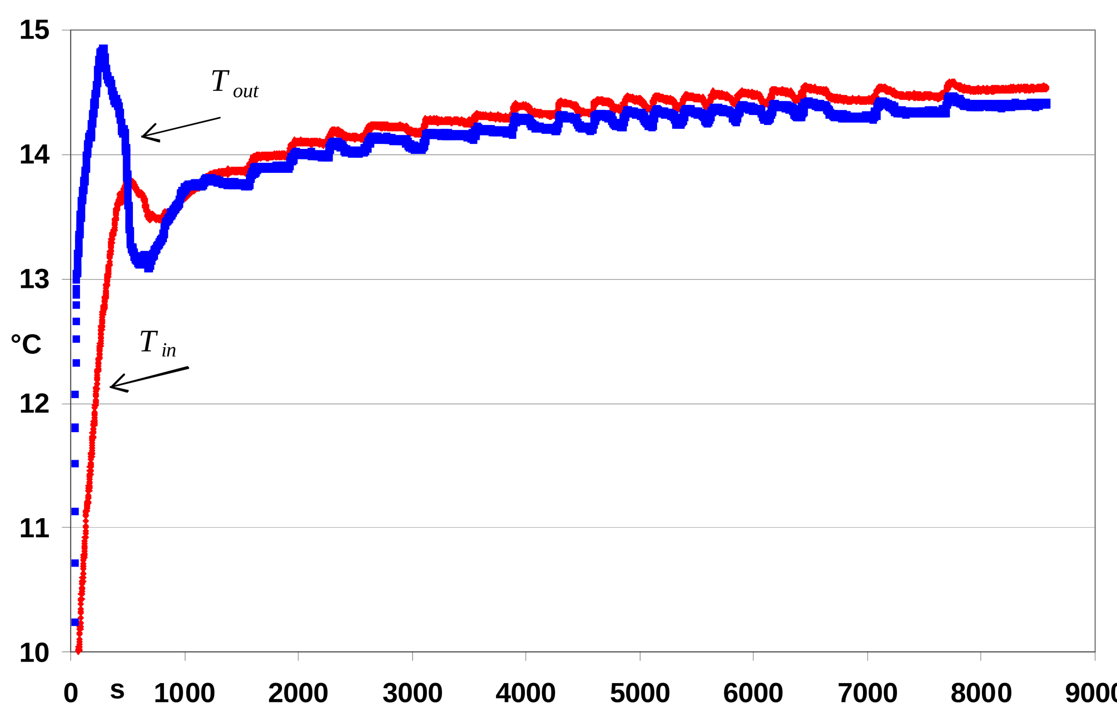
Preliminary calculations were carried out by a computational grid with 16032 triangular elements; final calculations were carried out by a computational grid with 64128 triangular elements. Results are grid independent.

The undisturbed ground temperature, T_g, has been determined by averaging T_{out} until all the fluid contained within the borehole passed through.

The experimental determination of T_g, has been matched with a numerical simulation carried out by means of COMSOL Multiphysics 3.4. This procedure has determined a +0.2 °C correction of the value obtained experimentally for the Fiesso D'Artico TRT.

Fiesso d'Artico: Tg = 14.3 °C ; Cesena: Tg = 14.6 °C

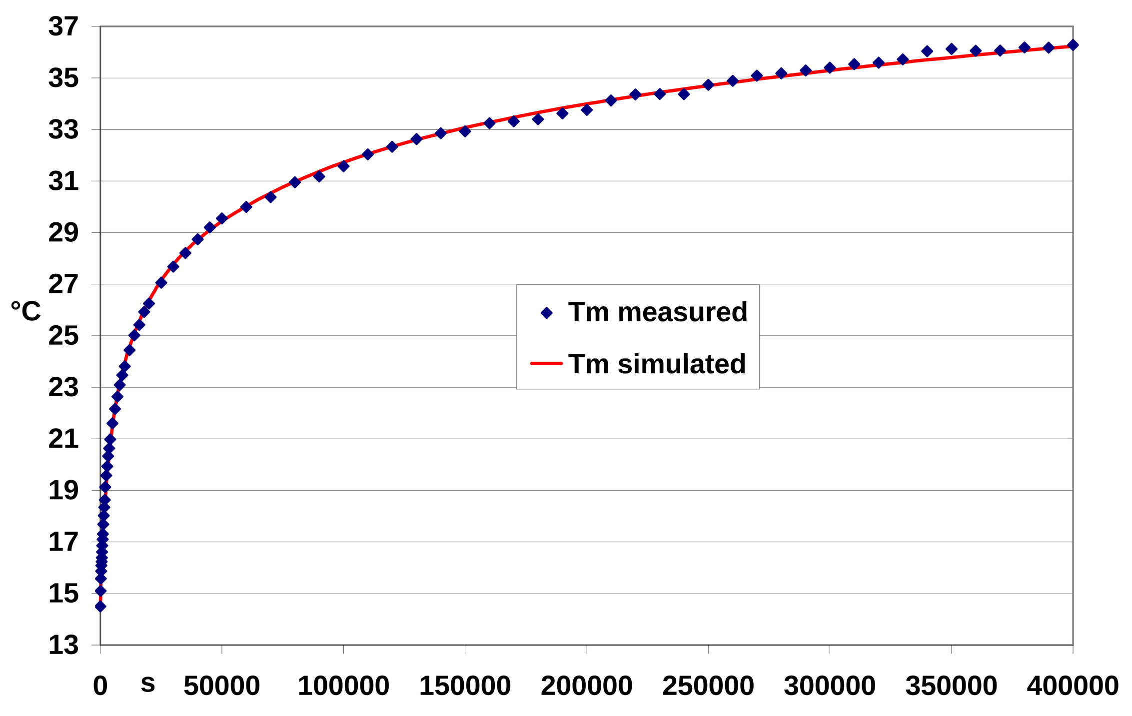
Plots of T_{in} and T_{out} versus time during the measurement of the undisturbed ground temperature, Fiesso D'Artico



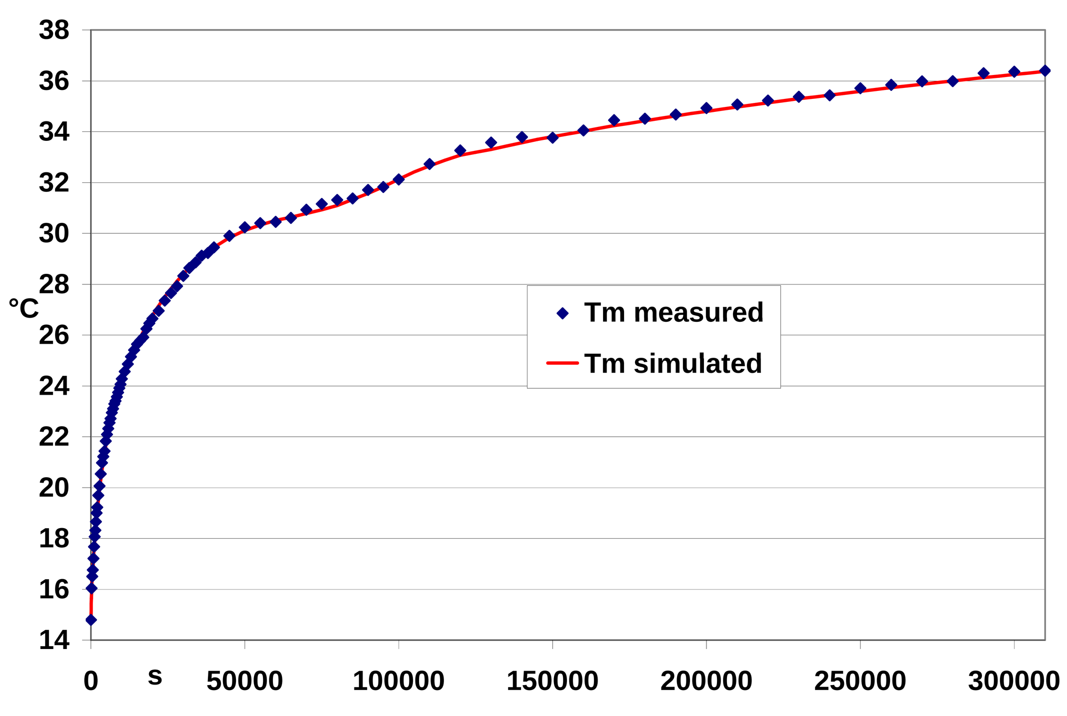
Simulation results; B1 = Fiesso D'Artico, B2 = Cesena

	B1	B2
Grout k, W/(mK)	1.13	1.08
Grout $\rho\, c_p$, J/(m³K)	1.8 x 10⁶	1.3 x 10⁶
Soil k, W/(mK)	1.77	1.50
Soil $\rho\, c_p$, J/(m³K)	2.5 x 10⁶	2.5 x 10⁶
α (= $k/\rho\, c_p$) ground, m²/s	0.708 x 10⁻⁶	0.600 x 10⁻⁶
Borehole thermal resistance, R_b, mK/W	0.0921	0.0950

Simulation results for Fiesso D'Artico BHE



Simulation results for Cesena BHE



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.