Energy Conversion and Management 171 (2018) 1177–1192

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Evaluation and improvement of the thermal performance of different types of horizontal ground heat exchangers based on techno-economic analysis

Mohammad Habibi, Ali Hakkaki-Fard*

RASES Lab, Department of Mechanical Engineering, Sharif University of Technology, Azadi Ave., Tehran, Iran

ARTICLE INFO

Keywords:
Ground source heat pump
Horizontal ground heat exchanger
Numerical simulation
Secondary soil
Moist soil

ABSTRACT

In recent years horizontal Ground Heat Exchangers (GHEs) has attracted a growing interest as heat source/sink for ground source heat pump systems. Horizontal GHEs initial installation costs are lower than the vertical ones; however, they require larger land area and more pipes. Therefore, it is necessary to reduce their required land area and pipe length by improving their thermal performance. In this study, a numerical modal based on 3-D simulation of GHE with computational fluid dynamics methods is developed. The model is used to evaluate the thermal performance and initial installation cost of horizontal GHEs. Four different types of horizontal GHEs: linear, spiral, horizontal and vertical slinky, and different soils types are considered. Obtained results indicated that the spiral and linear configurations have the lowest initial installation costs in single and parallel arrangements, respectively. Furthermore, a new design concept based on applying secondary soil with better thermal properties near the GHE pipes is introduced. It is shown that applying the secondary soil can improve the thermal GHE performance and reduce the initial installation cost of the horizontal GHE, when the thermal conductivity and volumetric heat capacity of the secondary soil is greater than those of the background soil.

1. Introduction

Today, it is well known that the building sector is responsible for nearly 40% of global energy consumption [1] and more than 36% of the total global CO_2 emissions [2]. On the other hand, more than 60% of the energy consumption of buildings is due to the Heating, Ventilation, and Air Conditioning (HVAC) systems [3] which are mainly supplied by non-renewable fossil resources [4]. Consequently, in order to keep our environment clean and green, it is essential to use renewable energy sources as a substitute for fossil resources in HVAC systems. Heat pumps as one of the most adapted heating/cooling solutions, are the only end-use heating/cooling technology that has a Coefficient of Performance (COP) greater than one. However, the energy efficiency of heat pumps decreases drastically as the temperature difference between hot and cold sources increases [5]. Among different types of heat pumps, ground source heat pumps (GSHPs) have been known to have higher energy efficiencies due to the lower underground temperature fluctuations. Furthermore, GSHP systems have several advantages, such as high COP, stable capacity, and less environmental impact. However, their high installation costs hinder their widespread deployment [6].

There are two main categories of GSHPs: open and closed loop systems. In closed-type system, heat is absorbed from or rejected to the ground through horizontal or vertical Ground Heat Exchangers (GHEs). In vertical GHEs, heat exchanger pipes are buried in boreholes with a depth range of 30 to 150 m. Vertical GHEs have better thermal performance, they are reliable and require a minimum land area [7,8]. However, their high initial installation cost, largely due to drilling deep boreholes, is their main disadvantage [9]. There are several studies that investigated the effect of various parameters on the thermal performance of vertical GHEs [10–20].

In horizontal GHEs, long pipes are buried in trenches with depths of 1–2 m. Thermal performance of horizontal GHEs are significantly lower than vertical GHEs, because the soil temperature in the shallow trenches varies seasonally [21]. Hence, horizontal GHEs require longer pipes and more land area. On the other hand, owing to the removal of drilling costs, their installation costs are significantly lower than vertical ones. For this reason, horizontal GHEs have a good compromise between efficiency and cost [22]. Horizontal GHEs can be further divided into three basic configurations: linear, slinky and spiral-coil-type GHEs. Slinky and spiral configurations provide higher heat exchange rate per trench unit length than linear type. This higher heat exchange rate is due to the larger heat transfer area per trench unit length and also the greater heat transfer coefficient owing to centrifugal force that induces a secondary flow in curved pipes [23].

There are several studies that investigated the effect of various parameters on the thermal performance of linear and slinky GHEs

---

* Corresponding author.
E-mail address: ahakaki@sharif.ir (A. Hakkaki-Fard).

https://doi.org/10.1016/j.enconman.2018.06.070
Received 30 March 2018; Received in revised form 18 June 2018; Accepted 19 June 2018

Nomenclature

A_0	maximum building heating load (W)
C	specific heat (kJ/kg s)
COP	Coefficient of Performance
D	diameter (m)
D_h	pipe hydraulic diameter (m)
d_constant	distance from the GHE that the ground temperature remains undisturbed (m)
f	thermal effect of GHE on the soil in the vicinity of the pipe (°C)
h_c	coefficient of convective heat transfer (W/m^2 K)
IIC	dimensionless Initial Investment Cost (–)
k	thermal conductivity (W/m K)
Ke	Kersten number
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
n	sandy soil porosity
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Q	thermal load/ heat exchange rate (W)
q	heat exchange rate per pipe unit length (W/m)
R	thermal resistance (m^2 °C/W)
Re	Reynolds number
r_loop	loop radius of the GHE (m)
S_r	normalized soil water content (–)
T	temperature (°C)
T_amp	amplitude of annual ground surface temperature (°C)
T_fluid	mean circulating fluid temperature of GHE (°C)
T_mean	annual average ground surface temperature (°C)
t	time (h)
t_c	time of occurrence of the coldest temperature since the start of year (h)
$V_\mathrm{excavation}$	excavation volume (m^3)
x, y, z	coordinate axes

Greek symbols

α_s	soil thermal diffusivity (m^2/h)
β	parameter related to the soil texture
ρ	density (kg/m^3)
ω	moisture content (kg/kg)

Subscripts

building	building
comp	compressor
dry	dry soil
ds	disturbed soil near the pipe
fluid	circulating fluid
in	inlet of GHE
out	outlet of GHE
pipe	pipe
sat	saturated soil/ wet soil
soil	soil/ undisturbed soil
water	water
with ss	with secondary soil
without ss	without secondary soil

[21,23–26]. For example, Chong et al. [27] simulated several configurations of slinky GHEs and three different soil types by a numerical transient model. They investigated the effect of loop diameter and loop pitch, required pipe length, and excavation volume on the thermal performance of GHEs. Their results showed that soil type is the most effective parameter in heat transfer process and the optimal configuration was obtained when both the loop diameter and the loop pitch were 1 m.

However, there are fewer studies available on spiral GHEs than other types of horizontal GHEs. To the best knowledge of the authors, the first experimental study on spiral GHEs was carried out by Yoon et al. in 2015 [7]. They experimentally evaluated and compared the thermal performance of linear, slinky and spiral GHEs. In that study, the thermal response tests (TRTs) were performed for a period of 30 h continuously for each type in a steel-box filled with dried sand. It was found that the spiral GHEs had the highest thermal performance among various types of GHEs when their loop pitch and loop diameter were equal. In another study, a comprehensive evaluation on thermal performance of spiral GHEs was carried out by Li et al. [28]. They employed a 3-D numerical simulation of spiral GHEs to evaluate the effect of buried depth, soil properties, and ambient air temperature on system performance. Their results indicated that the affecting parameters ranked from high to low importance include: soil thermal conductivity, installation depth and ambient air temperature. They also studied the effect of pipe spacing (in parallel configuration) on thermal performance of GHEs, but they did not consider its effect on installation cost.

In recent years, several studies are carried out to evaluate the thermal performance of different types of horizontal GHEs. For instance, Congedo et al. [22] numerically studied the efficiency and energy behavior of different horizontal GHEs. Their results demonstrated that the thermal conductivity of the ground around the heat exchanger is the most important parameter for the heat transfer performance of the system. In another study, Kim et al. [8] numerically studied the effect of soil thermal conductivity and pipe diameter on the thermal performance of slinky and spiral GHEs. Their results indicated that the spiral GHEs has better thermal performance than slinky GHEs. Moreover, they demonstrated that the soil thermal conductivity has a major effect on the thermal performance of GHEs, while the pipe diameter does not have any effect on its thermal performance. In a study by Dasare et al. [29], three types of horizontal GHEs including linear, slinky, and spiral were numerically simulated. In that study, the effect of trench depth, fluid velocity, and soil thermal conductivity on thermal performance of GHEs were evaluated. As expected, they indicated that the soil thermal conductivity is the most important parameter in the thermal performance of GHEs. They also observed that the fluid velocity had a linear relation with heat exchange rate of the GHEs and the effect of buried depth was insignificant. They also introduced and simulated a double layer GHEs for extracting higher heat transfer rates per trench unit length.

Based on the above review, the soil type is the most effective parameter in the heat transfer performance of the horizontal GHEs and increasing the thermal conductivity of the soil enhances the thermal performance of GHEs. In this context, Leong et al. [30] employed a numerical simulation to investigate the effect of soil moisture on thermal performance of horizontal GHEs. They found that by increasing the moisture content of the soil, the soil conductivity increases and thus the heat transfer rate of the horizontal GHEs augments. Some researchers tried to increase the heat exchange rate of vertical GHEs by applying high conductive soil around the GHEs. For example, Alberti et al. [31] reduced the thermal resistance of a borehole (vertical GHE) by utilizing a high conductive material as grout in a borehole. However, to the best knowledge of the authors, this idea has never been studied or applied so far in horizontal GHEs.

There are few studies available that economically evaluated the GHEs. For example, Hakkaki-Fard et al. [32] performed a techno-economic comparison of a direct expansion vertical GSHP and an air-