Energy & Buildings 180 (2018) 109–121

Contents lists available at ScienceDirect

Energy & Buildings

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

New perspectives in thermal performance test: Cost-effective apparatus and extended data analysis

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ARTICLE INFO

Article history:
Received 16 March 2018
Revised 29 May 2018
Accepted 5 August 2018
Available online 10 August 2018

Keywords:
Thermal performance test (TPT)
Thermal response test (TRT)
Ground-source heat pump (GSHP)
Ground heat exchanger
Bayesian inference
Unit heat exchange rate
GSHP design parameter estimation
Energy pile

ABSTRACT

Two different experimental methods, namely thermal response test (TRT) and thermal performance test (TPT), have been used in the field of ground-source heat pumps (GSHPs) for different purposes. TRT is a well-established method for estimating the design parameters of ground heat exchangers (GHEs), whereas TPT has recently been adopted to examine the thermal performance of newly developed GHEs. Although both methods provide important information, they are rarely performed together because they require different experimental apparatus. To overcome this limitation, we developed a cost-effective TPT apparatus by adding a general proportional-integral-derivative (PID) controller and a solid-state relay to an existing TRT apparatus without a hot water tank. The apparatus showed sufficiently fast and accurate controllability: when the setpoint was 25 °C, the rise time was ~7 min from the initial temperature of 16.9 °C, and the steady-state error was within ~±0.1 °C. Two TPTs were conducted using the developed apparatus and a 50 m-long borehole heat exchanger with two different setpoints of 30 °C and 40 °C. We applied a Bayesian inference technique using the infinite line source model as a forward model to extend the TPT data to the estimation of the GSHP design parameters. Thus, the information usually obtained from independent TPT and TRT can be obtained using a single TPT. Moreover, a new index, namely, the unit heat exchange rate, was defined to facilitate a comparison among TPT results obtained under different TPT setpoints, GHE configurations, and ground conditions.

1. Introduction

According to the International Energy Agency, the energy used by the building sector accounts for 35% of the global energy use [1]. Furthermore, the energy consumed by heating, ventilation, and air conditioning (HVAC) and domestic hot water systems accounts for approximately 60% of the energy use in the building sector. Thus, introducing renewable energy to energy systems in buildings could have a significant impact on enhancing the efficiency of system operation and reducing energy use in the building sector. In this regard, a ground-source heat pump (GSHP) is advantageous compared to a conventional air-source heat pump. Nevertheless, the high initial installation cost of a GSHP prevents its widespread use. Given the long service life of a building and its associated energy systems, introducing a GSHP is advantageous considering its low operating costs. However, building owners sometimes prefer the conventional system, as do plant engineers, because there is uncertainty as to whether the life cycle cost will be minimized by the implementation of a GSHP, which stems from the uncertainty in the GSHP design process. Therefore, excessive supplementary heat sources are sometimes employed to eliminate the uncertainty caused by GSHP introduction, or the system is over-designed by applying a large safety factor.

A number of studies were conducted to improve the design accuracy. The general process of the GSHP design involves two steps: (1) field information collection of hydro-thermal properties of the ground via soil sampling, pumping test, or thermal response test (TRT) and (2) design of a ground heat exchanger (GHE) with design parameters obtained from TRT. TRT is recognized as an industry standard for estimating the parameters required for sizing GHEs [2–4]. Because of the significant impact of the GHE design parameters on the initial cost of GSHP, many studies investigated ways to enhance the accuracy of TRT results (e.g., overcoming the limitations of the conventional constant heat rate experimental method and estimation method [5–7], which uses the approximated infinite line source (ILS) model [8–11], assessment of estimation uncertainty [12–15], and development of a new TRT method [16–19] and new parameter estimation method [7,20–23]).

In addition, many studies investigated design methods aside from TRT. They are specifically related to the reliability of the design method. A representative design method is the ASHRAE

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https://doi.org/10.1016/j.enbuild.2018.08.008
0378-7788/

Nomenclature

c	specific heat (J/(kg·K))
C	volumetric heat capacity (J/(m^3·K))
E	expectation
Ei	exponential integral
F	mean temperature of forward model (°C)
H	length of GHE (m)
p	probability distribution
$\mathbf{P}$	parameter vector
$\widehat{\mathbf{P}}_{\mathrm{PM}}$	estimated parameters using posterior mean
q	heat rate per unit length of GHE (W/m)
q_u	unit heat exchange rate per unit length of GHE (W/(m·K))
q_u^*	dimensionless q_u, $q_u^* = q_u/\lambda_{eff}$
Q_u	unit heat exchange rate (W/K)
Q_{GHE}	heat exchange (injection) rate (W)
Q_1, Q_3	first and third quartiles of probability distribution
r_σ	error ratio between measured and modeled temperatures
r_b	radius of borehole (m)
R_b	borehole thermal resistance (m·K/W)
t	time or elapsed time after heat injection (s)
T_f	temperature of circulating fluid (°C)
$\bar{T}_f$	mean fluid temperature (°C)
T_0	initial ground temperature (°C)
v	variance
$\dot{V}$	volumetric flow rate (m^3/s or l/min)
Y	measured mean temperature for inference, $Y = \bar{T}_f$ (°C)

Subscripts

in	inlet
n	time step or data number
N	total number of time steps or final time step
out	outlet
pred	prediction
s	soil or ground
set	setpoint

Greek letters

ε_c	absolute control error, $\varepsilon_c = \lvert T_{f,in} - T_{f,set}\rvert$ (°C)
λ_{eff}	effective thermal conductivity (W/(m·K))
ρ	density (kg/m^3)
σ	standard deviation or error
σ_F	error of modeled temperature (°C)
σ_Y	error of measured temperature (°C)
$\mathcal{N}$	normal distribution
$\Re$	parameter space

Acronyms, abbreviations

BHE	borehole heat exchanger
CI	credible interval
GHE	ground heat exchanger
GSHP	ground-source heat pump
ILS	infinite line source
MCMC	Markov chain Monte Carlo
PID	proportional-integral-derivative
PM	posterior mean
PPDF	posterior probability density function
SSR	solid-state relay
TPT	thermal performance test
Tri	triangular distribution
TRT	thermal response test

method [24–26]. An iterative simulation-based method using the g-function [27] is also widely adopted. Important research topics related to the design method are how to make the response function more accurate [28–35], how to accurately consider the thermal interaction among GHEs [36,37], and how to simplify the sizing process [38–40]. However, efforts devoted to TRT and design methods cannot drastically reduce the drilling cost, which accounts for the largest proportion of the installation cost of a vertical closed-loop GHE (i.e., the so-called borehole heat exchanger (BHE)).

An energy pile that combines the foundation pile supporting the building structure and the heat exchange pipes has recently been introduced to reduce the drilling cost. Compared to the conventional BHE, which usually has a diameter of 100–200 mm, the energy pile has a larger diameter that provides geometrical freedom for the heat exchanger configuration. Thus, energy piles with multiple U-tubes, W shape, and helical-type heat exchangers were proposed. In addition to the different geometries, the filling material of the energy pile is a high-strength concrete, whose thermo-mechanical properties differ from those of the conventional backfill or grouting material of the BHE. Energy piles exhibit different thermal performances and behaviors compared to a conventional BHE because of these differences in shape and material.

Therefore, the actual heat exchange rate of an installed energy pile must be examined because the geometrical complexity increases the uncertainty in the construction quality, while unconventional material properties cause the thermal performance and behavior to differ from those of a conventional BHE. In this context, a thermal performance test (TPT) was implemented to examine and compare the thermal performance of newly developed energy piles [41–55]. Unlike a TRT, which usually has a constant heat rate as an experimental condition, a TPT keeps the GHE's inlet temperature constant by controlling the power rate of heaters. Therefore, the configuration of the TPT apparatus differs from that of the TRT apparatus. Researchers stated that the TPT apparatus requires a hot water tank as a thermal buffer and complex control logic for the temperature control, which is why the TPT apparatus is more expensive than the TRT apparatus [41–43,45]. Although the information from both TPT and TRT facilitates a reliable design, it is generally not feasible to conduct both experiments together because of the time and cost associated with the requirement for two different experimental apparatus. Therefore, in most cases, only TRT is conducted to obtain the GSHP design parameters (i.e., effective ground thermal conductivity and borehole thermal resistance), but the design uncertainty may increase for new types of GHEs that differ from conventional BHEs.

To address this problem, first, we propose a new cost-effective TPT apparatus. The developed TPT apparatus does not need a hot water tank. It requires only two additional control components compared to a conventional TRT apparatus: a general proportional-integral-derivative (PID) controller and a solid-state relay (SSR). Therefore, if an existing TRT apparatus is used, the additional cost would be approximately USD 400. Although TPT is possible at a very low price, this work proves that the developed apparatus has an excellent control performance. Another advantage of our approach is that a compact portable TPT apparatus can be constructed as reported for the TRT apparatus [56,57] because the proposed TPT apparatus does not require a massive hot water tank.

Using the developed TPT apparatus, two TPTs were conducted utilizing a 50 m-long single U-tube BHE with two different set-points of 30 °C and 40 °C. The obtained TPT datasets were extended to estimate the ground thermal conductivity and borehole thermal resistance. The estimation of the GSHP design parameters using TPT data should be accompanied by a parameter estimation method because the conventional gradient fitting method using the approximated ILS model cannot be used. As a parameter estima-