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Inverse heat transfer applied to a hydrogeological and thermal response test for geothermal applications

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ABSTRACT

Actual thermal response tests, used to estimate the subsurface thermal conductivity in the geothermal domain, do not provide any estimate on the velocity of the groundwater flow and its orientation. These parameters are important for sizing geothermal borefield, since they influence the heat transfer around a geothermal borehole and the surrounding ground. To correct this shortcoming, a conceptual test has been developed in which heating cable sections inject heat in a borehole. Three temperature probes are strategically located at the borehole edge. This paper applies inverse heat transfer strategies to this thermal response test concept in order to identify the ground thermal conductivity, as well as the groundwater flow velocity and its direction. The suggested thermal response test and parameters estimation methodology are detailed. The influence of initial guessed values for the three unknown parameters was also studied. The work presented in this paper was carried out by numerical simulations.

1. Introduction

Since ground-coupled heat pump (GCHP) systems have a lower environmental impact and higher energy efficiency than conventional heating and cooling systems, the demand for GCHP has expanded greatly during the last decades. In Canada, the utilization of geothermal energy has grown from 3000 TJ in 2003 to 11 000 TJ in 2013 [1]. GCHP systems combine heat pumps with ground heat exchangers (GHE). Because the rate of exchange between a GHE and undisturbed ground depends on the thermal properties of the ground, such as the thermal conductivity, the undisturbed ground temperature and its thermal diffusivity, a proper design of GHEs asks for the knowledge of these properties. In situ thermal response tests (TRTs) are used to measure the subsurface thermal properties. The transient evolution of the temperature of heated water circulating in a GHE is measured at the inlet and outlet of a trial GHE. With proper models, it is possible to deduce the ground thermal properties from this test [2–4].

As it is simple to use and provides good estimates, the analytical line-source model, based on Kelvin's line-source equation [5], represents the common choice of model to evaluate the ground thermal conductivity. However, many assumptions are made when using the line-source model, such as a homogeneous and isotropic ground, and a heat transfer from the borehole that is entirely conductive and purely radial. In practice, these hypothesis are not necessarily true, depending on the geological materials where the TRT is executed. Water located in a saturated aquifer can move through ground pores and generate a flow motion. If the mean velocity of this flow is relatively high, it will affect the heat transfer between the ground and the borehole. This usually does not affect too much the results of the TRT (i.e., measurement of conductivity) as the effect of advection is usually observed after a relatively long time. However, it would be necessary to know the groundwater flow velocity and direction in order to design the GHEs properly. Consequently, results derived from conventional TRT can be incomplete, even inaccurate, when there is groundwater flow around the boreholes [3,6,7]. While some models allow correcting the data read by standard TRTs to account for groundwater flows [8–10], these tests were not designed to yield significant information on groundwater flow.

The impact of groundwater flow on the performance of geothermal borefields has been studied over the last years [11–13]. Advection enhances heat transfer between the GHE and the subsurface, which means that shorter GHEs are needed to provide the same performance when there is groundwater flow – geothermal borefield designing models must therefore consider groundwater

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Nomenclature

B	Borehole spacing [m]
CF	Correction factor [−]
Fo	Fourier number [−]
M	Number of temperature sensors [−]
N	Number of boreholes [−]
P	Pressure [Pa]
$\vec{P}$	Parameters vector
Pe	Peclet number [−]
R	Thermal resistance [mK/W]
S	Ordinary least squares norm
T	Temperature [K, °C]
Y	Measured temperature [K, °C]
$\vec{a}$	Non-dimensional velocity vector field [−]
c_p	Thermal capacity [J/kg K]
k	Thermal conductivity [W/mK]
q	Pulse [kW]
q'_0	Borehole heat transfer rate per unit length [W/m]
r	Radial coordinate [m]
t	Time [s]
u	Velocity [m/s]
x, y	Cartesian coordinates [m]

Greek symbols

α	Thermal diffusivity, [m^2/s]
θ	Relative temperature $T - T_g$, [K, °C]
χ	Ratio of volumetric thermal capacities [−]
κ	Ground permeability [m^2]
μ	Dynamic viscosity [[$Pa \cdot s$]]
ρ	Density [kg/m^3]
η	Ground porosity [−]
τ	Pulse time, [year, month, hour]
ϕ	Flow orientation [°]
ω	Random variables [−]
σ	Standard deviation of the measurement errors [K, °C]

Subscripts

b	Borehole
c	Critical
cs	close sensor
D	Darcy
eff	Effective
f	Fluid
fs	far sensor
g	Undisturbed ground
H	Heating
h	Hourly pulse
i	inside
m	Monthly pulse, mean
o	outside
p	Measurement point
rb	Relative to borehole radius
s	Solid
w	Water
y	Yearly pulse

Symbols

~	Non-dimensional

flows. In recent work, it has been demonstrated that with a moderate flow velocity, neglecting groundwater flow in design procedure can induce an overdesign of the borefield that can go up to 68% [14]. The direction of the flow is also an important parameter that can influence the optimal GHE layout [15]. Determining such parameters usually requires hydrogeological tests which might be prohibitive in terms of time and cost. Hence, there is a call for developing a combined hydrogeological and thermal test to acquire all the required estimates of ground properties in a single operation.

A concept of combined hydro-thermal response tests (H/TRT) has been proposed in Ref. [16]. This H/TRT is based on the work of Raymond et al. [17–19], using heating cable placed in a borehole to inject heat in the subsurface. With multiple temperature probes positioned in a horizontal plane around the cable, it is possible to find the thermal influence of groundwater flow and calculate its velocity and orientation. In a similar setup, Fic proved that the Darcy velocity of groundwater flow can be estimated from multiple temperature measurements as long as there is a nonzero horizontal temperature gradient in the ground [20].

Evaluating ground thermal conductivity from TRT data represents a typical example of inverse heat transfer problem (IHTP) [21]. This category of problems is usually solved by minimizing an error function between measurements and predictions of a model. The solution to inverse problems such as that of a TRT can depend on initial guess for each parameter, measurement uncertainties, control and placement of the heat source and temperature probes, power input for the source, etc. Moreover, using these techniques to estimate multiple parameters might prove to be difficult [22].

The purpose of this paper is to study the possibility of applying an inverse heat transfer method to an H/TRT. A parameter estimation methodology that determines thermal conductivity and groundwater flow parameters is presented. The concept, which is still at a theoretical stage, is tested with a numerical model. The performance of the methodology is investigated as a function of the estimation of the flow orientation, the initial guess of thermal conductivity and flow velocity used by the algorithm, the heat generation rate of the source and the measurements uncertainties.

2. H/TRT modeling

2.1. H/TRT set-up

The proposed concept of TRT is adapted from [16], which is based on Refs. [17–19]. A heating cable is placed in a borehole to inject heat in the subsurface. The test is performed in a borehole before it is filled with grout. As will be detailed below, it is assumed that a casing is present in the section of the borehole where the test is performed, which means that there is no risk of collapsing during the test. Fixed on the edge of the borehole, temperature sensors are then used to measure the evolution of the temperature in the borehole. The proposed setup is sketched in Fig. 1. Since the heat plume generated by the source will move towards the direction of the groundwater flow, a horizontal temperature gradient is created in and around the borehole. Each sensor will then monitor different temperature evolutions. An efficient analysis of these variations can potentially lead to an evaluation of the groundwater flow parameters, along with the ground thermal conductivity. However, it should be noted that the measurement of thermal and hydraulic properties from this concept only provides localized observations