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Effects of temperature, test duration and heat flux in thermal conductivity measurements under transient conditions in dry and fully saturated states

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Abstract. In shallow geothermal energy systems (SGES) thermal conduction can be considered the dominant process in the heat transfer between the primary circuit (borehole heat exchanger or thermoactive geostructure) and the surrounding ground. Thus, a proper characterization of soil thermal properties, namely of its thermal conductivity, is mandatory for evaluating this energy exchange. There are difficulties associated to the assessment of soil thermal conductivity by laboratory methods related, among other factors, to the samples' quality and to the measuring method itself. The purpose of this work is to analyse the effect of changing test control parameters in thermal conductivity measurements in transient conditions by means of a high accuracy thermal probe in both dry and fully saturated states. In order to eliminate potential measurements' deviations and errors due to sample variability the same reconstituted samples were used several times. In each condition the sand samples were systematically tested under different ambient temperatures (10ºC, 20ºC, and 40ºC) controlled by means of a climatic chamber. The effects of changing the tests heating time and imposed thermal fluxes were also analysed.

1 Introduction

With the inflation of global population and consequently the increase in energy demand, local low-enthalpy geothermal energy sources are becoming a crucial matter of interest [1] for building acclimatization. Shallow geothermal energy systems (SGES), which are commonly known as Ground Source Heat Pump systems (GSHP), use the nearly steady temperature of the ground surface layers as an energy source and/or an energy sink in both heating and cooling modes [2]. Such systems have shown to be sustainable alternatives for buildings acclimatization when compared with conventional air-conditioning systems [3].

SGES energy efficiency is highly dependent on the thermal energy transfer between the surface soil layers and the energy geostructure embedded within it. This heat transfer process is led by conduction due to an imposed temperature gradient occurring between soil and the geostructure (primary circuit of the GSHP) [4]. Hence, the evaluation of soil thermal properties, namely its thermal conductivity, is of major importance in analysing the heat transfer process [5].

Thermal conductivity, λ (W/(m.K)), is a physical property that measures the material capability to conduct heat [6]. According to Fourier´s law of heat conduction (Eq. 1), the heat flow rate vector $\boldsymbol{q}$ (W/m^2) for a given temperature gradient ∇T in (ºC/m) is directly proportional to λ [7]:

$$\boldsymbol{q} = -\lambda \, \nabla \, T \qquad (1)$$

Soil is a three-phase system consisting of solid particles and voids containing water and/or air. Its global thermal conductivity depends on thermal conductivity of each phase (solid, liquid and gas), as well as on its corresponding volumetric fraction and spatial arrangement [8].

Grain size distribution, mineralogy, relative density and moisture content, among others, are important factors affecting the thermal conductivity [9]. Several studies [*e.g.* 10 - 12] have shown the major influence of soil water content on thermal conductivity, and consequently on the heat transfer on the primary circuit.

Thermal conductivity λ can be measured in the laboratory by means of several techniques, which can be divided into two large groups; (i) steady-state methods and (ii) transient methods [6]. In steady-state methods thermal properties are measured by establishing a temperature gradient across the sample that does not change over time, while in transient methods the time-dependent heat dissipation is monitored. Steady-state

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methods tend to be more accurate, however, as regards soils, there is a relatively little evidence of this assumption. Transient methods tend to be more simple and rapid when compared with steady-state methods avoiding water migration in the sample which affects λ measured value. Whereas, steady-state methods with longer measurement durations allow achieving a stable temperature gradient in the soil sample and obtaining repeatable values [13]. Nevertheless, direct comparison between different methods requires evaluating and analysing undisturbed soil samples collected from the same place under the same conditions (moisture content, density, soil composition, soil structure, among others). All these factors make thermal conductivity measurement and comparison by using different techniques in a challenging process.

This paper presents part of a preliminary research on the study of the factors affecting λ measurements under transient conditions. For this purpose, systematic determinations of thermal conductivity on two sand samples were carried out in both dry and fully saturated situations and under different temperature boundary conditions, ranging between 10ºC and 40ºC. These values were considered the threshold values acting on the primary circuit of a SGES located in the city of Aveiro, Portugal. The impact of the applied heat flux was also tested, as well as the effect of the duration of the test heating time, which has varied between 100s and 1000s.

The hot line source transient method was used for the experiments. With this method a thermal needle probe is inserted in the soil sample.

2 Experimental study description

2.1 Transient test method

The needle probe method is based on the general assumption of a radial heat flow of a linear heat source of infinite length and infinitesimal diameter, in an isotropic and homogeneous medium. When an electric current of constant intensity passes through the needle probe (heat source or hot wire), the thermal conductivity of the sample can be derived from the resulting temperature change at a certain distance from the hot wire over a specific time interval.

Hence, the analytical solution (line source solution) of soil thermal conductivity obtained by applying a heat flux Q (W/m) during a heating time t (s) in a soil sample with radius r (m) can be expressed in relation to the temperature gradient ΔT (ºC/m) occurred in the soil sample as follows [14]:

$$\lambda = -\frac{Q}{4\pi\Delta T} Ei\left(\frac{r^2}{4Dt}\right) \quad 0 \leq t \leq t_1 \tag{2}$$

For sufficiently large values of elapsed time, Eq. 2 can be simplified to:

$$\lambda = \frac{Q}{4\pi(T_2 - T_1)} ln(t_2 - t_1) \tag{3}$$

which enables the evaluation of λ when temperature rises from T_1 to T_2, between instants t_1 and t_2, respectively.

2.2 Testing device

The equipment used in this study to measure λ is TPSYS02 system supplied by Hukseflux [15]. This equipment can measure thermal conductivity by means of a thermal probe. TP02 thermal probe, is 150mm length and 1.5mm diameter. It enables the measurement of λ within the range of 0.1-6 W/(m.K)] with high accuracy (±0.02 W/mK).

A scheme of the thermal probe is shown in Figure 1, where: (1) reference temperature sensor, (2) heating wire; (3) hot joint where T_hot is measured; (4) cold joint measuring T_cold; (5) plastic wire connecting the needle with the MCU; (6) 10mm base diameter, where the sensor is located.

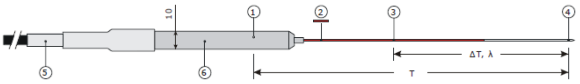

Fig. 1. TP02 design and components [15]

2.3 Tested samples (dry and fully saturated)

Fontainebleau sand was selected to perform systematic thermal conductivity measurements. This reference soil is a poorly graded sand, which grain-size distribution is presented in Figure 2. Maximum (17.20 kN/m^3) and minimum (14.11 kN/m^3) dry volumetric weights were determined following ASTM D 4253-00 standard [16]. The solid particles volumetric weight is 26.18 kN/m^3.

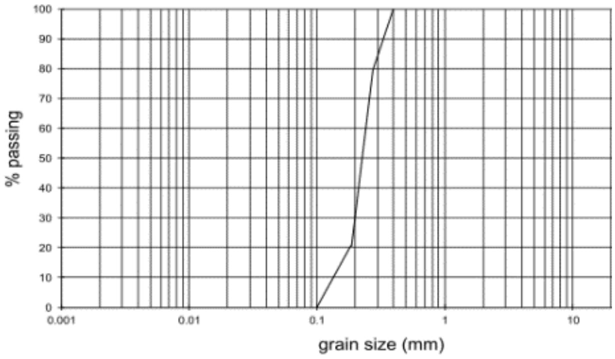

Fig. 2. Grain size distribution of Fontainbleau sand

In dry conditions samples were prepared at two different volumetric weights: (i) an intermediate value (15.35 kN/m^3) and (ii) the minimum value (14.11 kN/m^3), which correspond to n =0.41 and n=0.46 porosities ($e =$ 0.70 and e=0.85 void ratios), respectively.

The sample with higher volumetric weights (the most compacted) was also tested under saturated conditions.

λ measurements were carried out in the same two samples, allowing a direct comparison of thermal conductivities in dry and saturated conditions for the same test conditions. By using the same samples, the same solid particles structure was tested, isolating the effect of the test variables.

ASTM D 5334 – 08 standard [14] was followed, and a minimum diameter of the recipient containing the soil sample of 51 mm was used. The manual of the equipment recommends that the sample recipient radius should not be less than 15 times the needle probe radius, which is equivalent to 22.5mm, for the case of TP02 (1.5mm of diameter). Therefore, a metal recipient with 50mm diameter was selected. The length (height) of the recipient should permit the insertion of the entire needle in the soil sample, which in this case implies a length of 200 ±30 mm. Hence, a 210mm height recipient was selected.

Each soil sample was tested under strictly controlled ambient temperature conditions. These conditions were applied by means of a climatic chamber (Figure 3). Experiments performed in dry and saturated soil samples were carried out under three ambient temperature conditions: 10, 20 and 40ºC. These temperatures selection was based on the anticipated SGES operational temperatures.

Fig. 3. Climatic chamber (left) and saturated soil sample inside the container (right).

Before the heat injection the thermal needle TP02 was inserted in the centre of the sample which in turn was placed inside the climatic chamber under a prescribed ambient temperature. The needle was monitored until its temperature, registered in the probe thermocouples, equalized the one measured in the climatic chamber. At that instant the soil sample was in thermal equilibrium with the interior of the climatic chamber.

2.4 Test measurement series

Thermal conductivity measurements were carried out on the two specimens of Fontainebleau sand described above. By testing systematically the two samples under controlled temperature and saturation conditions, uncertainties related to heterogeneities and variability are minimized.

For each sample, a series of thermal tests was executed. For each series several tests were performed changing control parameters as described below.

The effect of ambient temperature boundary condition was tested by applying temperatures of: 10, 20 and 40ºC. This condition was controlled, as explained before, by a climatic chamber. For each change in temperature a new thermal equilibrium state inside the climatic chamber was attained after some time (one day minimum). The time elapsed to achieve this thermal equilibrium depended on the specimen initial condition. More time was required in the saturated sample, particularly for the highest temperature. For that case (T=40ºC) a plastic film was used to cover the soil sample in order to avoid water evaporation and to help maintaining the soil sample homogeneously saturated during the entire test.

In order to figure out the effect of the heating time on the thermal conductivity, measurements were carried out considering four heating time durations (100, 200, 500 and 1000 s), which were set by means of the logerNet software connected to the TPSYS02 device.

The effect of varying the heat flux was also studied. Two values were applied: $Q = 0.85$ and $Q = 2.5$ W/m.

Each test comprises two successive stages with the same duration, namely; a pre-heating stage, and a heating stage. Hence, each test's lasts twice the heating time. This procedure has the purpose of enhancing the soil sample thermal equilibrium before the heat flux injection.

3 Results and discussion

3.1 Effect of heating time and boundary temperature

The first variables analysed were heating time and the boundary (ambient) temperature. These two variables were analysed for the two selected dry densities under dry conditions. Thereby the effect of the relative density was also accounted for.

An initial test series was carried out for the reconstituted sand sample with a dry unit weight of 15.35 kN/m^3 and a second series for the one with 14.11 kN/m^3. Figures 4 present λ measurements for the two samples and for the two test variables considered.

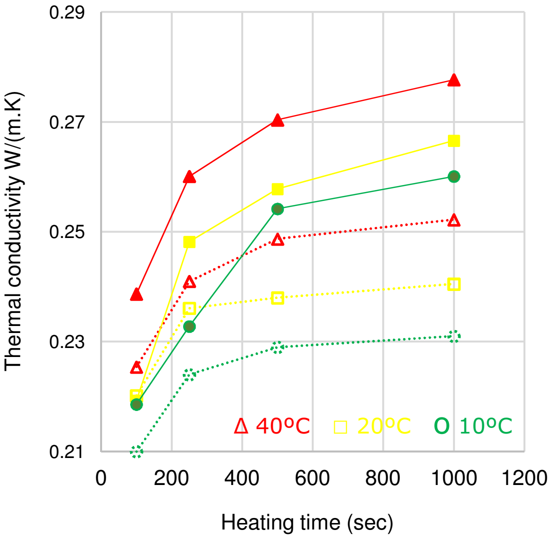

Fig. 4. Thermal conductivity measurements in dry sand samples (Q=0.85 W/m) (Full markers for the denser sample and empty markers represents the loose sample)

As it can be observed all the variables affect the measured values of thermal conductivity. It is clearly observed that λ increases with increasing ambient temperature and test duration. It is also noted that it converges to a stable value after a limited period of time.

The effect of the relative density is, as expected, significant. Obviously, the reduction of the sample voids, results in higher conductivity. Thermal conductivity λ varied 20%, for e=0.85, and 27%, for e=0.70, taking as reference value the minimum λ.

3.2 Effect of heating time, ambient temperature and heat flux (dry sample, intermediate density)

For the dry sample with intermediate density the effect of changing the magnitude of the heat flux was also tested. Therefore, for the same sample a new series of tests was performed for the same values of the test duration and ambient temperature. In Figure 5 are shown λ measurements for the three test variables considered (*t, T, Q*).

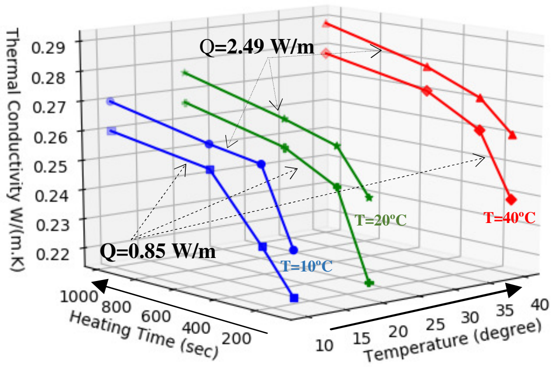

Fig. 5. Thermal conductivity of the specimen with intermediate density (15.35 kN/m^3) under dry conditions. Effect of heating time, temperature and thermal flux

For the same test conditions, an increase in the applied heat flux resulted in higher thermal conductivity values. Additionally, under a heat flux of *Q*=2.49 W/m, in the same sand sample, the same trends as the ones described previously, were observed, namely: an increase of λ with the heating time (100, 250, 500, and 1000s) and with the climatic chamber temperature (10, 20, and 40ºC).

The thermal conductivity values ranged in dry state between 0.22W/(m.K) for variables (*t*, *T*, *Q*): (100s, 10ºC, 0.85 W/m) and 0.29W/(m.K) for (1000s, 40ºC, 2.49 W/m). This increase in the measured value of λ has reached a relative difference of 31,8%. The relation obtained between thermal conductivity and heating time tends to be a logarithmic regression with R-squared values ranging between 0.944 and 0.968.

3.3 Effect of heating time and ambient temperature (dry and fully saturated sample, intermediate density)

The dry sample of intermediate density (*e*=0.7) was immersed in water until achieving fully saturated conditions. Thermal conductivity measurements were performed in the fully saturated state, changing the tests ambient temperature and heat duration time, for the same values as in the previous series. As the same sample was used a direct comparison between dry and saturated states is allowed.

Figure 6 shows the values of thermal conductivity measurements at both dry and saturated states. As expected, the differences are very significant, reaching an increase of more than 10 times in the thermal conductivity of the same sample under the same temperature boundary condition.

Globally the same trends were observed in the saturated sample, *i.e.*, under an increase in temperature and in the test time duration, a higher thermal conductivity estimate is obtained by this method.

Allover, in saturated conditions, λ values have increased from 2.58 W/(m.K) at (100s, 10ºC, 0.85W/m) to 3.59 W/(m.K) at (1000s, 40ºC, 0.85W/m), which results in a 39% relative difference (to the minimum value).

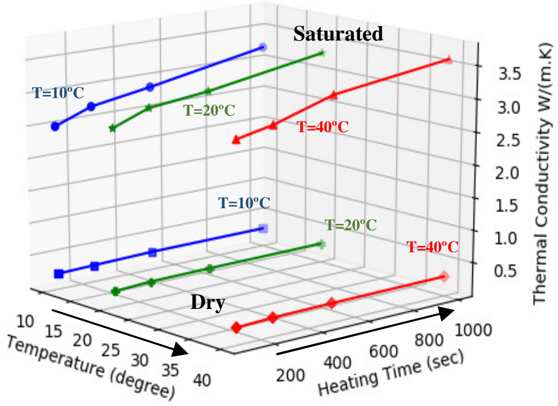

Fig. 6 Thermal conductivity of the specimen with intermediate density (15.35 kN/m^3) under dry and saturated conditions. Effect of heating time and temperature (Q=0.85 W/m)

4 Conclusions

This preliminary study has presented thermal conductivity measurements using a non-steady-state method by means of a thermal probe. The experiments carried out in Fontainebleau sand samples in both dry and fully saturated conditions have shown a clear dependence of λ on the sample state and test variables considered in this study.

Experiments have been performed under three temperature ambient controlled conditions similar to the ones anticipated in the ground where a SGES is embedded. By testing systematically the same sample, the effect of heterogeneity is eliminated and the differences obtained are a direct result of the change in test control parameters. The main conclusions of the performed tested series, are that λ increaseds with increasing test temperature and heat flux under both saturation states. The effect of the test heating time was also significant. The major differences were obtained under fully saturated conditions, where the λ measured relative to the minimum value have varied as much as 39%. Those differences in thermal conductivity values could be due to air or water convection in the soil voids and/or to the underlying theoretical model approximation.

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