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Ground heat exchanger design subject to uncertainties arising from thermal response test parameter estimation

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ABSTRACT

This paper presents a new design paradigm of ground heat exchanger (GHE), which takes account of uncertainty in the estimation of geothermal properties, including ground thermal conductivity and borehole thermal resistance from a thermal response test (TRT). Some challenges during the TRT parameter estimation process are discussed: A sensitivity analysis to a more accurate solution of the infinite line source model is introduced to identify the parameters to be estimated; a nonlinear least-square method is employed to estimate the selected parameters; and then validated by a traversing method. Afterwards, a case study is conducted to illustrate how the proposed method can be employed to a practical engineering application. The proposed uncertainty design method that provides a quantified margin of design output can be an alternative to traditional deterministic methods that simply add safety factor to expected design value.

1. Introduction

Ground coupled heat pump (GCHP) systems, as an efficient suppression measure against rising energy prices, attract worldwide interest due to their environmental protection, energy efficiency and being a renewable energy form [1,2]. However, the sizing problem of GCHP systems is a challenging issue for designers because of the complicated ground thermal properties, which is always obtained from a thermal response test (TRT). To properly determine the length of the ground heat exchanger, several methods have been developed, including "rules of thumbs" approach, easy-to-use approach, and software-based approach [3–5].

The "rules of thumbs" approach usually estimates total borehole length according to specified heat injection/extraction rate per unit borehole length, and a prudent value selected by designers may lead to over- or under-designs. Thus this approach might not be suitable when sizing large-scale GCHP systems [6].

Easy-to-use approaches, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) method and the International Ground Source Heat Pump Association (IGSHPA) method, are widely used in practice. The former was proposed by Kavanaugh and Rafferty [7] and updated by Kavanaugh [8], and the full version is described in the ASHRAE Handbook [9]. Based on the infinite cylindrical source model, this method sizes the total length of a GHE according to the monthly building energy needs and the design thermal loads. The latter is based on an infinite line source model and becomes a standard approach to size GHE in North America [10]. This approach utilizes heating/cooling loads in the hottest/coldest month and the BIN method to calculate season performance factor and the energy consumption of system. Based on analytical solutions of simple heat transfer models, both of the two approaches rely mostly on achieving an acceptable level of performance based on a worst case scenario.

Software-based approaches usually compute length of GHEs and the energy consumption of systems by meeting the user-specified minimum inlet temperature of heat pump(s) in winter or maximum inlet temperature of heat pump(s) in summer. As long as the temperature does not exceed the given value after long-time operation, say 10 years, the smallest length satisfying the requirement will be regarded as the simulation output.

There are a number of computer programs available for the GHE or the whole GCHP system design. For example, EED and GLHEPRO uses Eskilson's finite line source model to calculate the length of the borehole, where the temperature response of a cluster of GHEs is converted to a set of non-dimensional temperature response factors, referred as the well-known g-functions [11]. TRNSYS with DST component, developed by Pahud and Hellstrom [12], is the

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Nomenclature

α	thermal diffusivity, $m^2 s^{-1}$
c	specific heat capacity, $J kg^{-1} K^{-1}$
C	volumetric heat capacity, $C = \rho c$, $J m^{-3} K^{-1}$
d	diameter, m
F	shares, operation hours divide total hours of a cooling or heating season
G	volumetric flow rate, $m^3 s^{-1}$
κ	thermal conductivity, $W m^{-1} K^{-1}$
L	length, m
n	number of sets of data
ρ	density, $kg m^{-3}$
Q	thermal load, kW
q_l	heat transfer rate, $W m^{-1}$
r	radius, m
R	thermal resistance, $K m W^{-1}$
τ	time, s
T	temperature, °C
T_{max}	maximum entering temperature of HP
T_{min}	minimum entering temperature of HP
x_j	distance between the jth borehole and the calculated one, m

Abbreviations

GCHP	ground coupled heat pump
GHE	ground heat exchanger
TRT	thermal response test
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
IGSHPA	International Ground Source Heat Pump Association
HVAC	heating, ventilation and air conditioning
EER	energy efficiency ratio in cooling mode
COP	coefficient of performance in heating mode
RMSE	root mean square error
SC	sensitivity coefficient
RSC	relative sensitivity coefficient
PDF	probability density function
CDF	cumulative distribution function
CP	certain parameter
SP	scenario parameter
UP	uncertain parameter

Subscripts

0	initial state
f	fluid
s	soil (ground)
b	borehole
l	length
p	power
sp	short period heat pulse
in	inlet of GHE
out	outlet of GHE
h	heating mode
c	cooling mode

most representative numerical program in the GCHP field, which is capable of conducting whole system simulation, especially in optimizing control strategies [13]. A detailed list of design models for sizing GHE or GCHP system can be found in reference [14].

Literature review reveals that current GHE design methods are predominantly deterministic, providing point estimation over the vertical borehole length under a heating or cooling mode. It, thus, largely overlooks the error and noise inherent in the statistical nature of uncertainties. In order to overcome this limitation, a new GHE system design paradigm under uncertainty is proposed in the paper, focusing on TRT estimation-based uncertainty quantification.

Uncertainty and sensitivity analysis as well as design methods under uncertainty have been extensively applied in many reliability engineering fields [15], but it has just been a baby step toward the building systems domain. These works mostly relate to building design process, such as predicting ventilation strategies [16] or making architectural design choices [17]. A novel methodology based on a simple zone load calculation model was proposed in [18] to study the peak cooling load uncertainty. It offers an alternative framework to heating, ventilation and air conditioning (HVAC) system design field, making it possible to assess the risk associated to each design decision, rather than simply presenting peak loads based on single-case simulations. Soon afterwards, a more detailed HVAC system sizing framework was provided by Sun et al. [19]. These efforts will do help to call widespread attention on HVAC system design under uncertainty.

This paper is organized as follows. Next section presents a detailed description of conventional easy-to-use GHE design method and TRT parameter estimation method. Also the main factors contributing to infinite line source model are identified through a sensitivity analysis, and TRT parameter estimation process is introduced and then validated, where inverse modeling of a more accurate solution of infinite line source model is utilized, together with a nonlinear least-squares method. A general overview of the proposed methodology for analysis under uncertainty is introduced in he Section 3. And Section 4 presents a case study of GHE design under uncertainty. This case study is used to illustrate how the methodology can be applied to a typical design problem. Section 5 is some concluding remarks and proposals for future research.

2. Conventional method of sizing GHE and its challenges

2.1. Conventional method of sizing GHE

Different GHE design methods are introduced in Section 1, easy-to-use approach will be employed. It is true that ASHRAE approach and IGSHPA approach attract a lot of followers in countries that do not have their own GHP regulations [20]. However, the regulatory framework in these countries has already developed at the same pace. China is among one of them. A national standard called *Technical code for ground-source heat pump system* has been established in 2005 and revised in 2009 [21], which origins from IGSHPA approach with some innovative modifications to make it be adapted to the Chinese context. The base of Chinese design method is also the infinite line source model, matching with model used for TRT data evaluation; therefore, we decide to use this underlying model to conduct GHE reliability design under uncertainty.

The core issue of the GHE design is to size the total length of borehole. Conventionally, the total length of borehole is estimated by

$$L_c = \frac{1000Q_c[R_b + R_s \times F_c + R_{sp} \times (1 - F_c)]}{T_{\max} - T_0} \left(\frac{\text{EER} + 1}{\text{EER}}\right) \quad (1)$$

$$L_h = \frac{1000Q_h[R_b + R_s \times F_h + R_{sp} \times (1 - F_h)]}{T_0 - T_{\min}} \left(\frac{\text{COP} - 1}{\text{COP}}\right) \quad (2)$$

To size the length of the GHE, one needs to estimate (1) the peak thermal load of the air-conditioned space, cooling load Q_c and heating load Q_h, the operation shares in the cooling mode F_c and heating mode F_h, maximum and minimum entering temperature of heat pump, T_{max} and T_{min}, and the energy efficiency ratio in cooling mode