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A new approach to modelling of a horizontal geo-heat exchanger with an internal source term ☆,☆☆

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HIGHLIGHTS

- A new GHE model with an internal source term approach is presented.
- The theoretical results are in a good agreement with the experimental data.
- The effects of the technical parameters on the GHE's performance are investigated.

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ABSTRACT

This paper presents a new approach to considering the effect of seasonal changes in soil temperature on the performance of a horizontal geo heat exchanger. It is different from extant models which consider the seasonal changes in soil temperature by applying a real energy balance on the ground surface. In the new model, the seasonal changes in soil temperature, which are affected by the thermal interaction between the ground and the atmosphere, are expressed as an internal source term. The value of the internal source term depends on the soil density, soil specific heat, soil temperature difference during summer and winter, and time period. The simulation results show that the new approach, which takes into account the effect of periodic soil temperature fluctuations on the performance of the horizontal geo heat exchanger, is valid. The validated model is then used to conduct a sensitivity analysis to investigate the effects of the pipe length, fluid flow rate, inlet fluid temperature, and burial depth on the thermal performance of the horizontal geo heat exchanger.

1. Introduction

In recent years, geo heat exchangers (GHEs) have become attractive from a technical perspective in heating and cooling applications because of their renewable nature. GHEs use the ground/soil as a heat source or heat sink to harness the (renewable) thermal energy stored in the ground as the ground temperature is normally higher than the ambient air temperature during the winter and lower during the summer. Thus, the ground is a suitable medium to be used to extract/store the heat during the winter/summer. GHEs are usually coupled with heat pump and air conditioning systems to provide one of the most energy efficient ways of generating buildings' heating and cooling. There are two common configurations of GHEs, namely vertical and horizontal. Horizontal heat exchangers are relatively cheap to install, as they are only laid in a trench at a depth of up to 2 m below the surface. Their performance is affected by the continuous thermal interaction between the ground and the atmosphere. The diverse mechanisms of heat transfer occurring on the ground surface contribute to the thermal recovery of the ground conditions, especially when there is an imbalance between the heating and cooling operations [1].

There is much literature which discusses the theoretical study of horizontal GHEs, including the modelling of their linear [1–15], slinky [16–20], and flat-panel [21–23] arrangements. One of the key challenges associated with the theoretical study of the

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performance of a horizontal heat exchanger is to take into account the effect of seasonal changes in soil temperature. Gan [1] developed a two dimensional transient finite volume model of a horizontal GHE. The heat transfer on the ground surface is calculated by taking into account the effects of ambient air temperature and convection heat transfer. Esen et al. [2] presented a two dimensional explicit finite difference model of a horizontal GHE. The model's domain is considered from the centre of the pipe to the mid span between the pipes. The adiabatic condition is applied at the right and left boundaries as the domain is divided symmetrically. The constant far field soil temperature is applied at the bottom boundary. At the surface boundary, only convection is taken into account. Benazza et al. [3] presented a transient quasi three dimensional finite volume model of a horizontal GHE. Three different boundary conditions are applied to the soil domain, namely: symmetry adiabatic at the left and the right boundaries, undisturbed far field soil temperature at the bottom boundary, and convection on the ground surface boundary, with consideration of the dynamic ambient air temperature. Wu et al. [4] developed a two dimensional transient model of a horizontal GHE. The model is used to investigate the effects of variation in the ambient air temperature, soil thermal conductivity, wind speed, and intermittent operation on the performance of the heat exchanger. This model ignores the effects of solar radiation and evaporation which occurs on the ground surface. A comprehensive two dimensional model of a horizontal GHE has been developed by Demir et al. [5]. The model is developed by taking into account the effects of the full energy balance on the ground surface including long radiation, convection, solar radiation, sensible and latent heat transfer, precipitation and surface cover. Rezaei-Bazkiaei et al. [6,7] introduced a new approach in order to optimize the design of a horizontal GHE by using a non-homogeneous layer in the soil domain to enhance the GHE's performance. The heat transfer behaviour of the GHE system is developed based on the previous work by Demir et al. with the exception only in the intermediate layer. A horizontal heat exchanger model considering one dimensional unsteady heat conduction has been presented by Kupiec et al. [8]. In this model, the soil domain is treated as the slabs, consisting of upper and lower layers. The temperature of the upper slab is affected by periodical ambient air temperature and the temperature of the lower slab is assumed to remain constant. A performance comparison between a vertical and a horizontal GHE has been presented by Florides et al. [9]. The result shows that, under the same conditions, the outlet temperature of the vertical GHE is lower than that for the horizontal GHE. Fontaine et al. [10] developed an analytical transient model of a horizontal GHE to be applied to the permafrost region. The model provides a new feature to estimate the profile of soil temperature in directions parallel to the pipe. Naili et al. [11] presented an energy and exergy analysis of a horizontal GHE operated in a hot climate: Tunisia. The results showed that the energy and exergy efficiency vary from 18% to 52% and 12% to 36%, respectively. A new model to predict the undisturbed ground temperature was developed, based on the simplified correlation of the ambient air temperature, and has been presented by Ouzzane et al. [12]. It has been shown that the simplified correlation model produces good estimation results, however the results are less accurate than the global correlation model.

Xing et al. [13], developed an explicit two dimensional finite volume model for the horizontal foundation heat exchanger. The model considers the effects of convection, evaporation, and radiation on the ground surface. Lee et al. [14] continued Xing et al.'s work by improving the simulation capabilities of the model, including integrating the model with the building simulation programs, developing a better grid generation technique which produces better accuracy and simulation efficiency. Nam and Chae [15] developed a numerical simulation model of a building foundation horizontal GHE which is applied to an underground parking lot. The model considers the ground around the GHE as a porous medium comprising of gas, liquid, and solids. The fluctuation of the ground surface temperature is considered by applying the surface thermal energy balance to the surface boundary.

Chong et al. [16] developed a three dimensional numerical model of a horizontal slinky loop heat exchanger. The model is used to investigate the GHE's performance under variations of the loop pitch, loop diameter, and soil diffusivity. Xiong et al. [17], developed a slinky ground heat exchanger model which has better capability in its computational speed and could be integrated into building simulation programs. The model considers the variations of the ground surface's temperature by using a surface energy balance approach. Fujii et al. [18] conducted both experimental and numerical studies on a double layer-slinky coil horizontal heat exchanger. The results show that the double layer-slinky coil horizontal heat exchanger produces a remarkable heat transfer rate per unit of land area when compared with the single layer type. Adamovsky et al. [19] presented the thermal analysis for both the linear and the slinky types of horizontal GHEs. The results reveal that the linear type GHE produces better efficiency than the slinky type. Go et al. [20], investigated the effect of rainfall infiltration on the performance of a spiral coil horizontal heat exchanger. Under unsaturated soil conditions, the results obtained show that the GHE has a higher thermal efficiency when rainfall infiltration is considered.

Bortoloni and Bottarelli [21] presented an analytical line source model of a new configuration of the horizontal GHE, called a flat-panel ground heat exchanger. In this study, the new shape of the heat exchanger is treated as an equivalent to a slinky-coil, which has the same heat transfer surface. The soil domain is assumed to be isentropic and the surface's boundary condition is determined based on the sinusoidal analytical function of the soil temperature. Bottarelli et al. [22] developed a novel two dimensional flat-panel model of a horizontal GHE which uses the encapsulated phase change materials (PCMs) as the trench's filling material. The model considers groundwater in porous media. In addition, the model applies the dynamic surface energy balance, with an hourly scale, at the ground's surface. The effectiveness of the PCMs as the backfill material is compared with the use of the coarse gravel. The results show that the GHE with PCMs as backfill material has a lower performance than that with the coarse gravel. Bottarelli et al. [23] continued their work to investigate the effect of using the mixture of soil and PCMs as backfill materials. The results show that the GHE with the mixture of soil and encapsulated PCMs has a relatively higher surface temperature than that without PCMs during the winter, and, conversely, lower during the summer.

A review of the literature [1–23] shows that the existing models use traditional approaches to consider the periodic soil temperature fluctuations during seasonal changes. Some of the models use a simplified function of the ambient air temperature to consider the soil's fluctuations in temperature due to seasonal changes. The simplified approach produces less accurate results. Others apply the ground surface's dynamic energy balance in which the inputs are spatially and temporally difficult to collect, thereby making the model complicated and inefficient in terms of computational time.

This paper presents a novel three dimensional unsteady heat transfer model for a horizontal GHE. In the model, seasonal changes in soil temperature, caused by external factors such as solar radiation, evaporation, and vegetation cover, are presented as a single internal source term for the first time. This approach, in which the value of the internal source term depends on soil density, soil specific heat, soil temperature differences during summer and winter, and a specified time period, is more practical to use and it is expected to generate more precise outcomes. The