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Numerical study of horizontal ground heat exchangers for design optimization

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ABSTRACT

Despite ground source heat pump has been proven as highly efficient, high initial cost discourages homeowners and small-medium enterprises to opt for such systems. Horizontal ground heat exchangers offer relatively low-cost solution that may help promoting these systems usage worldwide. This study examines ways to optimize the designs for horizontal ground heat exchangers by using different layouts and pipe materials. CFD simulation of three dimensional models was performed to achieve this objective. All cases tested are able to yield comparable heat exchange rate for an equal trench length. However, the effective period differs one from the other. Additional initial and overhead costs are worthy as slinky ground heat exchangers prolongs heat transfer process when compared against straight configuration. Pipe materials with superior thermal conductivity also promote longer high efficiency operation. An improvement of 16% is reported when copper pipe is used instead of the conventional HDPE pipes. Effective period can be extended by 14% when ground heat exchangers are installed in vertical orientation. Thermal interference in slinky configuration is prevalent during initial operation. In a long run, the effect is observed to be minimal except in vertical orientation. However, it is avoidable beforehand at design stage.

1. Introduction

Energy is rejected to or absorbed from the Earth in ground source heat pump (GSHP) systems through ground heat exchangers (GHE). Basically, GHE are pipes buried in the ground either in boreholes 50–150 m deep or shallow horizontal trenches 1–2 m deep. Installations of horizontal GHE mainly involve excavation of trenches where pipes are laid and buried. That being said, horizontal GHE installations would be convenient where land area is not limited.

Horizontal GHE in slinky configuration provides greater thermal performance compared to straight pipe [1–4]. Such layout is advantageous in comparable trench length by boosting amount of heat transfer. Slinky or coil-like pipe geometry also enhances flow characteristics by inducing secondary flow due to action of centrifugal force [5–8].

GSHP system owners can choose to install slinky GHE either in horizontal or vertical orientations [9–11]. The loop diameter determines trench width in horizontal slinky GHE. In vertical slinky GHE, narrower trench is required whereby the bottom of the loop sits deeper in the ground. Due to slinky GHE placement in shallow trenches, the thermal performance is prone to the influence of varying conditions at ground surface [12–14].

Knowledge of climate interaction and ground thermal properties are increasingly important in designing such installations. Designs that can yield the highest thermal performance permitted by the land availability for trenching are desirable. Conversely, the designs should possess sensible balance between thermal performance and cost-effectiveness i.e., initial and operating costs.

Despite the growing number of GSHP systems in developed countries [15–20], efforts in promoting its usage in other parts of the world are essential. High efficiency slinky GHE designs may also appeal small businesses and homeowners to apply GSHP systems. Design and operating strategies to further elevate the efficiency of slinky GHE are valuable to accomplish this cause.

Enhanced-surface pipes yield better heat transfer by inciting turbulent eddies in heat exchangers in addition to increasing contact area [21–26]. Corrugated plastic pipes are reported to be used

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in Earth-air heat exchangers (EAHE) [27,28] and direct expansion GHE [29] for agricultural and residential buildings acclimatization. Meanwhile, corrugated [30] and twisted [31] metal pipes are used as heat pipe to conduct terrestrial heat onto surface of the ground.

GHE constructed from high thermal conductivity materials such as copper [32,33] show thermal performance enhancement compared to the widely used plastic materials. GHE using copper pipe have also been studied for EAHE [34] and direct expansion GHE [35] as well. Copper pipe is reliable with manufacturers provide up to 50-year warranty on their products. However, it may be problematic for applications underneath the ground surface.

Alternatively, composite copper pipes can be used as it is commercially available nowadays. This warrants the durability whereby coating layer provides protection against deterioration in harsh ground conditions. Nevertheless, the coating is expected to render the effective thermal conductivity of composite pipe. Combination of slinky-shape pipe with enhanced-surface and high thermal conductivity materials could prompt such studies to be undertaken.

Numerical modelling concerning horizontal GHE can be found in several studies but mostly were performed using straight configuration. On the contrary, studies on slinky GHE modelling are limited. The ones that are available were carried out by either in miniature-scale, representative geometry, two-dimensional, or cross sections containing one or two loops. However, real-scale spiral borehole GHE models were often studied as the geometry is easier to construct.

To the authors' best knowledge, there has not been any study carried out in modelling real-scale slinky horizontal GHE. Apart from complex interaction at ground surface boundary, the models construction is extremely difficult and time-consuming to begin with [36]. Another challenge is the expensive computational requirements such as CPU, GPU, physical memory and data storage.

The present work is an elaborate attempt to conduct real-scale modelling of moderate-size horizontal GHE. The three-dimensional numerical model employed is based on finite volume method. Numerical models performed using this method shows better stability on unstructured grids [37]. Comparative analysis on thermal performance was carried out by modelling horizontal GHE using different layouts. Additionally, the effect of thermal properties of different pipe materials was also investigated.

2. Description of numerical modelling

This investigation was conducted based on previous modelling for vertical GHE [38] that was validated with experimental results [39]. The current work adopted similar methodologies with previous modelling i.e., (1) hybrid mesh generation method; (2) CFD code used; (3) similar setup for main parameters; and (4) using properties and measured data recorded from experimental site. The CFD setup differs from previous modelling by considering varying conditions that would affect shallow GHE performance.

2.1. GHE models

For ease of reference, the GHE models tested are distinguished according to configurations, orientations and pipe materials as cases listed in Table 1. Pressure distribution as given in Fig. 1 can be used to describe the cases using different layouts including its flow path. GHE in straight configuration as in Case 1 is basically U-tube pipe placed at the trench bottom. The trench is 1.5 m deep with 1 m pipe separation distance was given.

Meanwhile, slinky configuration comprises a series of seven non-overlapping loops followed by straight return pipe as in Case 2–6. The loop diameter for each slinky loop is 1 m. In Case 1–4, the GHE were positioned inside the trench in a similar depth and orientation as in Case 1. In contrast, GHE in vertical orientation were laid upright in 2 m deep trenches as in Case 5 and 6. Perceivably, the loops center is at the same 1.5 m deep as the GHE laid in horizontal configuration. The return pipe is at the top in Case 5 as opposed to at the bottom in Case 6. Vertical pipes connect the GHE to ground surface in all cases.

Table 1
Horizontal GHE models according to configurations, orientations and pipe materials.

Case	Configuration	Orientation	Pipe material
1	Straight	Horizontal	HDPE
2	Slinky	Horizontal	HDPE
3	Slinky	Horizontal	Composite
4	Slinky	Horizontal	Copper
5	Slinky	Vertical	Composite
6	Slinky	Inverted vertical	Composite

The total pipe length for straight and slinky GHE is 17 m and 39 m, respectively. The dimensions for each analysis domain are 10 m length × 10 m wide × 5 m deep. The trench is symmetrical on both length and width directions of the analysis domain. An example of the three-dimensional unstructured grid and GHE positioning is given in Fig. 2.

Table 2 summarizes important grid parameters in all GHE layouts. Same grid sizing method for grid generation such as element or cell size and growth rate was used in all cases. GHE region employs fine cells and the cell size grows coarser along the ground region towards the outer boundaries.

Initially, the pipe was modelled as having zero wall thickness when generating the mesh. Shell conduction approach feature was utilized where the thickness of pipe wall was generated during the CFD solving process. The number of mesh elements in the model is minimized via this approach thus helps to expedite the calculation. The interface between pipe surface and surrounding ground was coupled to allow conjugate heat transfer condition. Table 3 lists the thermal properties of pipe materials and ground. The pipe inner diameter is 12.7 mm (0.5 inch) in all cases. The wall thickness for HDPE pipe in Case 1 and 2 is 1.75 mm. For composite pipe in Case 3, 5 and 6, the overall wall thickness is of HDPE pipe equivalent. The layer thickness for inner copper and LDPE coating is 1.25 mm and 0.5 mm, respectively.

The dual layer of composite pipe was treated as single wall thickness in the modelling. This was to avoid convoluted layer grid thus aid solution convergence. Therefore, effective properties for composite pipe as given in Table 3 were obtained and applied. For reference, the density, specific heat and thermal conductivity of LDPE used are 920 kg/m^3, 3400 J/kg K and 0.34 W/m K, respectively. Bare copper pipe is used in Case 4 where the wall thickness is the same as the inner copper layer of composite pipe.

2.2. Initial and boundary conditions

Ground heat flux is the process where heat is being transported between the Earth's atmosphere and ground surface. Subsequently, the heat is transported through conduction that in turn governs the ground temperature profile [41]. Ground heat flux has strong influence on horizontal GHE operation due to the position at shallow depth. For simplicity or lack of data availability reasons, many analytical or numerical models tend towards regarding the surface as a constant or imposed temperature boundary where the heat flux are allowed to vary [3,4,11,42–44].

Fig. 3 shows the varying near-surface air temperature at a test site in Saga University on Kyushu Island, Japan. The outer