Renewable Energy 85 (2016) 306–318

Contents lists available at ScienceDirect

Renewable Energy

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

Effect of disturbance on thermal response test, part 1: Development of disturbance analytical model, parametric study, and sensitivity analysis

Wonjun Choi [a,*], Ryozo Ooka [b]

[a] Department of Architecture, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[b] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
1 June 2015
Accepted 16 June 2015
Available online 2 July 2015

Keywords:
Ground-source heat pump (GSHP)
Thermal response test (TRT)
Experimental disturbance
Parametric study
Sensitivity analysis

ABSTRACT

To interpret thermal response tests (TRTs), analytical models that assume constant heat flux from the source are widely used because of their simplicity. However, in actual field conditions, the constant heat flux assumption is violated by the heat exchange between the above-ground TRT setup and outdoor environment. This results in perturbations in the temperature response and causes fluctuations in estimation and consequent estimation errors in the interpretation of TRTs. For a better design of experiments and obtaining quality data from a TRT, a systematic analysis of the disturbance factors is important. In this study, we developed an analytical model that describes the heat exchange in an above-ground TRT setup. On the basis of this model, a parametric study and sensitivity analysis were conducted in a systematic manner using disturbance-related parameters, such as test settings (heat injection rate and flow rate), above-ground connecting circuit parameters (insulation thickness, length, and radiation absorptivity), temperature of fluid, and weather conditions (solar irradiation, environmental temperature, and wind velocity). The above-ground circuit length and parameters related to radiative heat transfer showed the highest sensitivity coefficients. Based on the results, some suggestions are provided for experimenters on designing TRT setups and conducting TRTs to obtain quality data.

1. Introduction

For economical and reliable design of ground-source heat pumps (GSHPs), accurate parameter estimation from a thermal response test (TRT) is important. For the design of large-scale borefields, in particular, the accuracy of estimations of thermal conductivity and borehole thermal resistance has a great impact. A TRT can be interpreted by a regression method using analytical models or a numerical model combined with a parameter estimation technique. Among them, one of the most used methods is linear regression using the infinite line source (ILS) model [1] because it is simple and easy to use. It becomes more attractive when combined with the sequential plot method [2,3] because the estimation behavior and the convergence of the test can be known.

As boundary conditions, the ILS model assumes an adiabatic condition on the ground surface and a constant heat flux from the heat source. The infinite cylindrical source (ICS) model [4] also assumes the same boundary conditions. However, in reality, these assumptions are violated in most cases. Regarding the adiabatic surface condition, the assumption is violated by the heat exchange between the ground surface and atmosphere. The effect of heat flux from the ground surface would be small for a TRT of a relatively long vertical borehole heat exchanger (BHE). The assumption of constant heat flux from the source is violated because of voltage fluctuation from the power grid and heat exchange between the above-ground hydraulic circuit, which connects the TRT rig and BHE loop, and the outdoor environment.

The sequential plot method is very vulnerable to disturbance effects. In the early-period estimation, the disturbed temperature response often shows considerable fluctuation in estimation behavior. For stable estimation using the ILS model, some studies have approached the problem from mechanical and numerical perspectives [5–7]. Witte et al. [5] developed a TRT apparatus equipped with a water-to-air heat pump and a control system to maintain a constant temperature difference and flow rate. This setup allowed a sufficiently constant heat transfer rate to the

* Corresponding author.
E-mail address: wonjun@iis.u-tokyo.ac.jp (W. Choi).

http://dx.doi.org/10.1016/j.renene.2015.06.042
0960-1481/

Nomenclature

a_{ins}	radiation absorptivity of pipe insulation's surface
c	specific heat capacity [J/(kg K)]
f	friction coefficient
F_{cor}	correction factor for sol-air temperature
h_i	convective heat transfer coefficient of pipe inner surface [W/(m^2 K)]
h_o	overall heat transfer coefficient of outer surface [W/(m^2 K)]
H	length of borehole heat exchanger [m]
I_{sol}	global solar irradiation [W/m^2]
l	location on the connecting hydraulic circuit
L	half-length of the above-ground hydraulic circuit [m]
Nu	Nusselt number
P_i	i-th parameter
Pr	Prandtl number
q	heat injection rate per unit length of BHE [W/m]
Q	heat exchange rate between the circulating fluid and the outdoor environment [W]
Q_{amb}	heat exchange rate between the circulating fluid and the outdoor environment by convection and conduction [W]
Q_{BHE}	actual heat injection rate to the BHE [W]
Q_d	disturbed heat rate between the circulating fluid and the outdoor environment [W]
Q_{rig}	generated heat from heater (Q_{heater}) and pump (Q_{pump}) in the TRT rig [W]
r	radius [m]
R	thermal resistance [m K/W]
R_{tot}	overall thermal resistance [m K/W]
ΔR	difference between longwave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature [W/m^2]
Re	Reynolds number
t	elapsed time after the heat injection [s]
T	temperature [°C]
T_{env}	environmental temperature (T_{amb} or $T_{sol,a}$) [°C]
$T_{sol,a}$	sol-air temperature [°C]
v_w	wind velocity [m/s]
$\dot{V}$	volumetric flow rate [m^3/s]
z	altitude, height above ground [m]

Subscripts

amb	ambient air
BHE	borehole heat exchanger
c	convective
cf	circulating fluid
i	inner
in	inflow circuit (from outlet of TRT rig to BHE inlet)
ins	insulation
m	measured site
o	outer
out	outflow circuit (from BHE outlet to inlet of TRT rig)
p	pipe
rad	radiation
rig	TRT rig
surr	surroundings
tot	total

Greek letters

α	exponent of power law
ε	emissivity of surface
κ	non-dimensional parameter
λ	thermal conductivity [W/(m K)]
μ	dynamic viscosity [kg/(m s)]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	Stefan–Boltzmann constant [W/(m^2 K^4)]
τ	thickness [m]

Acronyms, abbreviations

ICS	infinite cylindrical source model
ILS	infinite line source model
Int-day	daytime of intermediate season
Int-night	nighttime of intermediate season
RSC	relative sensitivity coefficient
RSC_{max}	maximum relative sensitivity coefficient of each season
RSC^*	normalized relative sensitivity coefficient
SC	sensitivity coefficient
Sum-day	daytime of summer
Sum-night	nighttime of summer
TRT	thermal response test
Win-day	daytime of winter
Win-night	nighttime of winter

ground, thus resulting in a very stable estimation behavior. Some research groups [6,7] tried to correct disturbed heat injection rate by the inverse estimation of heat exchange rate from the outdoor environment. Their results showed a reduced difference between the measured and predicted fluid temperatures [7] and attenuated the oscillation amplitude of the sequential plot to some extent [6]. However, the effect of disturbance was still noticeable because voltage fluctuation and radiative heat transfer were not considered.

To consider the variable heat rate, some other methods are used. For example, recursive curve matching estimation using a temporal superposition-applied analytical model [8–14] and estimation using a numerical model combined with the parameter estimation technique [5,15–22] were successfully employed to account for the variable heat rate in a TRT. Although a more accurate estimation than that using analytical models based on the averaged heat rate can be expected by use of these methods, they require more time and effort for the estimation. Moreover, care should be taken when using the curve matching procedure employing superposition-applied analytical models because the estimation behavior cannot be known. It can overlook or miss some important subsurface conditions, such as groundwater flow and natural convection. As an alternative, the authors of the present study [23] suggested an interpretation method that combined the superposition-applied ILS model and gradient-based parameter estimation technique. This method provides the estimation behavior with consideration of the disturbance effect; the results obtained with this method demonstrated fast convergence and stable estimation behavior.

As mentioned previously, many studies have considered the disturbed TRT data. However, before considering the disturbed variable heat rate, consideration must be given to how an experimenter can obtain quality data, i.e., data that can be interpreted using an analytical model that assumes constant heat flux. In other words, insights into the factors that affect the quality of TRT data and the extent of their influence are important. In this respect, a systematic analysis of disturbance effects in TRTs is necessary. Because most TRTs, except for special-purpose experiments