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A practical method for computing the thermal properties of a Ground Heat Exchanger

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ABSTRACT

The aim of this paper is to show a practical way of estimating the thermal ground properties, namely the ground thermal conductivity, and in particular the thermal diffusivity and the volumetric heat capacity in a reliable manner, for sizing Ground Heat Exchangers (GHEs). A well-known thermal model, proposed by Blackwell in 1954, is applied and is validated both in the heating mode and in the cooling mode, using a GHE as a probe. The value of the thermal conductivity can be easily determined by the model but the procedure also requires knowledge of the ground specific heat capacity and density, which are normally deduced from the (non-accurate) geological data of the site.

In addition to the above, the thermal model is also solved analytically —based on the actual parameters used in the experiment—leading to the computation of the ground thermal diffusivity, the volumetric heat capacity and the thermal resistance of the GHE. The possible errors and drawbacks of the whole method are then discussed and finally a complete set of guidelines is provided to the field Engineer for estimating the ground thermal properties from a single test, rendering the use of the geological data of the side unnecessary.

1. Introduction

Geothermal heat pumps use the ground to reject heat during summer operation or absorb heat in winter operation. A common means of exchanging heat is through vertical ground heat exchangers that mainly consist of a descending and an ascending leg of polyethylene pipe connected at their ends in the ground with a U-joint. A borehole with a diameter of 0.1–0.2 m and a common depth of 100 m is drilled in the ground, the heat exchanger is placed in position and the borehole is filled with thermally enhanced bentonite or silica sand. The result is a good contact between the pipe and the ground and therefore a fluid, usually water, circulating in the pipes can be cooled or heated depending on its temperature relative to the adjacent ground. The classic models for the heat exchange process are the line and cylindrical heat source methods that are based on the theory of Carslaw and Jaeger [1]. The methods are relatively easy to apply and were used by many researchers to model and evaluate the response of ground heat exchangers [2–7]. Both methods are based on fitting data for a constant power supply to the water loop on *long-term* approximate solutions to the heat conduction problem. These methods are simple to apply given that all possible inaccuracies with regard to initial (and possibly late-stage) data are successfully treated.

Theoretical and experimental methods for measuring the thermal properties of solid or fluid materials include the steady-state method [8], the probe method first proposed by Refs. [3], the periodic heating method (for thin films) [9,10], the LS optimization numerical method [11,12] and the pulse heating method (for samples exposed closed to a heat source, not appropriate here) [13,14]. Estimates of soil thermal conductivity are based either on models (see an extensive summary in Ref. [15]) or on experimental data.

Transient methods for the measurement of thermal conductivity have a long history (e.g. Ref. [16]). Most field measurements of thermal conductivity are made using heated wire or needle probes modeled as perfect line conductors. So-called *transient probe methods* for determining thermal constants may be described as follows: a body of known dimensions and thermal constants (the “probe”), which contains a source of heat and a thermometer is immersed in the medium whose constants are

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Nomenclature

t	time s	R_b	thermal resistance m K W^{-1}
T	temperature variation K or °C	γ	Euler's constant
q	quantity of heat J	$Ei\{\bullet\}$	exponential integral
Q	Power (q/t) W	$erf(\bullet)$	error function
ρ	density kg m^{-3}	$erfc(\bullet)$	complementary error function
λ	thermal conductivity W m^{-1} K^{-1}	m	"probe" mass kg
c	specific heat capacity J kg^{-1} K^{-1}	c_p	"probe" specific heat capacity J kg^{-1} K^{-1}
α	thermal diffusivity = $\lambda/\rho c$ m^2 s^{-1}	λ_b	bentonitic clay thermal conductivity W m^{-1} K^{-1}
C_v	volumetric heat capacity J m^{-3} K^{-1}	d	minimum distance from origin to boundary m
L	"probe"/GHE length m	t_s	"heating" initial stable time s
r	radial distance from origin m	t_f	"heating" final ("cooling" initial) time s
H	thermal contact conductance W m^{-2} K^{-1}	t_r	reflection time s
		t_b	axial error time s
		T_e	experimental temperature K

unknown. With the aid of suitable theoretical relations, these constants are then deduced from a record of probe temperature versus elapsed time [3].

Van der Held and Van Drunen [16] employed a non-steady-state transient flow method based on an empirical formula proposed by Stalhane and Pyk [17] —that can be derived through a non-stationary solution of Fourier's (Heat) equation [1]— to measure experimentally the thermal conductivity of liquids. Up to that time the usual practice was the employment of methods based on the steady-state solution of Fourier's equation. Van der Held and collaborators [18] considerably improved the accuracy of the non-steady-state method above by lengthening the time during which measurements were possible by trying to suppress convection.

At the same time Blackwell [3] introduced what he called an improved transient-flow method with the use of a cylindrical thermal probe for determining the thermal conductivity and diffusivity of insulating materials in bulk. The work was first suggested by the geophysical problem of determining the thermal constants of natural rock *in situ*. Blackwell addressed the deficiencies encountered in previous methods and proposed ways to overcome these.

Vos [4] studied several aspects of a non-steady-state method for the determination of thermal conductivity and concluded that many difficulties must be overcome before an exact interpretation of the data is possible. He suggested that the non-steady-state method is even more appropriate —as opposed to a steady-state method— when the contribution of radiation does play a part and the thickness of the layers applied in the relative constructions is considerably greater than the thickness of the test-specimen on which measurements are being made.

Lachenbruch [5] used a 20-inch probe for the determinations *in situ* of the thermal conductivity of naturally frozen and thawed soils, snow, fresh-water ice, and sea ice in northern Alaska and suggested that if the probe is composed by almost entirely highly conducting metal, the practical method could permit a simultaneous determination of both the thermal conductivity and the thermal diffusivity *in situ*.

Needle probes are generally used solely for measuring thermal conductivity, as detailed in Ref. [19]. For the estimation of thermal diffusivity (and consequently specific heat) one can then use the (infinite) line source formulation of Carslaw and Jaeger [1]. This is however a procedure that requires an elegant approach with regard to possible errors in the mathematical truncation/approximation of equations as well as the fit parameters, due to the strong nonlinearity in thermal diffusivity. Note that for fluids, contact between sample and probe is often assumed to be ideal, and thermal contact conductance H is infinite and both conductivity and diffusivity can be determined from the steady-state dependence of temperature difference ΔT on time. For solid materials, ideal thermal contact between probe and sample cannot be assumed, and H must be determined through fit parameters for the initial, transient dependence of ΔT on time [20].

More recent indicative studies of the probe method usage include Goodrich's [21] measuring the thermal conductivity of active layer soils at four Canadian locations using a transient heat pulse probe, Elustondo and collaborators' [22] study of thermal conductivity probe design and the associated errors with the experimental use of thermal probes in the determination of thermal properties of materials, Krishnaiah and collaborators' [23] application and validation of a methodology suitable for determining the thermal properties of rock samples easily and quickly, and Overduin and collaborators' [24] study of the effect of latent heat during phase change when measuring thermal conductivity in freezing and thawing soil.

Other studies that expand or combine the standard line source and probe methods with other mathematical or statistical techniques include [20,25–27]. Garcia and collaborators [25] computed the thermal properties of five drill cores in Mexico based on the line-source method optimizing transient heat transfer experimental data. The estimation of the model parameters was optimized using the Gauss-Newton algorithm, with the analytical model being linearized through a Taylor series expansion, with fast convergence when the initial estimate of the parameter vector was near the least squares.

Goodhew and Griffiths [26] demonstrated that a time-dependent thermal probe technique, together with an iterative method of data analysis, can be used to measure simultaneously the two thermal properties of samples, namely the conductivity and the diffusivity. They computed numerically the thermal properties based on thermal-probe temperature time data obtained experimentally. Their numerical model required the selection of appropriate time-intervals.

Waite and collaborators [20] in estimating the thermal properties of ice Ih and of tetrahydrofuran hydrate using a standard needle probe and a suitably high data acquisition rate, emphasized on the fact that accurate thermal conductivity measurements can be obtained from a linear fit to many data points as opposed to the thermal diffusivity calculations that require a nonlinear fit to the data obtained in the first few tenths of a second of the