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Thermal conductivity map of the Avila region (Spain) based on thermal conductivity measurements of different rock and soil samples

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ABSTRACT

A thermal conductivity map constitutes an important basis with regards to the design and performance of geothermal heat pump installations. Although the execution of a Thermal Response Test means an ideal solution as it provides the average value of the thermal conductivity over the length of the borehole drilled for the BHE, in small projects it is not possible to carry out these tests because they involve a huge increase of the total budget of the user. This study describes a systematic methodology to produce a thermal conductivity map of an area geographically placed in the center of Spain, the province of Ávila. As a result, a map of thermal conductivity distribution of local rocks is proposed.

1. Introduction

The use of geothermal energy is at a point of rapid growth and is expected to continue growing in the future. With respect to Spain, this energy is basically used to generate sanitary hot water (SHW) and/or heat/cool a certain space. The geothermal electric generation in this country is at a very early stage although at the moment, it is being developed in areas like Tenerife where, because of its thermal characteristics, the first Spanish geothermal electric central is going to be placed.

At user level, the very low temperature geothermal energy is used in the production of SHW or heating. For both uses, a careful design of the geothermal installation is required; one of the essential parameters that is decisive is the thermal conductivity of the ground where the installation will be placed. When measuring this parameter, a "Thermal Response Test" (TRT) is needed in order to get accurate values of the whole subsoil to the right design of the geothermal installation. However, in spite of providing this value directly, this test involves an important rise of the price of implementation of a geothermal installation, of little significance (from an economical point of view) at big projects but unviable at small installations. In case of not making this essay, the most usual is not to determine the thermal conductivity of the land and consider the most unfavorable case, that is to say, that value of thermal conductivity (for the type of soil-rock where the installation is located) that requires the highest heat pump power (in function of theoretical tables), rising equally the global budget (Blázquez et al., 2016; Peláez et al., 2014).

In the present paper, measurements of the thermal conductivity of different samples of the characteristic geological materials that occur in the province of Ávila were carried out in the laboratory. Data obtained in soils were compared with the ones obtained by the use of the program ThermoMap developed by a diverse combination of institutions (*GeoZentrum*, *BRGM*, *ISOR*, *MFGI*, *IGR*, *BGS*, *EGEC*, *RBINS-GBS*, *REHAU*, *GBI*, *PLUS*, *IGME*) (Thermo Map, 2013). Data acquired in the laboratory and in the case of soils also verified by ThermoMap have allowed generating thus, a thermal conductivity map of the mentioned province. This knowledge will make possible to improve the design of the geothermal heat pump installations (Vijdea et al., 2014; Galgaroa et al., 2015; Clauser and Huenges, 1995; Barry-Macaulay et al., 2013).

The purpose of this study is to obtain values of thermal conductivity by measurements in the laboratory and using the program ThermoMap (only in the case of soils), representative of the Ávila region, to be presented as a thermal conductivity detailed map. For that, a procedure of localization, collection and preparation of samples at the laboratory and analysis of the thermal conductivity parameter of each one of the samples was developed. Thermal conductivities of soils were also estimated by the calculator ThermoMap to carry out a comparison of both methods in these samples.

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This map of thermal conductivities can be used along with the corresponding geological data, as basic information at the design phase of a geothermal heat pump project (Jackson and Taylor, 1986).

2. Materials and methods

2.1. Study site

As it has already been mentioned, the determination of the thermal conductivity parameter has been carried out on the most representative geological materials that are part of the province of Ávila; therefore, the map obtained as a result of this study will reflect an analysis of the geothermal situation of the province (in terms of thermal conductivities of the materials) and the possibilities of making use of this energy in this place (Fig. 1).

The Geological and Mining Institute of Spain "IGME" puts at the disposal of the users geological information of all the regions of Spain, in this way, this country is divided into a series of grids to scale 1:50.000 that contain the geology of the area represented. By graphic design software the grids that divide the province of Ávila were digitized and overlapped with the aim of locating each one of the materials found in the study area and calculating the expanse taking up by each one of them. Fig. 2 shows the rock types of this province (Geological and Mining Institute of Spain (IGME), 1972–2003).

As shown in Fig. 2, the province of Ávila is geologically formed by two clearly defined blocks:

- On the one hand, materials belonging to the Hercynian Massif, constituted by igneous rocks from the Upper Carboniferous-Low Permian (mainly granitic rocks) and metamorphic rocks from the Pre-Cambrian-Low Cambrian.
- On the other hand, there is a block constituted by sedimentary materials from the Mesozoic, Tertiary and Quaternary, located in the oriental area of the Amble's valley (Ávila) (César et al., 2014).

Additionally, Table 1 contains the list of materials that constitute the province represented in Fig. 2, the area taken up by each one of them expressed in: area unities (m^2) and as percentage (%) with respect to the total area of the province. It can be observed in this Table 1 that, more than half of materials placed in this province have granitic origin.

2.2. Sample collection

Due to the lack of information about the thermal conductivity properties of the materials of Ávila, a sampling selecting different sample collection points according to the rock type, lithology and geographical position was carried out. In this way, representative samples of the formations of this region were taken. Given the difficulty to measure the thermal conductivity property "in situ", samples were moved to the lab where, after opportune preparation, measurements were made. Basically two types of rocks have been collected and investigated: solid (rock) and unconsolidated (soil). With the aim of reproducing the conditions of the materials in nature, measurements of thermal conductivity were carried out for different states of water content, in those materials that allow changing its humidity (i.e. soils).

Fig. 3 shows the points where the samples representative of each material presented in Table 1 were taken. As it can be observed, for the same rock type, four different samples were collected with the object of getting a more precise determination of the mentioned thermal conductivity property and the correspondent geothermal map of the province. For three of the investigated rock types (leucogneiss, gneiss and quartzite) the four samples collected for these rocks come from sites next to each other due to the short area taken up by these materials.

2.3. Thermal conductivity measurements

2.3.1. KD2 Pro equipment

Equipment used at the measuring of thermal conductivities was the thermal properties analyzer commercially known as KD2 Pro developed by Decagon Devices (Decagon Devices, 2016). It is constituted by a portable controller and a certain sensor (RK-1) usually used in geothermal practice and customarily termed "*needle probe*" that make possible the measuring of two thermal properties: the thermal resistivity and the focus parameter of this work; the thermal conductivity. Its operation is based on the infinite line heat source theory and calculates the thermal conductivity by monitoring the dissipation of heat from the needle probe. Heat is applied to the needle for a set heating time, t_h and temperature is measured in the monitoring needle during heating and for an additional time equal to t_h after heating. The temperature during heating is computed from Equation (1).

$$T = m_0 + m_2 t + m_3 \ln t \quad (1)$$

Where:
m_0 is the ambient temperature during heating
m_2 is the rate of background temperature drift
m_3 is the slope of a line relating temperature rise to logarithm of temperature

Equation (2) represents the model during cooling.

$$T = m_1 + m_2 t + m_3 \ln \frac{t}{t - t_h} \quad (2)$$

The thermal conductivity is computed from Equation (3).

$$k = \frac{q}{4m_3} \quad (3)$$

q is the heat flux applied to the needle probe for a set time. This heat dissipates along the sample in a different way so and as it can be seen in Equation (3), this value is used by the equipment KD2 Pro to calculate the thermal conductivity value of the sample in question. However, KD2 Pro does not provide the heat flux applied and it only supplies the final thermal conductivity value.

Since these equations are long-time approximations to the exponential integral equations, only the final 2/3 of the data collected are used (ignoring early-time data) during heating and cooling. This approach has several advantages; the effects of contact resistance appear mainly in these early time data, so by analyzing only the later time data the measurement represents better the thermal conductivity of the sample. Also, Equations (1) and (2) can be solved by linear least squares, giving a solid and more adjusted result (Kluitenberg et al., 1993; Shiozawa and Campbell, 1990).

In this study, the RK-1 probe (3.9 mm in diameter and 6 cm in length) has been used to measure the thermal conductivity of the different materials placed in the province of Ávila. This probe is capable of measuring the thermal conductivity between the range of 0.1 and 6 W/mK and ±10% of accuracy.

Additionally, KD2 Pro calculates the accuracy of each measurement by comparing the experimental temperature data to the modelled temperature predicted by the analytical solution of infinite line source theory (Carslaw and Jaeger, 1959). The difference between experimental and modelled temperature is displayed as the coefficient of correlation. It must be clarified that this error term is not a statistical indicator of the measuring quality, but it serves as a qualitative indicator.

The long read times for the RK-1 sensor help to prevent errors caused by effects from the large diameter needle and contact