# Heat flow's propagation within a porous medium: analogical and numerical modeling

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## Abstract

Determining the thermal characteristics of geologic media has numerous applications for low enthalpy geothermal systems design and monitoring. Despite the interest in the topic, there appears to be a scarcity of experimental data in this respect, most of the thermal properties evaluations being based on numerical simulations and back analysis on few real data. Therefore analogical and numerical modeling of heat flows in an *ad hoc* designed thermal box are presented here. The designed thermal box is a low cost apparatus, easily implementable in most laboratories that conversely allow for accurate heat propagation measurements. Tests performed under different saturation degrees and under induced water fluxes were analysed to evaluate the effect of moisture content on the heat propagation and the relative amounts of conductive and convective phenomena into the medium. Cumulative multiple-impulse tests were also carried out in order to evaluate the heat storage capacity of the material. Analogical data processing confirmed that the heat induced propagates faster from dry to saturated conditions but is less dependent on intermediate water contents. A stronger increase in the heat propagation velocity was obtained introducing a water flow effect. Numerical simulations performed with OpenGeoSys code reached a good agreement with experimental data, enabling to evaluate the accuracy of the lab tests, to understand in detail the behaviour of the medium at different saturation degrees and to obtain more reliable thermal characteristics. Coupling laboratory measurements with numerical modeling seems to have good potentiality as a reliable and accurate tool for thermal property assessment.

## 1. INTRODUCTION

The distribution of thermal flows in porous media plays an important role in many geological and engineering applications, as well as closed and open loop low enthalpy geothermal systems such as borehole heat exchangers (BHE) and more complex applications of underground thermal energy storage (UTES). Therefore a reliable assessment of the shallow soil thermal properties is an essential starting point for the design, in order to reach an optimal coefficient of performance (COP) and consequently to exploit the underground heat in a sustainable way and, last, to economize the resources. However a proper soil characterization is rarely performed in most sites, the design being based only on literature data and numerical simulations of heat propagation.

The numerical simulations have become very useful in the last years in the geothermal field planning and management. Since the 80s many mathematical models were proposed to analyze data from geothermal field experience. Geothermal reservoir simulations have been applied to almost all the field cases, in order to obtain some previsions and hypothesis on reservoir depth and temperature, fracture networks, flow rates and consequently the power potential (Zyvoloski et al 1988, O'Sullivan et al 2001, Watanabe et al 2010). Mechanical, hydraulical and thermal processes occurring in enhanced geothermal systems were simulated on the base of several conceptual models which simplified the reservoir geometry in fracture network or porous media. The simulation of coupled THM processes requires complex calculation with numerical models, but it can enable one to understand the physics of the phenomenon and to obtain output parameters to compare with field observations. The degree of sophistication of the numerical models and their reliability is however strictly connected to the geologic complexity of the site.

Nevertheless, few numerical simulations have been performed before over simplified lab models.

Laboratory tests under known boundary conditions can be a strong aid in respect to a better understanding of soil properties and to a general reliability of numerical simulations. Indeed natural geological heterogeneity and the several processes involved in real geothermal systems, which are not always easy to simulate, poses some questions on the effectiveness of numerical simulations. Moreover it must be underlined that numerical simulations alone are rarely completely effective if a proper evaluation of thermal properties is not performed. according to leong et al (1998), coupling of ground data and detailed mathematical model of heat and moisture flow (i.e. numerical simulation) should be the starting point of bhe design.

Within this framework, some laboratory heat propagation tests were performed and coupled with numerical simulations. For this purpose, an *ad hoc* designed thermal box was specially built in order to evaluate, from a quali-quantitative point of view, changes in heat propagation under different moisture conditions. Analogical simulations of the distribution of the heat flow within a streaming aquifer was furthermore performed. Hence, the results of the lab tests were simulated with OpenGeoSys (OGS), an open-source initiative for the numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes (Kolditz et al 2012). This is a flexible numerical framework based on the Finite Element Method (FEM), provided to solve multifield problems in porous and fractured media for several geological and hydrological applications.

The main goal of this work was therefore to image, from analogical and numerical points of view, the heat distribution within the thermal box and to evaluate the changes in heat propagation at different saturation degrees. Another target was to understand the reliability of the lab apparatus, coupled with a numerical simulation, to determine the thermal properties of the porous medium. In the following sections, after an essential theoretical background on the thermal properties and the numerical simulation in geothermal topic, the testing procedure and apparatuses are presented. The approach applied in this work is certainly appealing for a wider application on different geologic media, e.g. as a necessary characterization tool for thermal property determination.

## 2. THEORETICAL BACKGROUND ON THERMAL PROPERTIES

Thermal properties of soils were widely studied in the past and research on this topic is still actual. The most important of these properties are thermal conductivity (λ), heat capacity (C) and thermal diffusivity (α), this last being the ratio of conductivity and capacity. These parameters are influenced by various factors, including: saturation degree (θ), density (γ), air content ($n_a$), temperature (T) and porosity (Φ) among the most important. Generally an increase of θ corresponds to an increase of λ but in a non-linear relation. In a λ-θ graph describing partially saturated sands behavior, data have been observed to be distributed on a curve characterized by two (Horton and Wierenga 1984, Hopmans and Dane 1986, Bristow 1998, Lu et al 2007, Chen 2008) or three (Smits et al 2010) distinct part with different slopes. Laboratory studies of Abu-Hamdeh and Reeder (2000) showed that λ in sandy and clay loam soils increases with an increasing bulk density at given θ and with an increasing moisture content at given bulk density. From a different point of view Ochsner et al (2001) showed that $n_a$ has a dominant influence on λ and C; notably, their measurements revealed that thermal properties of sandy and silty soils at room temperature can be described as a decreasing linear function of $n_a$. Midttømme and Roaldset (1998) showed that grain size distribution has an important role on controlling λ and its influence is more significant in fine-grained materials than in coarse-grained ones. The dependence of grain size distribution on λ may be related to the number of grain contacts per length of heat flow paths; for fine-grained materials, the high number of grain contacts offer more thermal resistance to the heat flow and consequently lower thermal conductivity (Griffiths et al 1992). Golovanov (1969), testing a coarse sand in laboratory conditions under flowing water conditions, concluded that an increase of λ due to additional heat transport by the moving water could be observed and that increase is influenced by water flow's velocity following exponential function.

Several methods have been proposed in the past years for calculating the thermal conductivity by empirical laws: reasonable predictions are those that do not deviate more than about ±25% from measured values (Farouki 1981). Few laboratory data, among those cited, studying consistently the effect of the different soil parameters mentioned on heat propagation are available.

## 3. MATERIALS AND METHODS

### 3.1 Thermal box setup

A plastic box, sized 1.0 x 0.4 x 0.4 m, was used to simulate thermal flows within the selected porous medium. Three sectors were predisposed, separated by permeable septa, in order to focus the simulation in the central section of the box and using the external sectors to control the water table conditions; two PVC pipes were placed aside, surrounded by an high porosity filling material and a small pump was posed to adjust water level in order to simulate the water flux (Fig. 1).

All of the box borders were thermally insulated by thin cork panels, only the upper surface was left in contact with the room temperature that was also continuously recorded. The central sector (about 0.6 m long and filled with a porous medium for 0.3 m of height) was equipped with a heat source, temperature and moisture sensors.

The heat source, after several tests done in order to achieve the most satisfactory device for experimental purposes, was an electrical resistance; the source was continuously controlled by a thermometer and a rheostat to assure the desired constant temperature and to perform more reliable tests.

Along the major axis of the box, 4 thermo-resistances Pt100 were placed, located at definite distances from the source, in different positions depending on the test. In dry conditions the T-sensors were located at 5 cm away from the source and they are spaced by 5 cm among each other; in wet conditions the source is 10 cm away from the first T-sensor and the others are also spaced by 10 cm. In addition, 4 Watermark soil moisture sensors, previously properly calibrated, were placed at 20 and 40 cm from the source, two on one side and two on the other side of the box.

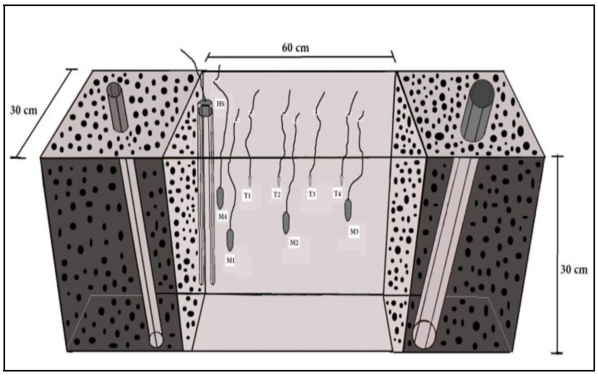


**Figure 1: Simplified scheme of the thermal box. With "T" and "M" are respectively indicated the temperature and moisture sensors, "HS" is the heat source.**

Tests were performed with increasing values of water content by increasing steps of 25%, from θ = 0% to complete saturation and water flux induced. A data-logger and an appropriate software were used for data acquisition, enabling to register, in continuous mode, all the controlling parameters (with a sampling interval of 1 minute or 5 minutes depending on the duration of the tests). The examined porous medium was a silty sand with a porosity value of 0.46 (Fig. 2).

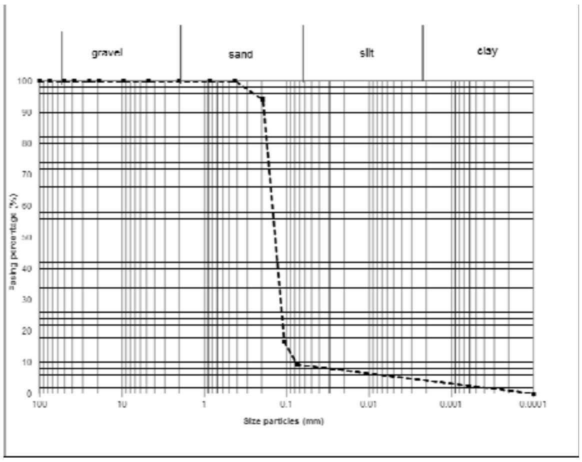


**Figure 2: Grain size distribution of the silty sand.**

A total of more than 30 experiments in different soil moisture conditions were carried out and both single-impulse and cumulative multiple-impulse tests were performed on it.

In single-impulse tests the heat source was switched on and stabilized at a constant temperature (60 °C during daytime) and it was turned off after the reaching of an equilibrium temperature by at least the sensor closer to the source. In the multiple-impulse tests the source was turned off after 10 hours, keeping the medium resting during the nighttime, and then turned on again the day after and reported to the same temperature; this was repeated for several days, at least 3 days. Both times, heating up and cooling down temperature curves were registered. The latter tests were carried out in order to understand and evaluate the heat storage capacity of the medium. Several tests were therefore conducted in three consecutive days heating up the medium for 10 hours per day and keep it resting and cooling off for the remaining part of the day, simulating common housing necessity in northern Italy.

### 3.2 Numerical model setup

The simulations were performed using the *heat_transport* process for the static tests and the coupled *heat_transport* and *liquid_flow* processes for the test with the water flux induced. Preliminary evaluations were performed by comparing ad hoc simulations with available analytical solutions. Then geometric elements (Fig. 3), discretization mesh, Dirichlet and Neumann boundary conditions, time steps definition, medium, material and fluid properties were set to launch the simulation in OGS.

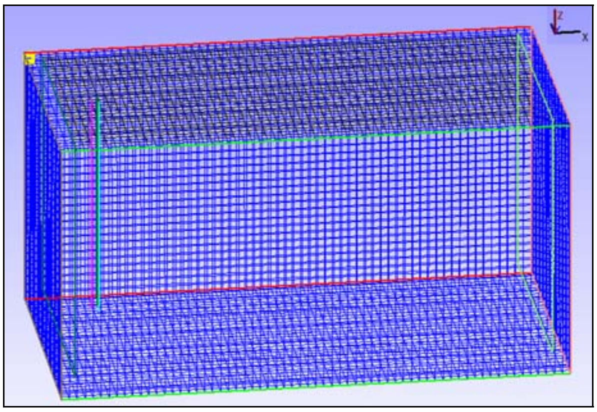

**Figure 3: Geometric elements and mesh of the thermal box reproduced in OGS environment.**

The simulations were performed setting up the same characteristics of each experimental test carried out on the thermal box. The borders were simulated as impermeable boundaries not allowing for heat flow from the sides of the box and only the upper boundary was a diffusing one. Boundary conditions in respect to the turning on and turning off times of the source and source temperature, room temperature and initial temperature in the medium were selected on the bases of each simulated experiment. In order to verify the accuracy of the numerical solution and the adherence with analogic data, several simulations were performed by changing thermal properties of the medium, looking for the best fit with the experimental data.

## 4. ANALOGICAL RESULTS

From a qualitative point of view, the shape of the time-temperature curves is roughly similar in all testing conditions, showing an increasing slope (whose curvature is dependent on sensors location), a regime of equilibrium (when reached by the heating conditions) and a quick drop after switching the heat source off. Example results for θ = 0, 50 and 100% with water flux are reported in Fig. 4.

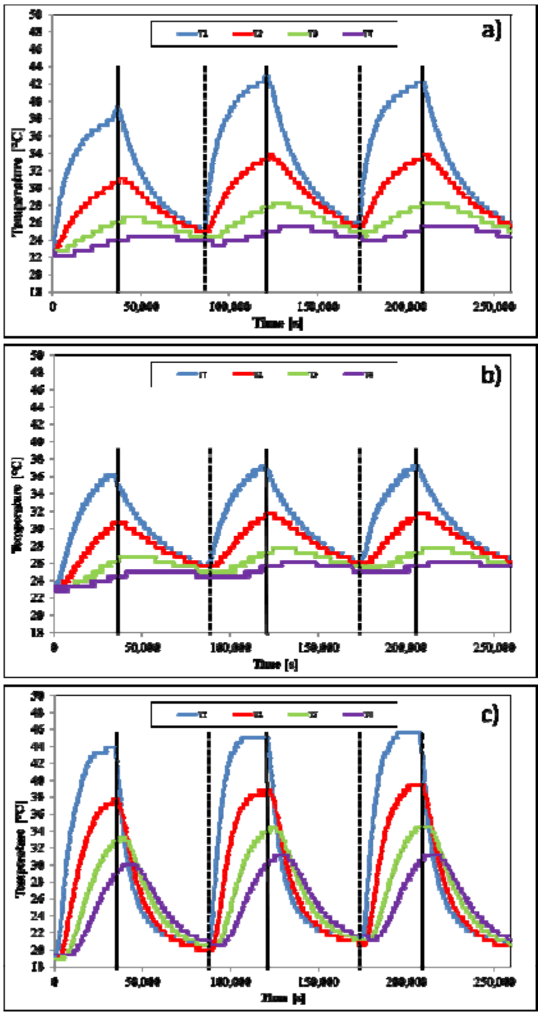


**Figure 4: Temperature vs. time graphs with θ = 0, 50 and 100% with water flux induced respectively from a to c (heat source temperature 55 °C). T1, T2, T3 and T4 are the results of each temperature sensor, the black continuous line show when the heat source was switched off, the dashed lines when it was re-switched on. In a) T-sensors are spaced by 5 cm, in b) and c) by 10 cm from the source and among each other.**

Nevertheless, different behaviours can be observed due to soil's moisture conditions, particularly in temperature peaks reached in each test and in the time necessary to reach these peaks. In order to compare the data from different saturation conditions, given that the medium initial temperature was not always the same owing to room conditions (few cent degrees changes among the tests), all the data have been first normalized to a previously stated reference temperature. Bearing in mind that in dry conditions the T-sensors were located at 5 cm away from the source, the comparison was performed between T2 in dry conditions and T1 in wet conditions, and T4 and T2 respectively.

The cumulative effect is not significant as it would be fair to expect, showing a 2.5 – 3.0 °C increase in starting temperature between the first and the second day only. The same considerations are true for the peaks of temperature, in which a remarkable increment, even if little (1.0 – 1.5 °C), can be observed between the first two testing days only (Fig. 4a). In the flux conditions the cooling down of the first and the second T-sensors took place more rapidly with respect to the others, highlighting a smaller cumulative effect at the beginning of the second testing day.

In each simulation, from the second day the temperature values registered by each T-sensor are roughly constant, even by monitoring five consecutive days. This observed situation is probably related to the finite dimensions of the box, which do not permit the examined medium to warm up in a considerable way. Namely, after the second testing day the energy input (heat flux injected) reaches an equilibrium state with the energy loss amount.

In Fig. 5 the processed results of the cumulative multiple-impulse tests are shown. From the peak temperature histograms the most noticeable situation is the difference between dry and wet conditions even with moderate water contents, and the little decrease from θ = 25% until θ = 100% (Fig. 5a).

The time of peak is roughly similar in the wet conditions and pretty constant along the direction of heat propagation; in the dry medium this parameter is 2-3 hours longer than in partially saturated and fully saturated conditions (Fig. 5b).

The mean gradients (Fig. 5c), as it would be correct to expect, mirror the results of the previous histograms, showing reduced values in dry condition and higher values roughly constant in wet conditions. These considerations are coherent with literature data (Abu-Hamdeh and Reeder 2000, Tarnawski and Leong 2000, Ochsner et al 2001). The mean gradient is a parameter which shows and summarizes in a good way how the heat propagation occurs and fits around the diffusivity value; namely, the bigger the mean gradient is, the best heat propagation is performed.

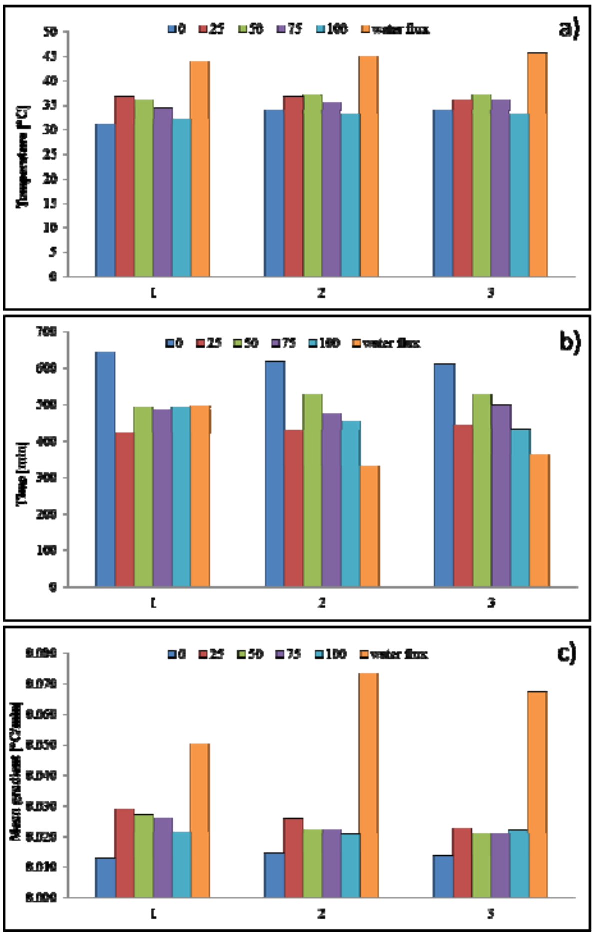


**Figure 5: Histograms showing temperature peaks (a) normalized to a reference initial temperature (18.9 °C), time of peak (b) and mean gradients (c) recorded at 10 cm from the source, in the first three days of test.**

### 4.1 Thermal properties assessment

The methodology used for a roughly estimation of thermal properties from experimental data is based on heat conduction from a linear heat source in a homogeneous and isotropic porous medium at uniform initial temperature. According to the theoretical solution for a linear heat source (De Vries and Peck 1958, Campbell et al 1991) and similar quantitative evaluations done (Abu-Hamdeh and Reeder 2000), Eq. [1] was used:

$$T-T(t_0) = (q'/4\pi\lambda)\ \ln(t-t_0) + d \qquad [1]$$

Where $T(t_0)$ is the initial temperature, q' is the energy input from the linear heat source, λ is the thermal conductivity, $t_0$ is a time correction to account for finite dimensions and contact resistance of the heat source and d is a constant. Assuming $t_0 \ll t$ so that $\ln(t-t_0) \approx \ln(t)$ and if the relation between T and ln(t) is linear, then λ can be estimated from the change in temperature T between two times, $t_1$ and $t_2$, by Eq. [2]:

$$\lambda = (q'/4\pi)\ [\ln(t_2)-\ln(t_1)]/[T(t_2)- T(t_1)] \qquad [2]$$

Substituting $q'=I^2R_S$ in Eq. [2], thermal conductivity can be calculated as follows:

$$\lambda=(I^2R_S)/4\pi S \qquad [3]$$

where I is the applied current (5.2 A in this study), $R_S$ is the specific resistance of the source (0.71 $\Omega\ m^{-1}$ in this study) and S is the slope of the straight-line portion of the T vs. ln(t) curve with $t \gg t_0$. In Table 1, S values and corresponding thermal conductivity values calculated for each moisture condition examined are shown.

**Table 1: Thermal conductivity values from dry to saturated conditions calculated with Eq. [3], S values determined from experimental data and the fitting coefficient $R^2$.**

| θ [% vol.] | S [°C] | $R^2$ | λ [W $m^{-1}$ $K^{-1}$] Eq. [3] |
|---|---|---|---|
| 0 | 1.862 | 0.937 | **0.828** |
| 25 | 1.122 | 0.917 | **1.372** |
| 50 | 1.087 | 0.944 | **1.416** |
| 75 | 0.997 | 0.937 | **1.544** |
| 100 | 0.944 | 0.938 | **1.631** |
| 100 + flux | 0.457 | 0.861 | **3.368** |

Actually, the experimental setup of the thermal box is not perfectly adherent to the linear heat source method. Some heat reach the top and the probe of the soil box before the end of the quite large heating time. This partially violates the assumption of infinite soil surrounding the heater. However the procedure was adopted for a first order thermal property estimation and in a second time it was compared to numerical simulations' results with more rigorous boundary conditions. Table 1 shows the λ value under flux conditions for stressing the big slope difference from static to dynamic conditions, which demonstrates the great contribution in heat propagation by convective phenomenon.

Thermal conductivity values obtained with Eq. [3] are comparable with literature data (Abu-Hamdeh and Reeder 2000, Tarnawski and Leong 2000, Ochsner et al 2001, Chen 2008). As an average, the results show the lower value of conductivity in dry conditions (λ = 0.8 W m-1 K-1) and a range 1.4 ÷ 1.6 W m-1 K-1 from 25% moisture content to completely saturated conditions.

As far as the tests performed with the water flux are concerned, it can be said that the convective phenomenon contributes to the propagation for about the 50%, roughly doubling the thermal conductivity to 3.4 W $m^{-1}$ $K^{-1}$, even if it must be reminded that Eq. [3] works only for conductive phenomenon (Abu-Hamdeh and Reeder 2000).

## 5. NUMERICAL RESULTS

Bearing in mind the results from experimental tests and the thermal conductivity assessment carried out with Eq. [3], we performed several simulations from dry to saturated conditions and with an induced water flux. All of the numerical simulations are intended to reproduce the same analogical testing configurations The overall thermal conductivity can be obtained with the geometric mean method (Farouki 1981) expressed below in Eq. [4]:

$$\lambda_b = \lambda_f^{\Phi} \lambda_s^{(1-\Phi)} \quad [4]$$

where $\lambda_b$, $\lambda_f$ and $\lambda_s$ are the thermal conductivity of the medium, of the fluid phase and of the solid phase respectively and $\Phi$ is the porosity. Another method often employed for calculating the bulk conductivity is the parallel flow method, expressed by Eq. [5]:

$$\lambda_b = \lambda_f \Phi + \lambda_s (1-\Phi) \quad [5]$$

The fluid and solid thermal conductivities were kept constant during the simulations, being the temperature range in which the tests took place variable from about 20 to 60 °C. The soil grain thermal conductivity is 2.2 W $m^{-1}$ $K^{-1}$ and for water and air 0.58 and 0.024 W $m^{-1}$ $K^{-1}$ were respectively chosen.

The specific heat capacity is 800 J $kg^{-1}$ $K^{-1}$ for solid grains, 4,200 and 1,000 J $kg^{-1}$ $K^{-1}$ for water and air. For the solid grain density 2,730 kg $m^{-3}$ was chosen, the water and air density are 1,000 and 1.18 kg $m^{-3}$ respectively. OpenGeoSys enables one to choose which method to apply and the model which more fits the experimental results is the parallel flow, as Fig. 6 shows.

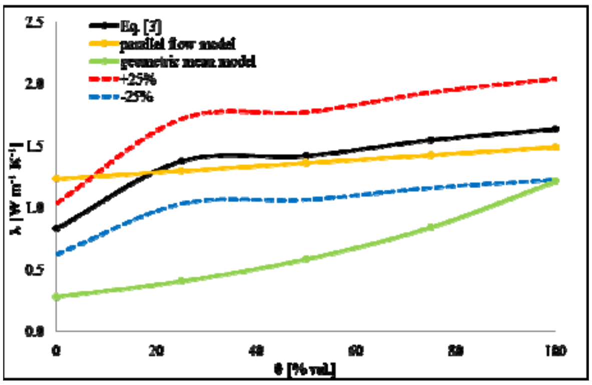


**Figure 6: Comparison between thermal conductivities obtained from Eq. [3] and calculated by parallel flow and geometric mean models.**

Figure 7 reports some results of the numerical simulations for θ = 0, 50 and 100% with water flux induced and it can be immediately noted that the curves are totally similar to those from the experimental tests (see Fig. 4).

Generally, the numerical code simulated in appreciable way the heat propagation within the thermal box, describing effectively both the heating up and the cooling down during the two days of the test. The little cumulative effect highlighted in the lab tests is satisfactorily reproduced by the numerical simulation, showing the biggest values in the dry conditions where T2 reached 26 °C at the end of the first testing day (from a 24 °C initial temperature). In partially saturated conditions (fig. 7c) T1 raised his temperature of 2 °C only, while in dynamic state 1°C of increase was registered. In addition, the more rapid cooling down registered by the first T-sensor in the flux conditions is also well represented matching the experimental data.

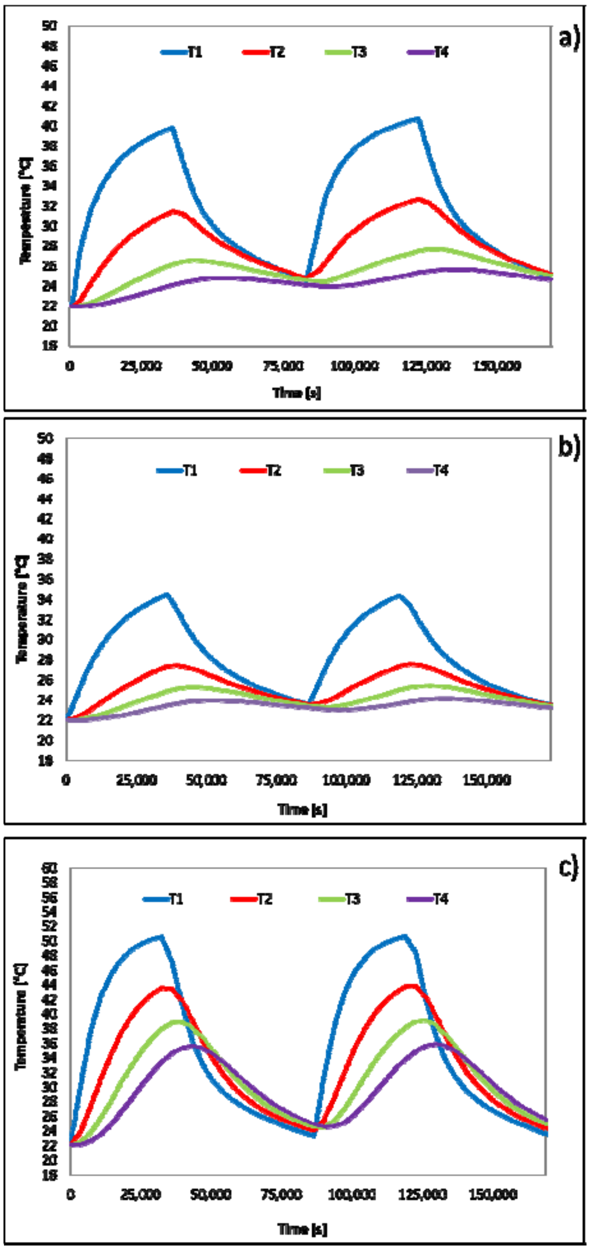


**Figure 7: Temperature vs. time graphs from numerical simulation results. a) θ = 0%, b) θ = 50% and c) θ = 100% with water flux induced (heat source temperature 55 °C). In a) T-sensors are spaced by 5 cm, in b) and c) by 10 cm from the source and among each other.**

## 6. DISCUSSIONS AND CONCLUSIONS

After an essential theoretical background on the thermal properties and the parameters influencing them, a description of the tests performed and the results of temperature monitoring within the thermal box have been shown, presenting the outcomes of both analogical and numerical modeling. Many heat flow simulations on the silty-sandy porous medium were carried out under different moisture conditions and water flow; a simultaneous numerical modeling was performed in order to evaluate the accuracy of the lab tests and to understand in detail the differences in heat propagation

The performed lab tests showed appreciable results in a quali-quantitative point of view. From dry to saturated conditions heat propagates more rapidly, exploiting the higher thermal diffusivity of water with respect to the air. These outcomes confirm the state of art of the heat propagation within a porous medium, underlining that a storage capacity could be exploited in appreciable way by UTES systems. This is confirmed with more precise results by the numerical simulation, which showed that the cumulative effect reached between the first and the second day increases, although by little amount, from dry to saturated conditions.

Figure 8 shows the appreciable agreement reached between experimental and numerical data. The dry conditions are in effective match, the wet conditions are a bit underestimated and the dynamic state shows a little overestimation. Nevertheless, the simulation can be considered a useful tool for the purposes of this study, describing in detail the behavior of the tested porous medium for understanding its capability in store the heat and which condition of saturation could be mainly exploited for the heat storage.

Future research will forecast more experiments with different materials, positions of T sensors (both in horizontal and in vertical) and directions of water flux induced, and the tests will be focused on the influence of heat exchangers geometry with respect to water flux directions. Furthermore, thermal property laboratory measurements are in progress in order to compare it with semi-empirical evaluations here presented.

This study demonstrated how coupling lab measurements with numerical simulation could be a useful tool to evaluate the thermal properties. The numerical simulation alone is not able to determine these key factors, but coupling it with lab measurements on the *in situ* soil could lead to a reliable property assessment. Thus a more accurate understanding of the behavior of the geologic media would be certainly appealing for designing of the shallow geothermal systems.

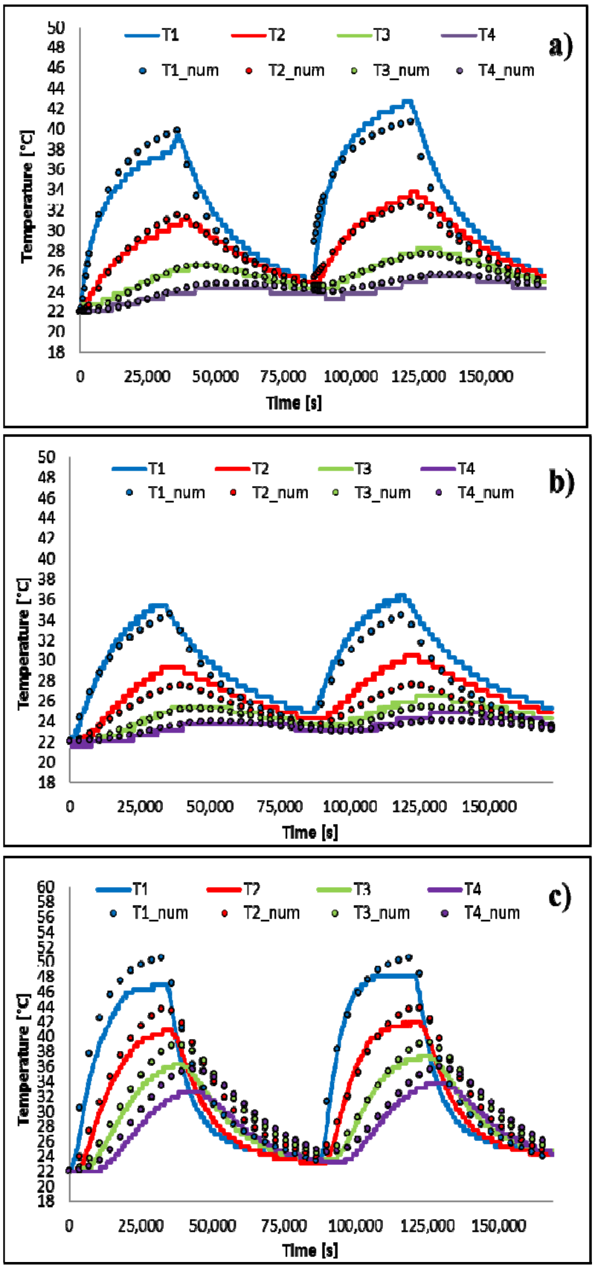


**Figure 8: Temperature vs. time graphs comparison between experimental and numerical results. a) θ = 0%, b) θ = 50% and c) θ = 100% with water flux induced (heat source temperature 55 °C). Continuous lines are the experimental data, dotted lines are the numerical data.**

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