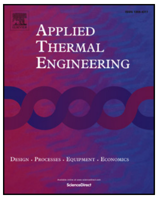
Applied Thermal Engineering 144 (2018) 1030–1036

Contents lists available at ScienceDirect

Applied Thermal Engineering

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



Research Paper

Study on design error of ground source heat pump system and its influencing factors

Zongwei Han*, Biao Li*, Shuwei Zhang, Chenguang Bai, Honghao Hu

SEP Key Laboratory of Eco-Industry, School of Metallurgy, Northeastern University, Shenyang 110819, China

HIGHLIGHTS

- An accurate 3D numerical model of a ground source heat pump system was built.
- Based on this model, the design error of ASHRAE method was analyzed.
- The influencing factors of the design error were also studied.

ARTICLE INFO

Keywords:
Ground heat exchanger
Design method
Simulation experiments
Dynamic performance
Design error

ABSTRACT

The ground heat exchanger (GHE) is vital to the energy conservation and economy of a ground source heat pump system (GSHPS). The ASHRAE method is the commonest way to design GHEs. However, the mathematical model of this method includes some assumptions and simplifications that may make the results inaccurate. In this paper, a dynamic simulation model of a GSHPS was established and verified. The GSHPS designed according to the ASHRAE method was investigated annually. The result shows that the ASHRAE method tends to overestimate the length of the GHEs by up to 13.90% under the reference condition. The design error of the ASHRAE method is affected by many factors. When the drilling spacing is less than 4 m, the required pipe length is longer, and the design error becomes smaller. When the drilling distance is between 4 m and 6 m, the influence of drilling spacing is small. As the thermal conductivity of the backfill material and the fluid flow rate in the tube increase, the design errors also increase. The drilling depth is less important in the design error of the ASHRAE method.

1. Introduction

In recent years, building energy consumption for heating and cooling has increased rapidly, now accounting for about 40% of the total global energy consumption, and this contributes to 30% of total global emissions of CO_2 [1,2]. GSHPs are efficient and energy-saving for heating and air conditioning, being widely used in residential and commercial buildings, and the total area using the GSHPS just in China was as much as 350 million square meters by the end of 2015 [3,4]. This system, however, also has some shortcomings, especially excessive construction costs and poor reliability in the long term. The GHE is an important part of the GSHPS, having a great significant influence on the operation performance and economy of the system [5,6]. Presently, GHEs and GSHPSs can be designed by three main types of methods: (1) the semi-empirical formula recommended in the ASHRAE handbook [7,8]; (2) professional design software [9,10]; (3) maximum heat transfer limits per depth of GHEs, estimated by experience [11,12]. In addition, some novel design methods have also been proposed in recent years [13–15]. However, these methods are still theoretical and have not been applied in engineering practice. The ASHRAE method is frequently used in the design of GHEs in practical engineering for its ease of calculation and wide application range [16]. This method is based on the line source model. However, the heat transfer process between the buried pipe and the surrounding soil is simplified and the surrounding soil is treated as a uniform medium in the line source model. Moreover, the influence of the complexity and uncertainty of the heat exchange of the actual soil and some other factors (such as the drilling space, the fluid velocity in the buried pipe, the backfilling material and the depth of drilling) on the design results is neglected. Therefore, the design results of the method may contain errors, which may be different under different engineering conditions. Studying the errors of the ASHRAE method and its influencing factors will help to improve the stability of the GSHPS and reduce the construction costs.

The design results for the length of the GHEs can be affected by

---

* Corresponding authors.
E-mail address: hanzongwei_neu@163.com (Z. Han).

https://doi.org/10.1016/j.applthermaleng.2018.09.010
Received 13 March 2018; Received in revised form 14 June 2018; Accepted 3 September 2018

many factors. Based on simulation software, Liebel et al. [17] and Capozza [18] found that the groundwater flow in aquifers had a significant impact on the performance of GHEs, and the total length of GHEs could be reduced by 9–25%, and the installation costs and operating costs could be decreased by 16% and 6% respectively in groundwater conditions. A study by Mensah et al. [19] showed that the flow rate of circulating water in the buried pipe and the COP of the heat pump unit could change the design result of the GHE length, and that reducing the maximum heat load could greatly reduce the total length of the GHE. Sharqawy et al. [20] studied the effect of heat convection between the soil surface and air on the length of the GHE, finding that the GHE was 10% shorter when the heat convection between the soil surface and air was considered, compared with heat insulation on the soil surface. Zhang. et al. [21] analyzed the influence of the center distance of the buried pipe, the thermal conductivity of the backfill material, the drilling space, circulating fluid, arrangement of boreholes on the heat transfer performance of buried pipe, and the total length of the GHE was compared under such different parameters.

The ASHRAE method for designing GHEs may have errors. Bae et al. [22] compared with the total length of a single U-tube and a double U-tube, suggesting that the total length designed by ASHRAE method could be different under different thermal conductivities of grout material and pipe spacing. Based on the existing ground source heat pump system, Cullin et al. [23] calculated the total length of the buried pipe according to a professional software and the method recommended by ASHRAE, respectively. Compared with the total length of the GHEs of the existing system, the design error produced by the software was less than 6%, while the ASHRAE method could produce error from −21% to 167%. Staiti et al. [24] designed GHEs by the ASHRAE method and a commercial design software named GLHEPRO under the same working conditions. The results showed that the total length of the GHEs designed by the ASHRAE method was approximately 27% higher than that of the software. Capozza et al. [25] used the ASHRAE method and an approximate calculation model to design the GHE under the same basic parameters, and found that the length of the buried pipe by the former was 10% less than the latter. Fossa et al proposed an improved ASHRAE method. By comparing the temperature penalty T_p that is vital in designing the length of GHEs, the presented method was more accurate. Then, the GSHPS designed by the improved method was operated in 10 years [26,27]. Philippe et al found that the T_p would be −0.24 °C after 10 years of operation if the system was designed according to ASHRAE handbook [28].

It is easy to understand, from the above studies, that the length of the GHEs is important to the heat pump system. Although the ASHRAE method, the commonest way to design GHEs, has some advantages such as convenience and little calculation, the actual result of this method may be far from the best answer. In other words, this method may lead the total length of the ground heat exchanger being too long, reduce the economy of the ground source heat pump system, and it may also be so short that the system cannot provide or extract the required heat.

In this paper, a three-dimensional dynamic simulation model of a ground source heat pump system was established on the common commercial software Fluent. The heat pump unit and the ground heat exchangers was connected and coupled dynamically by a program. Based on this model, the error of the ASHRAE method and its influencing factors were analyzed. It was hoped to provide some reference and suggestions for the accurate design of ground heat exchangers and stable operation of ground source heat pump systems.

2. Physical model

2.1. Geometric model

To analyze the design errors of the GHE and its influencing factors, a three-dimensional dynamic numerical simulation model of a GSHPS was established in this paper. This model includes a heat pump unit and underground heat exchange system (including a single U-shaped buried pipe and circulating fluid in the tube, backfill material and surrounding soil). Importantly, the heat pump unit and underground heat exchange system were connected through a software program to achieve dynamic heat exchange and simulate the dynamic operation of the GSHPS. The basic design parameters of the GHE are shown in Table 1.

Table 1
Parameters of GHE.

Outer diameter of buried pipe	Inner diameter of buried pipe	Center distance of the pipe	Drilling diameter	The soil size
32 mm	26 mm	120 mm	260 mm	5 m × 5 m × 70 m

In the grid division, the grid was relatively dispersed in the depth direction and away from the center of the borehole because of the small temperature gradient to improve the calculation speed. At the same time, considering the change of the velocity and temperature in the U-tube, and the temperature gradient near the borehole, the grid was encrypted to ensure the accuracy of the calculation result. The grid of a single GHE is shown in Fig. 1, and the thermal properties of the circulating fluid, backfill material and surrounding soil under the reference conditions are shown in Table 2.

2.2. Model validation

In actual GSHPSs, the underground heat exchange system often contains multiple GHEs with different drilling depths, and most importantly, it is not easy to get accurate thermal properties of underground soil under an unknown geologic structure. Therefore, an outdoor full-scale test device of the underground heat exchange system might not produce an ideal result that could be used to validate and verify the numerical model built in this paper, even after a lot of expense and resources were consumed. In contrast, the physical and thermal parameters of soils in an indoor lab rig can be measured accurately, and the experimental environment is not easily disturbed, which guarantees the accuracy of the obtained data. Therefore, the accuracy of the numerical simulation model built in this paper would be testified on the indoor lab rig. The relevant experimental parameters and results can be found in the literature [29]. As the inlet and outlet temperature of the buried pipe directly reflect the heat exchange performance of the GHE, the accuracy of the numerical simulation model was verified by the relative error of the inlet and outlet temperature of the pipe. The relative error can be calculated as follows: $(t_{\exp} - t_{\text{sim}})/t_{\text{sim}} \times 100\%$, where $t_{\exp}$ is the experimental temperature and t_{sim} is the simulated temperature. During the test duration, the relative error of the inlet and outlet water temperature between the simulation model and the experiment device was less than ± 5%, which shows that the accuracy of the simulation model can be trusted.

3. System construction and error analysis

3.1. Design method

When designing GHEs, engineers often follow the suggestions of the ASHRAE handbook and determine the size and shape of the GHEs according to the ASHRAE method [8,17,30]. In this method, the pipe length of the buried pipe heat exchanger needs to be designed respectively under cooling and heating conditions, and the larger of these is the final length of the GHEs. The main equations are as follows:

The cooling length:

$$L_c = \frac{1000Q_c\,[R_f + R_{pe} + R_b + R_s \times F_c + R_{sp} \times (1{-}F_c)]}{t_{\max}{-}t_{\infty}}\left(\frac{COP_c + 1}{COP_c}\right) \tag{1}$$