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Interpretation of ongoing thermal response tests of vertical (BHE) borehole heat exchangers with predictive uncertainty based stopping criterion

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A B S T R A C T

This paper presents a method for analyzing and establishing a stopping criterion for ongoing (TRT) thermal response tests of vertical (BHE) borehole heat exchangers. The predictive uncertainty of the late-time BHE fluid temperature (50 h) forms the basis for determining the time after which further temperature measurements do not significantly improve the calibration of the numerical borehole model. The method relies solely on measured fluid temperatures and can, in principle, be generalized to different BHE geometries and configurations. The method is applied to synthetic and actual TRTs of single and double U BHEs. Predictive uncertainty of the late-time fluid temperature is comparable to measurement uncertainty after 12–28 h of testing at which reliable estimates of soil thermal conductivity and borehole thermal resistance are obtained. Minimum testing times are found to scale with borehole thermal resistance in the synthetic tests. It is further demonstrated that for actual tests, ambient thermal disturbances bias estimates of soil thermal conductivity and inflate predictive uncertainty which increases minimum testing times. The method serves as a diagnostic tool for ongoing TRTs as well as a means to minimize testing times which has potential implications for the associated cost and logistics of field operations.

1. Introduction

The exploitation of shallow geothermal energy has increased globally within recent decades in the pursuit of sustainable, low carbon emission energy sources [1]. In the evaluation of shallow, borehole-based geothermal energy systems, (TRT) thermal response testing of vertical (BHE) borehole heat exchangers is a widely used field method for estimating soil thermal conductivity and borehole thermal resistance. In the TRT, the BHE carrier fluid is circulated at a specified rate while being continuously warmed by a heater. Heat dissipates to the borehole and subsequently the ground and records of the fluid inlet- and outlet temperature and the fluid flow rate are compiled during the test. In the standard method of interpretation, the radial and temporal temperature response depends on the borehole thermal resistance, ground thermal diffusivity and the supplied heating power and is modelled by an infinite line source in an infinite medium [2]. The line source model does not accurately capture the borehole thermal dynamics at early times and minimum testing time depends on ground thermal diffusivity and the radius of the borehole [3]. The simplification of the borehole in the line source model implies rather long, minimum testing times. In Germany and Spain, it is common practice to carry out 72 h thermal response tests however the recommended testing time is 48 h when the interpretation is based on the line source model as suggested by ASHRAE [4].

In recent years, research has been focused on improving the short-time description of the borehole thermal dynamics by the development of analytical and numerical solutions to the heat conduction equation with cylindrical, vertical and angular contrasts in the thermal parameters (e.g. Refs. [5–10]). [11] provide an extensive review of forward modeling approaches that can be applied in thermal response test analysis and they provide a comprehensive list of literature references. The minimum testing time is potentially reduced when the early-time borehole thermal dynamics are accurately captured by the borehole model. Obviously, the test duration has potential implications for the rate at which consecutive TRTs can be carried out, the running costs of field operations and the likelihood of completing a successful test.

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[12] and [13] present an improved thermal response test method in which a fixed and relatively high inlet temperature is maintained throughout the test, increasing the dissipation of heat in the borehole which potentially reduces testing times. The improved thermal response test, in terms of testing times, makes use of customized equipment which potentially implies higher costs. [14] estimated the required testing time for applying the line source model in the interpretation of a series of completed TRTs to be in the interval 5–21 h by utilizing an analytical composite thermal resistance model. The method requires that soil thermal conductivity is known beforehand and, as such, it cannot be used for evaluating a test in progress. It is therefore relevant to define a stopping criterion that can be evaluated on the basis of measured fluid temperatures, as the TRT progresses, in order to minimize testing times. This has not been done in previous literature.

The thermal response test equipment at VIA University College, Horsens, Denmark can be equipped with a 3G mobile network device that facilitates online monitoring of ongoing TRTs. Real-time data acquisition allows the engineer to verify that the test is being executed correctly and to quickly identify test disruption caused by e.g. power outage. Equally important, real time data acquisition facilitates analysis of ongoing tests. In this paper, we outline a method for analyzing ongoing TRTs and we establish a stopping criterion that can be evaluated as the test progresses. The stopping criterion is defined by the time after which the uncertainty associated with the model prediction of the fluid temperature at 50 h (line source based reference test duration) is reduced to a level comparable to the measurement noise (in the order of ±0.05 °C). At this time, the predicted outcome of the test, in terms of fluid temperatures, is as certain, in a statistical sense, as corresponding fluid temperature measurements after 50 h of testing. The method relies solely on observed fluid temperatures and makes no assumptions other than those of the forward borehole model. The forward response in the parameter estimation is calculated with a numerical composite thermal resistance model. The parameter estimation is done by inversion modelling of observed fluid temperatures in which the discrepancy between model and observed fluid temperatures is minimized in a least-squares sense.

The paper is organized as follows. Firstly, the borehole model, calibration procedure and the predictive uncertainty based stopping criterion are described in the Methods section. Secondly, the test site at VIA University College, Horsens, Denmark and the actual TRTs are presented briefly. A description of the synthetic tests that form the basis for the conceptual demonstration of the method is given. The method is then applied to six sets of synthetic thermal response data, one experimental TRT [16] and three tests of experimental BHEs at the VIA Energy Park at VIA University College, Horsens, Denmark. Finally, the results are discussed and conclusions are drawn.

2. Methods

2.1. Borehole model

The fluid temperature response is calculated with a numerical, composite thermal resistance model (the (EP) equivalent pipe model, see Ref. [15]). The EP model is identical to the borehole model presented in Ref. [5]. [16] utilized a similar analytical borehole model to interpret thermal response test data from a sand box experiment (see Fig. 13 p. 83 in Ref. [16]). Other studies who utilize the EP model for analyzing TRTs include [17,18].

In the EP model, the BHE piping is approximated by a single equivalent pipe with radius r_e in order to preserve radial symmetry (Fig. 1).

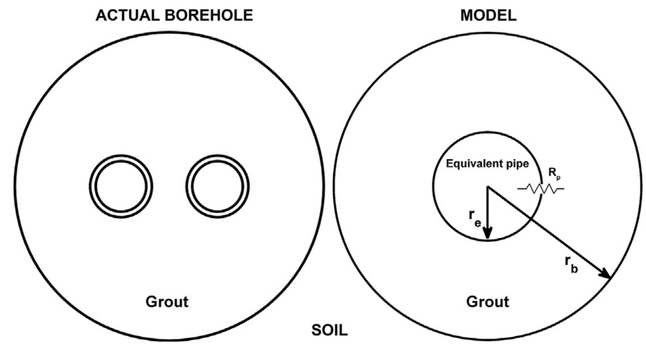

Fig. 1. The actual borehole exemplified with a single-U BHE and the equivalent pipe borehole model.

The equivalent pipe has volumetric heat capacity $(\rho c)_{eq}$ [J/m^3/K] and the thermal gradient in the pipe is zero. The equivalent pipe is heated by a time-varying heat source, in accordance with the heat rate applied during the TRT. R_p [Km/W] is the combined convective and conductive thermal resistance of the fluid and the pipes. The grout has thermal conductivity and volumetric heat capacity λ_g [W/m/K] and $(\rho c)_g$, respectively. The soil has thermal conductivity and volumetric heat capacity λ_s and $(\rho c)_s$, respectively. The borehole radius is r_b. Mathematically, the radial heat conduction in the grout and the soil reads:

$$\frac{1}{\alpha(r)}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}; \quad \alpha(r) = \begin{cases} \alpha_g, & r_e < r < r_b \\ \alpha_s, & r > r_b \end{cases} \tag{1}$$

α_g and α_s are the thermal diffusivities of the grout and soil, respectively [m^2/s]; T is the temperature [K]; t is time [s] and; r [m] is the radial distance from the borehole center. Vertical heat conduction during the TRT is ignored in Eq. (1). This assumption is valid for borehole lengths down to at least 40 m as demonstrated by Ref. [20] pp. 152–154.

Equation (1) is solved numerically by a second-order Crank-Nicolson finite difference scheme. The corresponding explicit finite difference formulation is described in detail in Ref. [15]. Model tests were made to ensure that modelled temperatures are independent of the chosen level of temporal and spatial discretization.

The model domain terminates radially at distance r_∞ in a zero-gradient (no-flow) boundary condition:

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = r_\infty \tag{2}$$

The distance to the model boundary is chosen so that the radial heat flow at r_∞ is negligible. Based on the line source model, the number of model annuli in the soil N_s required for satisfying the assumption in Eq. (2) is given by Eq. (2.61) in Ref. [15]:

$$N_s = 1 + int\left[\frac{\lambda_g}{\Delta u \cdot \lambda_s} \cdot ln\left(\frac{\sqrt{p_{max} \cdot 4 \cdot \alpha_s \cdot t_{max}}}{r_b}\right)\right] \tag{3}$$

int[…] denotes the integer part of the expression in the parenthesis, Δu is the dimensionless model annuli width (see Eq. (2.61) in Ref. [15]); p_{max} is a number to be set and t_{max} is the simulated time i.e. the duration of the test [15]. sets $p_{max} = 4$ for which heat flow at r_∞ is less than 2% of the injected heat throughout the test. The explicit numerical solution of is then compared to the corresponding analytical solution for a domain that extends to infinity in the radial direction (p. 17, [15]). [15] found maximum deviations between the numerical and analytical solutions to be 0.004 °C. To further investigate the degree to which Eq. (2) is