Geothermics 54 (2015) 35–42

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Determining the thermal diffusivity of the ground based on subsoil temperatures. Preliminary results of an experimental geothermal borehole study Q-THERMIE-UNIOVI

D. Arias-Penas[a,*], M.P. Castro-García[b], M.A. Rey-Ronco[b], T. Alonso-Sánchez[a]

[a] Departamento de Explotación y Prospección de Minas, Universidad de Oviedo, Spain
[b] Departamento de Energía, Universidad de Oviedo, Spain

ARTICLE INFO

Article history:
Received 11 October 2013
Accepted 30 October 2014

Keywords:
Thermal diffusivity
Borehole
Thermal conductivity
Mathematical model
Regular flow of heat through a surface

ABSTRACT

This article presents the preliminary results of a method for determining ground thermal diffusivity using temperatures recorded at different depths below the surface ground. The theoretical framework is based on the regular flow of heat through the surface, and the experimental framework involves measuring temperatures with sensors placed inside a geothermal borehole. The project has been made possible by the Universidad de Oviedo's Energy, Environment and Climate Change Cluster, and was carried out at their facilities in Gijón (Asturias, Spain). To solve the differential equation, a common model for variations in surface temperature was used to describe the environmental conditions, and the temperatures recorded at various depths with the sensors were compared with the predictions set forth in the theoretical framework. Based on the results obtained so far, the method is believed to show encouraging results although difficulties were encountered in interpretation due to variations in water table level during the period of measurements.

1. Introduction

The thermal conductivity λ and thermal diffusivity α of the ground are fundamental parameters in the design of shallow geothermal plants, and the determination of them has been the subject of many research projects and scientific publications. Thermal conductivity, thermal diffusivity and specific heat capacity each can be measured by several well-established methods, but measuring any two of them would lead to the third through the relationship:

$$\alpha = \frac{\lambda}{\rho \cdot C_\rho}$$

where α is the thermal diffusivity, λ is the thermal conductivity, ρ is the bulk density and C_ρ is the specific heat (Sanner et al., 2008; Yang et al., 2002; Borinaga-Treviño et al., 2013).

Such parameters can be determined in the laboratory using direct or absolute methods based on Fourier's heat conduction equation, where a heat source is applied to a mineral sample. One then measures either the heat released by the source directly, or the heat flow in the cold part of the sample (Dos Santos and Gregorio, 2003).

They can also be determined in the laboratory with comparative methods, by testing a sample with a known thermal conductivity followed by the unknown sample, and measuring the thermal gradient of the former (Llavona, 1995).

There are also theoretical models which make it possible to determine the thermal conductivity of a mineral aggregate by treating it as a mixture of water, air and mineral particles. For example, the Vries model (Adeniyi et al., 2012) calculates ground thermal conductivity as the weighted average of the conductivities of the different components of the soil.

Another way to determine these parameters in situ in a geothermal borehole is with the Thermal Response Test, which provides the thermal conductivity of the ground "λ" and the thermal resistance of the borehole "Rb" (Sanner et al., 2003; Mattsson et al., 2008). Whereas earlier approaches determined boreholes' average thermal properties by measuring the temperature of the geothermal fluid as it entered and exited the borehole (Eklof and Gehlin, 1996; Austin, 1995) later projects have used sensors distributed at different depths along the borehole (Acuña et al., 2009; Pau-Delgado, 2010).

The thermal diffusivity is also an important parameter in designing the geothermal heat pump system, in which extraction of thermal energy is accomplished by using a ground heat exchanger.

* Corresponding author. Tel.: +34 985104251.
E-mail addresses: UO155929@uniovi.es (D. Arias-Penas), castromaria@uniovi.es (M.P. Castro-García), rey@uniovi.es (M.A. Rey-Ronco), tjalonso@uniovi.es (T. Alonso-Sánchez).

http://dx.doi.org/10.1016/j.geothermics.2014.10.006
0375-6505/

The heat transfer between the ground heat exchanger and the surrounding geological formations occurs primarily by conduction due to a temperature contrast between the heat exchanger and the surrounding soil. The effective thermal diffusivity of the ground influences the temperature of soils near the ground surface by controlling the degree of attenuation of the surface temperature cycles with depth. It also influences the temperature of the ground around the heat exchanger.

The thermal diffusivity of soils and rocks can be obtained from laboratory experiments which, however, often yield unsatisfactory results since they usually deal with a small size sample in spite of heterogeneities of the real field. Furthermore, in the case of soils, it is difficult to take undisturbed samples as preserved as the natural condition of the materials.

Therefore, field measured ground temperature data have been widely used as an alternative to estimate the thermal diffusivity. Time series data sets and groundwater temperatures of wells can be analyzed to estimate the apparent thermal diffusivity by using the analytical solution of the one-dimensional heat conduction equation. Temperature time series data measured in soils at a shallow depth generally show annual cyclic variations, which can be effectively described by the one-dimensional heat conduction model.

Most approaches in the literature to use subsurface temperatures assume that temperatures measured in a borehole should be in equilibrium with the surrounding media. However, it has long been recognized that convection close to the borehole causes borehole temperatures to be different from the surrounding media, and thereafter misleads the interpretation of temperature data. Climatically driven processes at or near the ground surface, including air temperature, can generate and influence, the downward propagating subsurface climate signal. These processes most notably include the effects of snow cover, soil freezing, evapotranspiration, and vegetative changes. The seasonal variability of temperature at the Earth surface is closely approximated by a simple harmonic function and the annual signal is the dominant signal within the range of depths observed. The propagation behavior of the annual signal can be analyzed by two characterizations of downward conductive heat transport of a harmonic temperature function imposed at the surface of a homogenous medium: One the one hand, the exponential attenuation of the amplitude of the harmonic function with depth and on the other hand, linear phase shift of the harmonic function with depth. Interval wave velocities and thermal diffusivities can be calculated from the phase shift of the annual signal to estimate changing thermal properties as a function of depth (Koo and Song, 2008; Smerdon et al., 2003).

This article proposes a system for determining ground thermal diffusivity by measuring the natural underground temperature variation caused by changes in the temperature of the surface in the ground. This variation depends on ground thermal diffusivity and is governed by the general equation for the transmission of heat through conduction.

2. Theoretical framework

The system is constituted by the ground, which is treated as an infinite hemisphere and homogeneous medium, with a flat limit perpendicular to the direction of the heat flow. The surface temperature varies regularly depending on the time of day and the season. The temperature at each point in the ground also varies regularly over time in accordance with the surface boundary condition. The heat flow represented by the difference in temperature between the surface and the ground is unidimensional and vertical (x axis).

The laws of heat transfer through the ground by conduction are represented by Fourier's general equation, where the thermal diffusivity of the medium is homogeneous, states:

$$\frac{\partial T}{\partial t} = \alpha \cdot \nabla^2 T = \alpha \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{1}$$

where $T=f(x,t)$ is the temperature at time t and a given position $P(x,y,z)$ and α is the thermal diffusivity of the ground. Because the heat is assusmed to be unidimensional $\partial^2 T/\partial y^2$ and $\partial^2 T/\partial z^2$ are equal zero, such that $\partial^2 T/\partial t^2 = \alpha \cdot \partial^2 T/\partial x^2$.

It may be assumed that variation in surface temperature obeys an harmonic sinusoidal function as proposed in (Ingersoll et al., 1954):

$$T(0, t) = T + A_0 \cdot \sin(\omega \cdot t + \varnothing_0) \tag{2}$$

where:

- $\omega = (2\pi)/\tau$ is the angular frequency.
- τ is the temperature oscillation period. When analyzing the daily variations in temperature, one should use: $\tau = 24\,\text{h} = 86{,}400\,\text{s}$ which is equivalent to one full day. When analyzing the yearly variations in temperature, one should use $\tau = 12$ months $= 365$ days $= 31{,}536{,}000$ s, which is equivalent to one full year.
- A_0 is the amplitude of the temperature fluctuation, and is $A_0 = (T_{\max} - T_{\min})/2$.
- $T_{\max}$ and $T_{\min}$ are the maximum and minimum values, respectively, of the sinusoidal approximation of the annual temperature cycle.
  - $\bar{T}$ is the average temperature on the surface and it is obtained as: $\bar{T} = (T_{\max} + T_{\min})/2$.
  - $\varnothing_0$ is the phase of the surface temperature, which is related to the start times.

The solution to the Eq. (1) based on the conditions given is the following:

$$T(x, t) = \bar{T} + A_0 \cdot e^{-x \cdot \sqrt{\omega/(2 \cdot \alpha)}} \cdot \sin\left(\omega \cdot t + \varnothing_0 - x \cdot \sqrt{\frac{\omega}{2 \cdot \alpha}} \right) \tag{3}$$

Eqs. (2) and (3) are similar in form, in that:

$$T(x, t) = \bar{T} + A \cdot \sin(\omega \cdot t + \text{phi}) \tag{4}$$

However, the coefficients in both equations are different. In the former, the coefficient that multiplies the sine is A_0 whereas in the latter is, $A = A_0 \cdot e^{-x \cdot \sqrt{\omega/(2 \cdot \alpha)}}$. This coefficient A shows the maximum amplitude of the function $T(x,t)$ at a depth of x_1, subsequently referred to as A_{mx_1}. Something similar takes place in the case of phase shift. In Eq. (2) is $\varnothing_0$ while in Eq. (3) is phi $= \varnothing_0 - x.\sqrt{\omega/(2 \cdot \alpha)}$. It can be observed that as depth increases, the maximum amplitude of $T(x,t)$ decreases. Likewise, it can be inferred from Eq. (3) that, the greater the depth, the later in time the maximum amplitude occurs.

Eq. (3) includes average ground surface temperature $\bar{T}$, and the product of three terms.

- A_0, which is independent from time and depth, and depends only on the amplitude of the sinusoidal function for variation in surface temperature.
- $e^{-x.\sqrt{\omega/(2 \cdot \alpha)}}$ which depends on depth of measurement x, and on the thermal diffusivity of the ground α.
- $\sin\left(\omega \cdot t + \varnothing_0 - x.\sqrt{\omega/(2 \cdot \alpha)}\right)$ which depends on depth x, t and on thermal diffusivity α.