Design, Construction and Commissioning of an Apparatus for Measuring the Thermal Conductivity of Geothermal Grouting Materials Based on the Transient Hot Wire Method [†]

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Abstract: The aim of the present study is to develop an apparatus for the measurement of the thermal conductivity of geothermal grouting materials. The apparatus, named MCT, is designed and constructed as a direct application of a mathematical model of heat transference for conduction in an infinite homogeneous isotropic medium using a linear heat source of infinite length, infinitesimal radius and radial heat flow. This application is known as the transient hot wire method. The apparatus mainly consists of a hot wire, a power supply, a temperature sensor and a datalogger. The commissioning of the developed apparatus is carried out by means of the calibration of the temperature sensor, as well as measurements of thermal conductivity using four reference samples whose thermal conductivity is known. Each of the reference samples is formed of two solid rectangular prisms of the same material and of the same dimensions. MCT is precise and accurate. In good experimental conditions the uncertainty of the measurements is within 10%. In addition, the MCT apparatus is light and with reduced dimensions.

Keywords: transient hot wire method; thermal conductivity; geothermal grout

1. Introduction

The transient hot wire method is applied for measuring the thermal conductivity. It is an absolute, direct and transient method that consists in passing, during a given time, the electric current through a hot wire that is placed in a medium which we want to determine its thermal conductivity [1]. The generation of heat in the hot wire produces an increase in temperature that depends on the thermal conductivity of the medium.

The transient hot wire method has the following advantages: It is a fast, precise and economical method, with an extensive use and it allows obtaining the thermal conductivity at room temperature [2]. However, it has the following limitations: Heterogeneous materials, anisotropic materials, semitransparent materials, materials that can conduct electricity and materials with high thermal conductivity [1,3].

2. Materials and Methods

The theoretical basis, the developed apparatus and the tests carried out are shown below.

2.1. Theoretical Basis

The hypotheses of the mathematical model are the following: Linear heat source of infinite length and infinitesimal radius that dissipates a radial heat flow in an infinite homogeneous isotropic medium with uniform initial temperature and constant thermal diffusivity [1,4]. It is also assumed that all heat transfer is by conduction and that there are no heat sources or heat sinks. In this way, the governing equation will be given by the Equation (1).

$$\frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T}{\partial r} \right) = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} \tag{1}$$

To solve this partial differential equation, two boundary conditions are needed: Equations (2) and (3). An initial condition is also needed: Equation (4).

$$\lim_{r \to 0}\left[r \cdot \frac{\partial T}{\partial r} \right] = -\frac{q}{2 \cdot \pi \cdot \lambda} \qquad t > 0 \tag{2}$$

$$\lim_{r \to \infty}\left[\Delta T(r,t) \right] = 0 \qquad t \geq 0 \tag{3}$$

$$\Delta T(r,t) = 0 \qquad t = 0 \tag{4}$$

where, $\Delta T(r,t)$ is the increase in temperature at a point placed at a radial distance "r" of the hot wire and at a time "t" measured from the start of heating, q is the heating power per unit length and α is the thermal diffusivity of the medium.

The solution of Equation (1) can be approximated to the following expression [2,4]:

$$\Delta T(r,t) \cong \frac{q}{4 \cdot \pi \cdot \lambda} \cdot \ln t + \frac{q}{4 \cdot \pi \cdot \lambda} \cdot \left[\ln\left(\frac{4 \cdot \alpha}{r^2} \right) - \gamma \right] \tag{5}$$

where, λ is the thermal conductivity and γ is Euler's constant. As can be seen, Equation (5) represents a straight line of slope "m":

$$\Delta T(r,t) = m \cdot \ln t + n \tag{6}$$

Therefore, the thermal conductivity is computed from Equation (7).

$$\lambda = \frac{q}{4 \cdot \pi \cdot m} \tag{7}$$

In practice, the heating power per unit length is obtained by Equation (8).

$$q = \frac{\Delta V \cdot I}{L} \tag{8}$$

where, I is the electrical current passing through the hot wire, L is the hot wire length and ΔV is the voltage drop along it.

In order to determine the slope "m" it is necessary to plot the heating curve on a semilogarithmic scale (temperature rise vs. the natural logarithm of time). The central part of the heating curve is a straight line and its slope is calculated using a least squares fit.

2.2. Apparatus

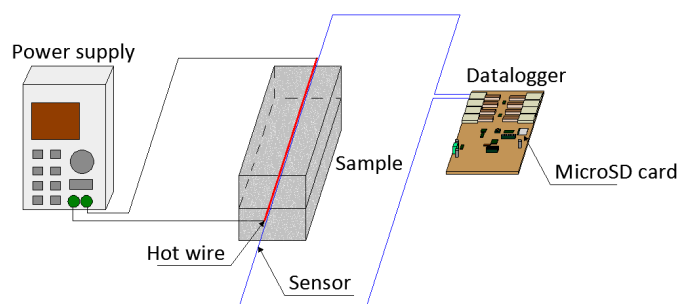Figure 1 shows the main components of the developed apparatus, named MCT.

Figure 1. Main components of MCT.

The hot wire is made of nichrome (nickel and chromium alloy) with a variable length of 0–510 mm and a diameter of 0.2 mm. An adjustable DC power supply (0–3 A) is used. The K-type thermocouple sensor is placed parallel to 1 mm of the hot wire. The datalogger is a PCB (Printed Circuit Board) developed by the research team. The PCB stores data measured during the tests on a microSD card. It is also used, as auxiliary material, a multimeter, a flexometer, a weight of 5 kg (in order to minimize contact resistance) and two other K-type thermocouples (in order to measure the temperature of the outer face of the sample and to measure the room temperature).

The commissioning of the apparatus has been performed using four reference samples whose thermal conductivity is known. This reference samples are: Skamol SM-65 (Skamol A/S), Macizo M5R (Cerámica La Espina S.L.), MAXIAL 310 (RHI) and CN-90BA (Cerámica del Nalón S.A.). Table 1 shows the material and thermal conductivity of the four reference samples.

Table 1. Reference samples.

Sample	Material	λ [W/m·K]
Skamol SM-65	Diatomite	0.13
Macizo M5R	Red clay	0.70
MAXIAL 310	Chamotte	1.20
CN-90BA	Alumina	2.80

Each of the reference samples is formed of two solid rectangular prisms of the same material and of the same dimensions: (110 × 50 × 35) mm, (180 × 70 × 50) mm and (240 × 120 × 60) mm.

Before carrying out the tests, the reference samples were in a drying oven at 60 °C for 24 h and then left at room temperature for 48 h.

2.3. Tests

The commissioning of the MCT apparatus (Figure 2) is carried out by means of the calibration of the K-type thermocouple sensor using a mercury thermometer, as well as the measurements of thermal conductivity using the four reference samples shown on Table 1.
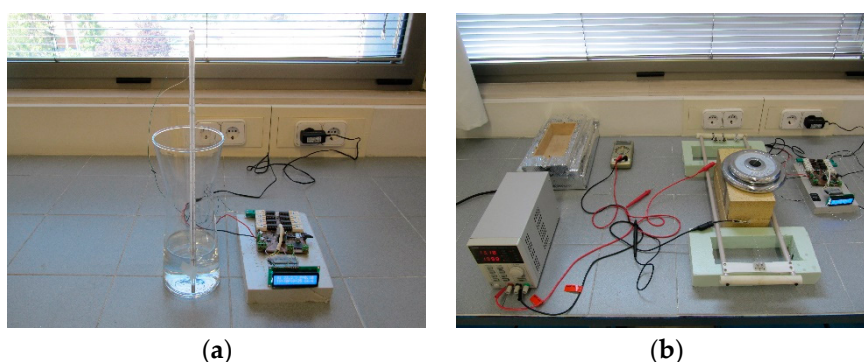

(**a**)　　　　　　　　　　　　　　　　　　(**b**)

Figure 2. Commissioning of MCT. (**a**) Calibration; (**b**) Measurement of thermal conductivity.

The thermal conductivity calculation using the developed apparatus is done through the following steps:

1. Placement of the sample.
2. Placement of the weight of 5 kg on the sample.
3. Selection of the electrical current (0–3 A).
4. Beginning of the heating and the data logging at the same time.
5. Voltage drop measurement using a multimeter.
6. Hot wire length measurement using a flexometer.
7. End of the heating and the data logging after 15 min.
8. Download the microSD card from the datalogger to the computer.
9. Plotting the heating curve.
10. Obtaining the thermal conductivity.

All the measurements of thermal conductivity were made at room temperature, specifically with a relative humidity of 65% and a temperature of 25 °C.

Three tests have been performed on each sample. The thermal conductivity of each sample is the average value.

3. Results and Discussion

As an example of calculation of thermal conductivity we will use a test carried out on the Skamol SM-65 sample. Figure 3 shows the heating curve and the regression line (central part of the heating curve between tmin and tmax).

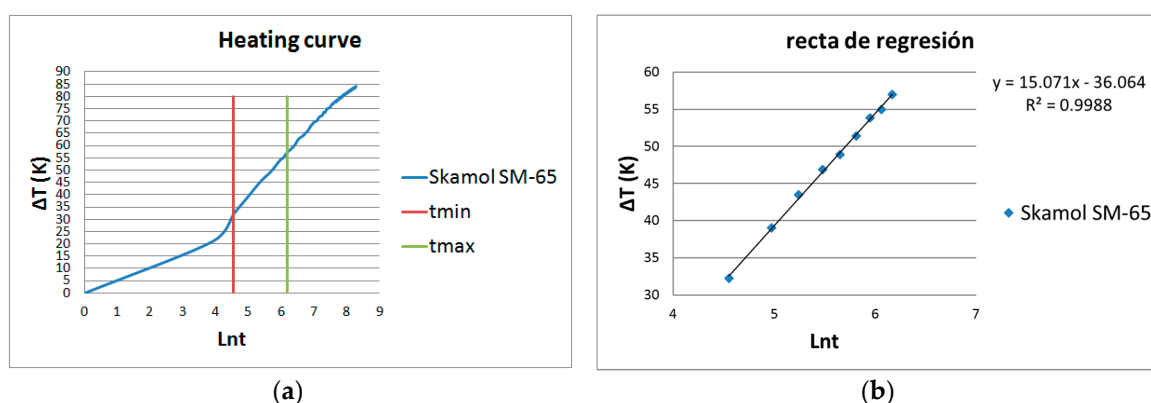**Figure 3.** Skamol SM-65 sample. (**a**) Heating curve; (**b**) Regression line.

Figure 3b shows that the slope of the regression line is 15.071. In this example the electrical current is 1 A, the hot wire length is 0.11 m and the voltage drop is 2.75 V. Therefore the thermal conductivity value is 0.13 W/m·K. It is the same value that the value declared by the manufacturer of the sample (Table 1).

After performing all tests, it can be concluded that in good experimental conditions the uncertainty of the measurements is within 10%.

4. Conclusions

The following conclusions have been obtained:

- A precise and accurate apparatus based on the transient hot wire method has been designed and constructed. This apparatus, named MCT, allows measure the thermal conductivity of geothermal grouting materials in a few minutes. In addition, the MCT apparatus is light and with reduced dimensions.
- The commissioning of MCT has been carried out by means of the calibration of the K-type thermocouple sensor using a mercury thermometer, as well as the measurements of thermal

conductivity using four reference samples with a thermal conductivity in the range of (0.13–2.80) W/m·K. In all cases the uncertainty of the measurements is within 10%.

Conflicts of Interest: The authors declare no conflict of interest.

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