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Testing a model of flow and heat transfer for u-shaped geothermal exchangers

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ABSTRACT

Among renewable resources, geothermal energy is one of the most promising for its independence on weather conditions. However, design and installation of borehole heat exchangers on low enthalpy regions must consider numerous influencing factors. Here, we focus on the efficiency improvement in hot water production and heating and cooling of buildings of a pilot geothermal plant, which was implemented as part of a hybrid system within the frame of a research project at the University of Camerino (Italy). The aims of the geothermal plant were to study the subsoil thermal properties and monitoring the parameters of the system during operation. As an important application for the design and sizing of low enthalpy geothermal systems, we propose a mathematical model to study the heat transfer between the fluid circulating in the pipes and the underground, where the mutual influence between the soil and the exchanger is considered. We present results of these approximated solutions based on experimental measurements acquired in the actual geothermal exchangers. Laboratory and in situ tests were also carried out to investigate the underground thermal properties and thermal regime of the heterogeneous soil sedimentary succession.

1. INTRODUCTION

The European Union strongly promotes the transition to clean (low hydrocarbons) and renewable energies. Strength points for low enthalpy geothermics to provide economic and safe solutions for the future energy supply are certainly the very low or zero environmental impact, the uninterrupted production (not depending on meteorological variables), with the possibility of a summer / winter cycle for heating and cooling buildings, groups of buildings and industrial plants. The low-enthalpy geothermal solution (consisting of vertical probes of ~100 m in length coupled with a ground-source heat pump) is flexible, durable and easily combinable with other renewable or high-efficiency sources.

A geothermal heat pump takes advantage of the constant ground temperature, to obtain higher efficiencies than conventional heat pumps [1-2]. Ground is used as a sink (cooling mode) or source (heating mode) of thermal energy and is nearly unlimited [3]. Therefore, the thermal performance of ground source heat pumps (GSHPs) depends on the heat transfer between a borehole heat exchanger and its surrounding soil/rock [4]. Besides the type of thermal regime, the performance of borehole heat exchangers relies on the overall thermal resistance of the borehole, which can be strongly affected by the underground thermal conductivity (accounting for most of the heat that can be extracted). Furthermore, grouting materials ensure the stability of well walls and, at the same time, they should allow optimal heat transfer from the carrier fluid circulating in the borehole pipes to the ground and vice versa.

Since the GSHPs and their interaction with the different materials and soil are only partially modelled, an experimental plant was realized to reach a detailed knowledge of all local ground properties such as thermal conductivity, borehole thermal resistance, undisturbed ground temperature and specific heat capacity. The plant was tested and monitored as a part of a project (MATREND project, financially supported by University of Camerino), with the aim of obtaining a complete dataset to better model the implementation of the system.

The plant uses classical U-shaped pipe arrangements in vertical exchangers, for which we propose a mathematical model that describes the main thermal processes involved. In more detail, the model deals with the heat transfer occurring in the subsoil, thus it focuses on the conductive heat exchange into the soil and the convective heat transfer between the soil and the carrier fluid into the borehole pipes. Besides, the two thermal processes influence each other and such interactions are taken into account by a coupled system between soil and exchanger. Some simplifying hypotheses have to be adopted in the formulation of the model. To test the predictive capacity of this mathematical model, data collected from the monitoring of the pilot system were used. After a consistent validation, such model could give a double perspective result: firstly, it is an economic and fast way to assess the performance of a borehole exchanger; in addition, it is the starting point for the realisation of a more refined and comprehensive model that addresses the study and the operational planning of an array of geothermal exchangers.

In Section 2, the installation area of the pilot plant is described, together with relevant features of the whole experimental plant and the corresponding ground properties. In Section 3, the mathematical model for the heat transfer into the exchanger and in the surrounding soil is discussed and a brief validation of the model is presented. In Section 4, concluding remarks and further developments of this study are provided.

2. TEST AREA

The test area is located in the surroundings of Camerino, an ancient University town in Central Italy next to the Apennines mountain chain (Figure 1). This is an area of continuous marine sedimentation (from Upper Trias to Neogene), the Umbria-Marche (U-M) sedimentary succession [5].

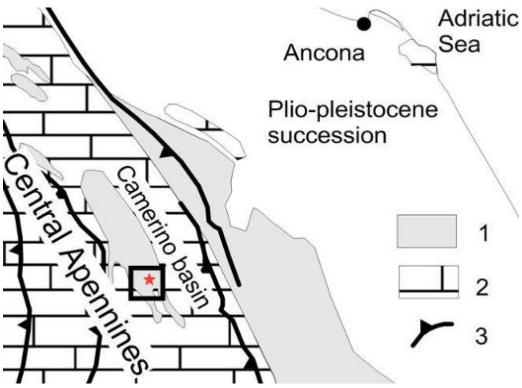

Figure 1. Geological sketch map: black square = study area, red star = Camerino town; (1) Miocene turbidites; (2) calcareous-marly sequence; (3) thrusts

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 a younger marine siliciclastic formations, unconformably deposed between Late Miocene and Lower Pleistocene [6] and recording the stages of the Apennines compression. In particular, our pilot plant is located within the Camerino Basin, an Upper Miocene intermountain syncline (Figure 1; [7]). This basin is filled by an alternation of finely layered 2 olitic to 2 olitic-arenaceous and locally arenaceous 2 olitic deposits (Camerino Formation), unconformably resting on the marly Schlier formation.

The Camerino Formation is not affected by important water flow, with the exception of the highly arenaceous top part. Eventually small increases in the groundwater flow can be determined by infiltration and circulation of meteoric water, facilitated by the presence of fracture systems.

2.1 The MATREND plant

The pilot energy system [8] includes a Solid Oxide Fuel Cell (SOFC), an electrochemical device which produces electricity and heat at the same time, a Ground Source Heat Pump (GSHP), with two single U-shaped geothermal probes, 95 m deep and 9 m apart, and an electric and thermal energy storage with tanks, lithium pile and a latent heat storage tank with phase change materials (PCM). The SOFC produces simultaneously electricity, partially used to start the GSHP, and Domestic Hot Water (DHW) using natural gas. Thus it is comparable to a condensing boiler, the current benchmark technology, but the gas consume is cut of about 50% [9]. To produce the same amount of heat, a condensing boiler consumes more gas than a SOFC and a GSHP. A SOFC is characterized by high-electrical efficiency, even greater than 50%. It means that electricity production is larger than heat output and the excess of electricity is available for domestic use.

A monitoring system was realized to record continuously the operating data of the plant every 30 seconds. Several parameters are measured such as: indoor and outdoor temperature, total energy consume, and daily energy consume for SOFC and GSHP, total and instant flow, inlet and outlet temperature, instant temperature difference, instant power for well B1, well B2, building, SOFC thermal storage, gas consumption etc.

2.2 Ground properties

Investigations of underground thermal properties and thermal characteristics of the filling grouts of the pilot geothermal plant were carried out by means of laboratory and in-situ tests. Two bentonitic commercial mixtures (G1 and G2) with different thermal, compositional and granulometric characteristics were used as grouting materials. Laboratory analyses showed a lower value of thermal conductivity and thermal diffusivity for G1 (1.65 ± 0.02 W m^{-1} K^{-1} and $(0.61 \pm 0.01) \cdot 10^{-6}$ m^2 s^{-1}, respectively) than G2 (2.13 ± 0.02 W m^{-1} K^{-1} and $(0.80 \pm 0.01) \cdot 10^{-6}$ m^2 s^{-1}) [10-11].

To evaluate the undisturbed underground temperature, the in situ experiments included borehole thermal logs and thermal response tests (TRT). The latter was performed by injecting a constant heat rate per unit length into the boreholes for a period of more than 60 hours.

The temperature log for undisturbed underground temperature was performed prior to TRTs. A precision temperature acquisition system with a 4-wire shielded cable and equipped with a Pt-resistance sensor was used. Temperatures were recorded at regular depth intervals every 5 m until 20 m depth (i.e. where the maximum depth at which the underground was expected to be influenced by seasonal variations), and then at 2.5-m-depth intervals.

The temperature-depth profiles recorded in the two boreholes B1 and B2 are presented in Figure 2. The average temperature measured is 12.57 °C for B1 and 12.56 °C for B2 [10-11].

The inferred effective (average) thermal conductivity of the subsoil is slightly different in the two boreholes (2.48 W m^{-1} K^{-1} in B1 and 2.09 W m^{-1} K^{-1} in B2) as well as thermal resistance (0.191 m K^{-1} W^{-1} in B1 and 0.187 m K^{-1} W^{-1} in B2).

Preliminary results of rock thermal properties were obtained from laboratory measurements. For the consolidated lithotype (sandstone) the transient divided bar (TDB) apparatus was used (see [12] for details on the method). To measure thermal properties of unconsolidated pelitic and pelitic-arenaceous lithotypes, a needle probe was used.

The 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 2.6 MJ m^{-3} K^{-1}). Thermal diffusivity is on average about $1.0 \cdot 10^{-6}$ m^2 s^{-1}.

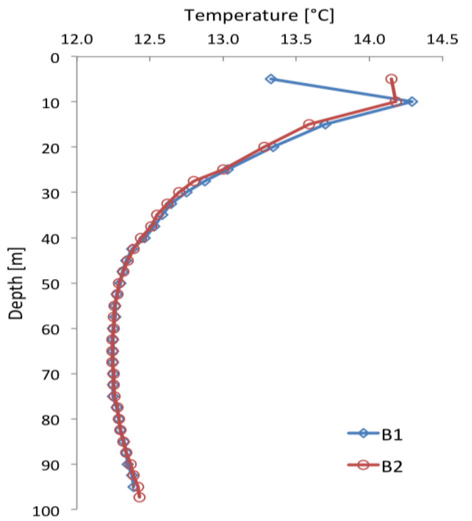

Figure 2. Undisturbed temperature profiles measured in boreholes B1 and B2

3. MODELLING OF A BOREHOLE EXCHANGER

The behavior of borehole heat exchangers, which are part of the system seen in Section 2.1, can be described by a mathematical model. In the following, we describe the model proposed for these devices and some of the results obtained in the corresponding test activity.

3.1 The mathematical model

The Fluid Dynamics problem of the fluid flow and heat transfer inside a geothermal exchanger can be formally described by well-known Navier-Stokes equations [13-14]. In this forced convection problem, when the carrier fluid is mostly water, the following assumptions hold: the fluid is incompressible and Newtonian, the thermal conductivity and the viscosity are constant, there is no internal heat generation and the viscous dissipation is negligible. The flow is also considered dynamically and thermally fully developed. Moreover, to make the model as simplest as possible, without discarding significant physical processes, the geometric description of the exchanger is simplified by supposing a pipe having irrelevant wall effect and in direct contact with the ground. So the borehole with the filling material and the pipe wall thickness are discarded. This last assumption could appear an oversimplification for a reliable model of a borehole exchanger. Actually, this is not a big issue since the heat transfer from the ground to the carrier fluid undergoes two main types of resistances, i.e. the resistance of the soil to the heat conduction and the other is the resistance from the grout material and the pipe walls, but the former is dominant over the latter that becomes negligible in first approximation [15].

In the present study, our focus is on the heat transfer rather than on the fluid flow. Usually, in a convective phenomenon, the heat transfer problem cannot be decoupled by the flow problem but, under the previous assumptions, it admits an analytical solution. In fact, a U-shaped heat exchanger mainly consists of straight pipes, except for the U-turn at the bottom of the device gathering the downward and upward pipes, but the U-turn is discarded in the quantitative analysis since its length is irrelevant with respect to the total length of the exchanger. We provide a concise description of the computation of the fluid temperature on rectilinear pipes; see [16] for a detailed description. In order to fix ideas, we consider the downward pipe; similar arguments hold for the upward one. Let L be the length of the pipe, which has circular cross section of radius r and whose symmetry axis is z-axis. We denote with T_w the temperature at the pipe wall, with T_0 the temperature of the fluid entering the pipe, with T_m the mean temperature on circular sections and with q'' the wall heat flux.

Let us consider the first principle of Thermodynamics

$$\frac{dT_m}{dz} = \frac{2}{r}\frac{q''}{\rho c_p U}, \qquad z \in (0, L), \tag{1}$$

where U is the mean velocity of the fluid flow, ρ is the fluid density, c_p is the fluid specific heat, $q'' = h(T_w - T_m)$ from the definition of the heat flux, and h is the heat transfer coefficient. Eq.(1), together with the initial condition $T_m(0) = T_0$, can be explicitly solved exploiting standard arguments of ordinary differential equations theory. Thus, we can compute the mean temperature of the fluid at the outlet face, $T_m(L)$, that is

$$T_m(L) = T_w - (T_w - T_0)\exp\left(-\frac{kNuL}{\rho c_p r^2 U}\right), \tag{2}$$

where the heat transfer coefficient h has been determined by means of the Nusselt number, i.e.

$$Nu = \frac{2hr}{k}, \tag{3}$$

with k the thermal conductivity of the fluid. In laminar state, it can be shown that $Nu = 3.66$ [16], while in turbulent state it is estimated by empirical formulas based on Reynolds and Prandtl numbers [16-17].

In Eq.(2), a key role is played by the wall temperature T_w, which corresponds to the temperature of the surrounding soil. Thus we need a model that describes how the heat conduction occurs into the soil. The temperature of the soil T_s is computed by using the heat equation on a three-dimensional slice with depth suitable for containing the exchanger. Note that this model is quite accurate when convective phenomena, such as soil moisture dynamics due to the rain infiltration and groundwater presence, can be neglected. Such diffusive problem admits a unique solution that can be written in terms of the Green's function of the heat operator. We address the reader to [17] both for the statement of the diffusive problem and the description of its analytic solution.

So, the soil and the exchanger mutually influence. In other words, fixing the winter operational mode of the device, the fluid into the pipe exchanges heat with the surrounding soil, modifying in this way the temperature of the soil that provides a slightly different effect on the fluid flowing subsequently in the pipe. To take into account such interaction between soil and exchanger, a coupled system soil-exchanger is obtained by unifying the previous two models, namely the model of heat conduction for the soil and the model of heat transfer for the exchanger. In more detail, the unknown of the first problem is the temperature of the soil T_s anywhere around the exchanger, while the last problem must be divided into two problems: one for the downward flow, where the unknown is the temperature of the fluid into the downward pipe T_d, and the other for the upward flow, where the unknown is the temperature of the fluid into the upward pipe T_u. The soil temperature T_s is coupled to those of the fluid, i.e. T_d, T_u, by the source term of the heat equation, having support in the cylinder corresponding to the borehole. On the contrary, T_d and T_u are coupled to T_s by the heat flux in Eq.(1). We omit the formal statement of the problem for the soil-exchanger system and also further details on the not trivial solution process and its approximation procedure; however, they have been described in [18]. For clarity, a step of the approximation procedure is noteworthy to make Eq.(2) and the soil temperature profile in Figure 2 consistent. We divide the depth of the exchanger into sufficiently small subintervals, such that in each of them the soil temperature T_w can be considered constant. In this way, Eq.(2) is valid in each subinterval and the soil temperature profile can vary with depth.

3.2 Brief validation of the model

The resulting material from the drilling operations has been used to obtain the average thermal diffusivity of the soil, i.e. $\alpha_s = 1.085 \cdot 10^{-6}$ m^2 s^{-1}, also the undisturbed temperature profile of the underground was taken into account. The pipe inside the borehole is a standard polyethylene pipe with external diameter of 0.032 m, that is $r = 0.016$ m. The fluid inside the device is a mixture of water (67%) and ethylene glycol (33%) and its physical properties are: density $\rho = 1.0411 \cdot 10^3$ kg m^{-3}, specific heat $c_p = 3.6915 \cdot 10^3$ J kg^{-1} K^{-1}, dynamic viscosity $\mu = 2.7334 \cdot 10^{-3}$ kg m^{-1} s^{-1}, thermal conductivity $k = 4.7930 \cdot 10^{-1}$ W m^{-1} K^{-1}, thermal diffusivity $\alpha = 1.2471 \cdot 10^{-7}$ m^2 s^{-1}. Finally, the mean velocity of the fluid is about 0.41 m s^{-1}.

To check the reliability of the proposed model, we choose two time intervals, I1, I2, with this characteristic: they must be sufficiently long intervals where the geothermal pump has operated almost continuously; in other words, they must not contain significant stop in the operating time of the pump, since otherwise a kind of thermal rebalancing could start into the soil but the mathematical model, at the moment, does not provide support for this process. I1 consists in two days in the first half of January 2018 while I2 consists in four days and a half in the second half of December 2017. We pick inlet and outlet temperatures of the exchangers every 5 hours, thus we will have 10 time points of interests into I1 and 23 time points into I2.

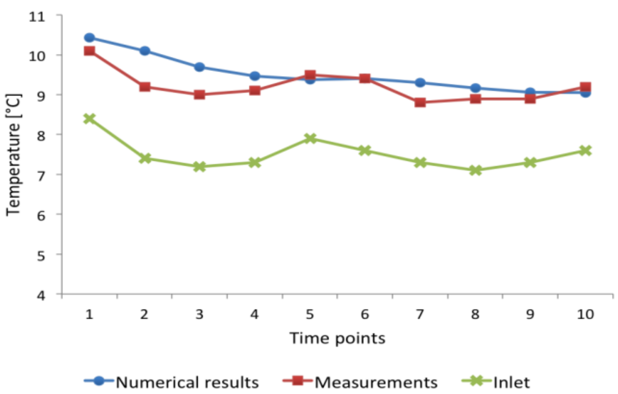

Figure 3. Comparison between numerical and real temperatures on the outlet face of exchanger B1 in the time interval I1

Numerical results and comparisons between them and experimental data are shown in Figures 3-6; in particular, Figures 3, 4 refer to the time interval I1 while Figures 5, 6 refer to I2. In Figure 3, where exchanger B1 is considered, the line with square markers gives the experimental outlet temperatures, the line with circle markers gives the numerical outlet temperatures and the line with cross markers gives the inlet temperatures, while the x-axis represents time and two successive time instants are 5 hours apart from each other, as mentioned before. The line of numerical results follows the line of experimental data, with a maximum gap occurring in the first hours and remaining lower than 1 degree.

As time goes on, the numerical outlet temperatures get nearer to the measured ones; in fact, the situation described by the model better fits the experimental setting. In more detail, I1 and I2 are time intervals of uninterrupted working of the heat pump but they have been extracted from longer sequence of measurements, thus at the initial time the soil temperature profile could be not exactly equal to the undisturbed profile, due to the existence of some previous heat exchange. On the other hand, the numerical simulation assigns to the soil at the initial time step the known undisturbed profile, since the real soil profile cannot be measured by the sensor system of the geothermal plant.

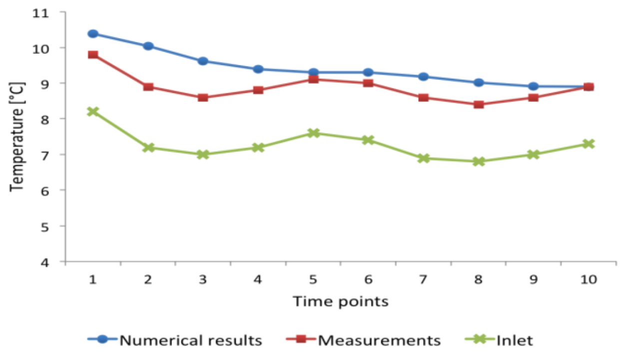

Figure 4. Comparison between numerical and real temperatures on the outlet face of exchanger B2 in the time interval I1

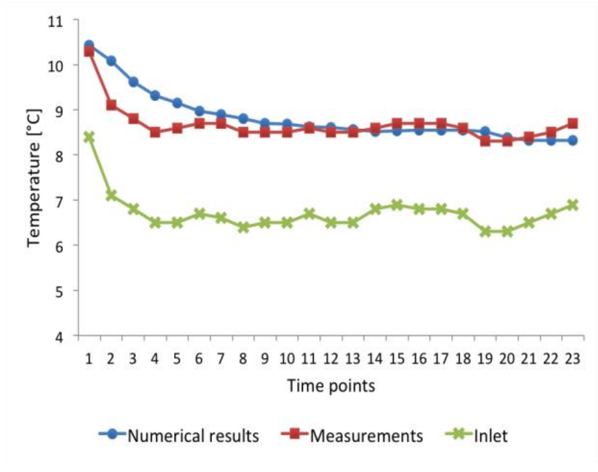

Figure 5. Comparison between numerical and real temperatures on the outlet face of exchanger B1 in the time interval I2

In Figure 4, where exchanger B2 is considered, the line markers have the same meaning of the ones in Figure 3; also in this case, the numerical results are in agreement with the experimental data, even if a slightly bigger gap between them is encountered at the beginning of I1.

Figures 5, 6 show results on the interval I2. In particular, in Figure 5 referring to exchanger B1, there is a good agreement between the numerical temperature profile and the measured temperature profile, apart from a short initial time where the same remark made above holds. Also, numerical results from exchanger B2 closely follow the measured data as shown in Figure 6.

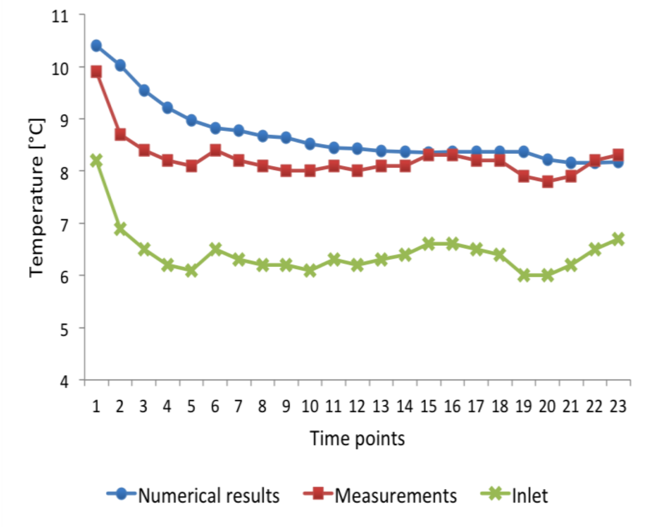

Figure 6. Comparison between numerical and real temperatures on the outlet face of exchanger B2 in the time interval I2

In first approximation, the mathematical model seems to give results quite similar to the real situation, especially in the longer time interval I2. However, to gain accuracy of the model, future measurements should be done with ad-hoc setup of the boundary conditions, such as the soil temperature at the beginning of the monitoring that must be as closely as possible to the undisturbed temperature profile; the operation time of the geothermal pump that must be rather continuous in the monitoring interval.

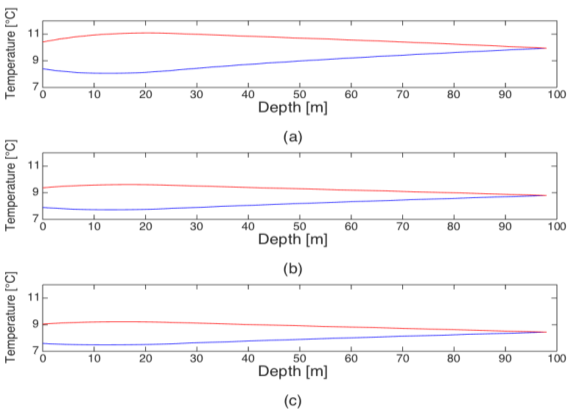

Figure 7. Temperature profiles in the downward (blue) and upward (red) pipe for exchanger B1 in I1

It may sound interesting to observe how the fluid temperature varies at increasing depth as the fluid flows into the device, even if such results are purely numerical and cannot be compared with measured profiles being them unavailable. Since so far exchanger B1 has revealed a better agreement between numerical and real data, we focus exclusively on it. Figures 7, 8 show the developing of the temperature profile of the fluid into exchanger B1 with respect to the depth for three selected time instants, namely the initial time, the middle time and the last time; blue line refers to the downward pipe while red line to the upward pipe.

In Figure 7(a), the fluid entering the pipe feels soon the presence of the cold soil and its temperature cools down, this fact occurs only in a shallow zone according to the profile of the undisturbed soil for the cold season. Then, the fluid undergoes a quite quickly warm-up, which keeps on more slowly along the upward pipe. Finally, the ascending fluid finds the cool soil influenced by the seasonal air temperature, so it quickly decreases its temperature. In Figure 7(b), it is noteworthy that the incoming fluid undergoes a smaller cooling because of the lower inlet temperature and also because in the meanwhile the soil temperature has locally increased under the influence of the warmer incoming fluid. At bigger depth, the fluid exchanges a smaller amount of heat with the soil than in Figure 7(a), in fact, its temperature reveals a slower increase; this is due to the previous heat transfer that tends to reduce the temperature gradients between soil and exchanger. In Figure 7(c), at the final time, such phenomenon is even more evident and the two profiles for the descending and ascending fluid tend to become symmetric. An analogous behavior can be detected in Figure 8, showing the temperature profiles of the downward and upward fluid into exchanger B1 at increasing time instants belonging to the interval I2.

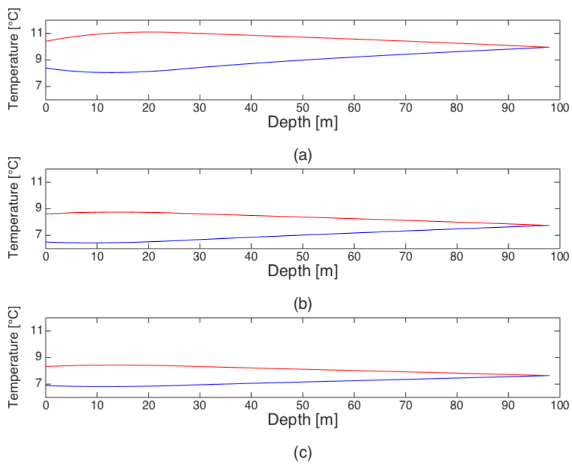

Figure 8. Temperature profiles in the downward (blue) and upward (red) pipe for exchanger B1 in I2

4. CONCLUSIONS

The experimental plant described in this paper and realized in the academic project MATREND has fulfilled its first objective: moving towards a better integration between research and industry. It exploited a multidisciplinary knowledge to realize a hybrid renewable micro-cogeneration system, combining a Ground Source Heat Pump and a Solid Oxide Fuel Cell. A variety of experiments were carried out to improve the overall performance of such hybrid plant, according to the heating and cooling requests, the hot water demand and the electricity needs of the building coupled with the system. At the same time, some weak points have been detected. For instance, crucial for a correct operation of the system is the exploitation of the produced heat, which means to provide for water tank with big enough capacity. Also, sensor system suffered from a kind of stiffness in their positioning as well as in their remote control. However, such drawbacks did not affect the exploitation of the system neither prevented to develop multidisciplinary studies and to collect a large amount of data.

The first investigations developed on the system focus on the geological setting. Sufficiently far from any perturbation of the system, the temperature profile of the undisturbed soil has been measured in the cold season. During the borehole perforations, the classification of the stratigraphic succession of layers has been derived and this allowed the study of the lithology, e.g. the estimation of the averaged soil thermal diffusivity; also a study on local thermal conductivities has been started.

Considering only a part of this hybrid system, a research item we developed is the heat transfer inside the borehole exchangers. The proposed mathematical model consists in the coupling of the conductive heat equation for the soil temperature and a simplified version of the convective heat transfer for the fluid temperature. Results obtained from numerical simulations are in good agreement with on-field measurements, especially the ones in a sufficiently long observation time. In fact, in a long period, the interactions between soil and fluid strongly influence the heat transfer and the model is able to take them into account. Although the model needs an extensive validation including also cooling operative mode of the pump, so far the assumptions fixed to achieve a formulation not too much demanding have turned out reasonable. Besides, the strength of a mathematical tool that approaches the occurring physical phenomena from a quantitative point of view is to be predictive with respect to the evolution in time of the performance of the exchangers. Thus, the model may be exploited in the sizing operations of a complex geothermal system as well as in the estimate of relevant geometric or physical parameters involved in the realization of borehole heat exchangers. However, the model can be improved in a number of ways, such as including the thermal resistance of the borehole filling material and of the pipe wall, as well as detailed thermal characteristics of the soil layers coming from lithology investigations. Finally, the proposed model is suitable for scalability, in fact, more than one exchanger could be considered for the thermal interaction of an array of geothermal exchangers.

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NOMENCLATURE

L	pipe length, m
r	pipe radius, m
U	mean fluid velocity m.s^{-1}
c_p	specific heat of the fluid, J.kg^{-1}.K^{-1}
q’’	heat flux at the pipe wall, W.m^{-2}
h	heat transfer coefficient, W.m^{-2}.K
Nu	Nusselt number
k	thermal conductivity of the fluid, W.m^{-1}.K^{-1}
T_w	pipe wall temperature
T_0	inlet fluid temperature
T_m	mean temperature on pipe cross sections
T_s	soil temperature
T_d	fluid temperature in the downward pipe
T_u	fluid temperature in the upward pipe

Greek symbols

α	thermal diffusivity of the fluid, m^2.s^{-1}
α_s	thermal diffusivity of the soil, m^2.s^{-1}
μ	dynamic viscosity of the fluid, kg.m^{-1}.s^{-1}
ρ	density of the fluid, kg.m^{-3}

Subscripts

w	pipe wall
m	mean value
s	soil
d	downward pipe of the exchanger
u	upward pipe of the exchanger