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Interpretation of the first hours of a thermal response test using the time derivative of the temperature

Philippe Pasquier

Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, P.O. Box 6079, Centre-Ville, Montréal, Québec H3C 3A7, Canada

HIGHLIGHTS

- Four first-order approximations to interpret a thermal response test are presented.
- Smoothing and averaging operations are used to assess correctly the time derivative.
- The ground thermal conductivity is deduced from the first 3 h of a test.
- The approach is successfully tested on three real thermal response tests.
- For highly resistive boreholes, the approximations might prove inaccurate.

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ABSTRACT

Four new first-order approximation models using the time derivative of fluid temperature to interpret the first hours of the heating and recovery phases of a thermal response test are presented. The time derivative being sensitive to experimental noise and artifacts, the gain brought by various filtering operations is discussed and illustrated for real temperature measurements. The new interpretation models are tested on two synthetic and three real data sets. It is shown that analyzing the time derivatives measured during the first three hours of a real thermal response test with a constrained first-order approximation model can provide a thermal conductivity estimation within 10% of a reference value. The effect of the borehole equivalent resistance and of ground and grout thermal conductivity on the time derivative is also analyzed with a thermal resistance and capacity model to identify possible limitations of the linear models for practical applications. These results provide the first evidences that the time derivative can be used to interpret a thermal response test and open the door to a new family of interpretation methods that could potentially shorten the duration of thermal response tests from 72 to 3 h or allow interpretation of tests when only the first few hours are available.

1. Introduction

The growing energy needs around the world have sparked renewed interest in ground-coupled heat pump systems over the last decade. Indeed, the use of these systems for space heating can significantly reduce energy consumption as most of the energy is extracted from the ground [1] through a ground heat exchanger (GHE). To avoid a costly oversizing of the ground loop, the design process requires knowing rather accurately the thermal conductivity of the geological material where the GHE will be constructed [2]. For most practical applications, a thermal response test (TRT) [3] allows in situ measurements of the ground thermal properties. However, The prohibitive cost of a TRT remains an issue that prevents its widespread use.

During a TRT, the fluid circulating in a GHE is heated at a constant rate and the evolution of its temperature is monitored by a TRT unit, as shown in Fig. 1. As the fluid temperature rise is mostly function of the ground thermal conductivity, borehole equivalent thermal resistance, and heating power, interpreting the results of a TRT provides readily the required design parameters. The prevailing interpretation technique relies on the first-order approximation of the infinite line-source model [4]. Under the assumption of a constant heating power, a linear regression model is fitted to the late temperature measurements to estimate the mean time derivative of the temperature and deduct the thermal conductivity and borehole equivalent resistance.

The first-order approximation made to linearize the infinite line-source model requires to neglect the early measurements for the interpretation, which leads to a TRT duration of 36–72 h. As pointed out recently [5], TRT duration has been a controversial subject in the past. Indeed, TRT suppliers must provide accurate test results while being competitive enough to justify the additional cost associated with the

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E-mail address: philippe.pasquier@polymtl.ca.

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Nomenclature

Symbols

a	Nuttall coefficient [–]
α	thermal diffusivity [$\mathrm{m^2\ s^{-1}}$]
c	specific heat capacity [$\mathrm{J\ kg^{-1}\ K^{-1}}$]
C	volumetric heat capacity [$\mathrm{J\ m^{-3}\ K^{-1}}$]
D	distance between a pipe and the borehole centre [m]
γ	Euler number [–]
H	borehole length [m]
k	thermal conductivity [$\mathrm{W\ m^{-1}\ K^{-1}}$]
n	number of time steps or nodes [–]
N	window length [–]
q	normalized heating power [W/m]
R	thermal resistance [$\mathrm{mK\ W^{-1}}$ *or* $\mathrm{K\ W^{-1}}$]
r	radius [m]
ρ	density [$\mathrm{kg/m^3}$]
t	time [s]
$\tilde{t}$	heating phase duration [s]
T	temperature [K]
$\dot{T}$	time derivative of the temperature [$\mathrm{K\ s^{-1}}$]
$\dot{V}$	circulation flow rate in a pipe [$\mathrm{m^3\ s^{-1}}$]
w	Nuttall filter [–]

Subscripts

b	borehole
c	critical
f	fluid
g	grout
k	time index
n	neighbor
p	pipe material
r	residence
s	soil
t	time
0	initial condition

Acronyms

FOA	first-order approximation
GHE	ground heat exchanger
ILSM	infinite line-source model
MGT	maximum gradient technique
TNP	thermal needle probe
TRCM	thermal resistance and capacity model
TRT	thermal response test

realization of a TRT. Since reducing TRT duration might help reduce costs and the risks of test interruption due to generator failure, temporary power outage, vandalism, or fluid leakage, reducing the duration of a TRT while providing reliable estimates is still an important issue [6,7] and an area of active research [8–12].

Thus far, the interpretation of a TRT is based only on the temperature measurements. However, since the development of the first transient needle probes (TNPs) in the 1950s [13–17], the time derivative of the temperature has been used. As soon as 1950, Hooper and Lepper [13] were already using the temperature derivative to compensate for the finite diameter of the TNP and improve the thermal conductivity obtained. In the 1970s, the *source differentiation technique* [18], also called *maximum gradient technique* [19,20], was developed to reduce TNP test duration. In this approach, the temperature is differentiated with respect to time and the thermal conductivity is expressed as a function of the maximum gradient and time at which the maximum temperature change occurs. In other fields such as hydrogeology and reservoir engineering, the hydraulic head/pressure is used jointly with the time derivative to identify the hydraulic parameters and reservoir geometry [21].

Despite its high potential, using the derivative of the temperature to interpret a TRT is difficult owing to the relatively high borehole capacity and long fluid residence time, which deform the temperature signal and hinder the use of the techniques developed for TNPs. The goal of this paper is to present and validate experimentally four new first-order approximation models using the measured time derivatives of fluid temperature to interpret the first hours of the heating and recovery phases of a TRT and to compare the thermal conductivity obtained with the values given by other interpretation models.

The methodological approach followed in this work involves deriving analytically a simple interpretation model to illustrate the rationale behind the new first-order approximations proposed in this work (Section 2). The third section presents briefly a thermal resistance and capacity model and the program *TRT-SInterp*, which is devoted to TRT interpretation by optimization. The latter is used to provide a reference value to compare the various interpretation models proposed. Then, to identify the possible limitations of the new interpretation models, Section 4 investigates the evolution of the time derivative for various borehole equivalent resistance. The time derivative being sensitive to experimental noise and artifacts, Section 5 presents strategies for its robust assessment using signal processing techniques. Finally, five data sets obtained from two numerical and three real TRTs are used in Section 6 to illustrate the potential of derivative-based methods. It is shown that using the time derivative of the temperature can provide a reliable estimation of the ground thermal conductivity using only the measurements made during the first hours of a TRT. This work shows for the first time the potential of the temperature derivative to interpret TRTs and also identifies new research avenues for TRT interpretation.

2. A simple illustration with the infinite line-source model

To illustrate simply how the time derivative can be useful for interpreting the first few hours of a TRT, the infinite line-source model (ILSM) [4] is used to describe the temporal evolution of the ground temperature along the borehole wall. Using the ILSM and the superposition principle to account for variations in the heating power, the mean fluid temperature is given by

$$T_f(t) = T_0 + qR_b + \sum_{i=1}^{n_t} \frac{q_i - q_{i-1}}{4\pi k_s} \int_x^{\infty} \frac{e^{-u}}{u} du \tag{1}$$

where T_0 is the undisturbed ground temperature, q is the normalized heating power, R_b is the equivalent borehole resistance, r_b is the borehole radius, n_t is the number of time steps, $x = r_b^2/(4\alpha(t - t_{i-1}))$, and k_s and α are the thermal conductivity and diffusivity, respectively. It is worth noting that the integral in Eq. (1) is the exponential integral function, which has the following convergent power series [22]:

$$\int_x^{\infty} \frac{e^{-u}}{u} du = \ln\left(\frac{1}{x}\right) - \gamma + \sum_{k=1}^{\infty} \frac{(-1)^{k+1} x^k}{k\, k!} \tag{2}$$

with $\gamma = 0.577215...$, the Euler constant. For a typical TRT and GHE, the mean fluid temperature provided by Eq. (1) during the heating and recovery phases is illustrated in Fig. 2a.