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Simulation of thermal performance of horizontal slinky-loop heat exchangers for ground source heat pumps

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HIGHLIGHTS

- Three dimensional modelling of practical slinky heat exchangers for different loop pitches and diameters.
- Smaller loop pitches lead to better thermal performance, lower installation cost but higher material cost.
- Loop diameter has less influence than loop pitch on the thermal performance.

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ABSTRACT

This paper presents results obtained from a numerical simulation for the horizontal slinky-loop heat exchanger of a ground-source heat pump system. A three-dimensional numerical model was developed and the results of the thermal performance of various heat exchanger configurations are presented. The investigation was carried out on five types of loop pitch (loop spacing), three types of loop diameter, three values of soil thermal properties, and allowing continuous and intermittent operation. Comparison was made for the heat transfer rate, the amount of pipe material needed, as well as excavation work required for the horizontal slinky-loop heat exchanger. The results indicate that system parameters have a significant effect on the thermal performance of the system.

1. Introduction

Since the late 1940s, ground-source heat pump (GSHP) systems have been proven to be an energy efficient and well developed technology that utilises the soil to extract heat. This is because soil temperature is not subject to large variations such as those observed for outdoor air temperature, which varies, for example, from 0 °C to 16 °C (i.e. in the winter season).

There are two main types of ground-loop heat exchangers used in GSHP systems, namely vertical ground-loop borehole heat exchangers and horizontal ground-loop heat exchangers. Common vertical ground-loop heat exchanger configurations include the concentric tube heat exchanger, U-tube heat exchanger and pile ground heat exchanger. Widely used horizontal ground-loop heat exchanger configurations are the straight pipe heat exchanger and slinky-loop heat exchanger [1–4].

Over the last 30 years, a number of performance analyses of vertical ground-loop heat exchanger configurations have been carried out, either using numerical modelling or via experiments. This is mainly because this configuration has been more widely used, as it requires less land area for installation. Furthermore, it often offers a better and more steady thermal performance compared to the horizontal configurations, because there is less temperature variation in the deep ground region. In recent years, research on pile ground heat exchangers has increased because this system can be installed within foundation piles of new buildings, especially in urban areas [5–10]. Increasingly, research into the horizontal ground-loop heat exchanger configuration for GSHP systems is being carried out, both in the area of numerical modelling and field experiments, on thermal performance, thermal impact, and energy behaviour for different loop configurations and working conditions [11–15].

Wu et al. [15] reported on the effect of the loop diameter and loop pitch (i.e., loop spacing) on the thermal performance of a slinky-loop heat exchanger. The predicted heat extraction rate for loop diameters of 0.6 m, 0.8 m and 1.0 m at 140 h was found to be 24.6 W/m, 27 W/m and 30 W/m, respectively. They also calculated that the heat extraction rate for a slinky-loop heat exchanger with loop pitch of 1.2 m, 1.6 m, 2 m and 3 m equalled 42.5 W/m, 39.3 W/m, 36.1 W/m and 30 W/m, respectively, again after 140 h

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of operation. However, because the simulation lasted less than 6 days (i.e., 140 h), the thermal performance of the heat exchanger had not yet reached equilibrium. Therefore, it would be preferable to carry out a longer term simulation of operation (i.e., 60 days), which will lead to a better understanding of the overall performance and provide more reliable data for designing a slinky-loop heat exchanger GSHP system.

Congedo et al. [3] investigated the thermal performance of three different types of heat exchangers (straight (linear), helical and slinky) using FLUENT [16]. All three heat exchangers were modelled with a 50 mm pipe diameter, which was buried at 1.5 m, 2.0 m and 2.5 m below the ground surface. They analysed the effect of depth of installation, the soil thermal conductivity, the heat transfer fluid velocity of the system, and finally the influence of loop pitch, for helical and slinky-loop heat exchangers. In their helical and slinky-loop heat exchanger models, they selected a loop diameter of 0.4 m and loop pitch values of 0.1 m, 0.2 m and 0.3 m. However, these configurations were not compatible with commercial slinky-loop heat exchangers.

RETScreen [17] reported on a horizontal ground-loop heat exchanger consisting of a series of pipes installed one to two metres below the soil surface which could provide 18.18 to 28.57 W/m output for cooling and heating capacity. Similarly, E.M.R [18] suggested that the heating output capacities for this system were around 18.18 to 22.22 W/m.

A review of the literature [11–15,19] shows that there is not much information or optimisation design data available for the installation of commercial horizontal slinky-loop heat exchangers in the UK, especially on the thermal performance for the long-term and intermittent operation related to this type of system. It also shows that increasing numbers of horizontal slinky-loop heat exchangers are being installed in the UK, while no scientific design procedure has been developed in order to size the slinky-loop heat exchangers correctly.

This paper will investigate the thermal performance of various configurations of a horizontal slinky-loop heat exchanger GSHP system for long-term operation. A three-dimensional simulation software package, FLUENT, was used to analyse the thermal performance of horizontal slinky-loop heat exchangers. The performance was evaluated through an analysis of the effect of the size of the loop diameter, the loop pitch and thermal properties of soil for heating operation.

1.1. Slinky-loop heat exchanger

The slinky-loop configuration is also known as the coiled-loop or spiral-loop. In the UK, the slinky-loop heat exchanger configuration is installed horizontally as well as vertically. For the vertical slinky-loop configuration, the heat exchanger is generally placed in a 0.3 m wide trench at a depth of 2 m from the ground surface level [20]. For horizontal slinky-loop configurations, the heat exchanger is laid out at the bottom of the trench; the trench width normally depends on the slinky-loop diameter, and it varies per country [21,22]. The horizontal slinky-loop heat exchanger system is typically less expensive than a comparable vertical closed-loop system because no drilling is necessary and a trench with a depth of 1–2 m only is required [11]. The depth of the heat exchanger determines the amount of excavation work. The main factor is the cost of excavating and refilling the volume of soil.

1.2. UK heat pump market assessment

According to the European Heat Pump Association (EHPA) [23], the number of units sold in the UK increased from 2000 in 2006 to 3500 units in 2007. BSRIA [24] reports that the market for GSHPs has been growing quickly since 2009; the number of total heat pump units installed has reached around 16,000. It was estimated that the sale of GSHP units would exceed 21,000 after the year 2010.

The GSHP market has grown rapidly over the past few years, due to the on-going efforts to improve the drilling methods, to reduce the installation cost of the ground-loop heat exchangers [25], and as a result of the high and still rising gas and electricity prices [26]. Another important factor influencing this growth is the commitment of the UK government to reduce the CO_2 and other greenhouse gas emissions by 80% compared to 1990 levels [27]. In this context, the UK government have provided 50 million pounds of capital grants to fund the installation of various microgeneration technologies, including GSHPs, to organisations in the UK, the public and not-for-profit sectors, through the Phase 2 of the Low Carbon Buildings Programme (LCBP2) [28].

GSHP systems have therefore become a popular choice for space heating, hot water and air conditioning in new built commercial and residential buildings. It has been classified as one of the most effective renewable energy systems and it can be easily installed at a new construction project, where existing landscaping will not be disturbed [29]. One of the advantages of installing the closed-loop GSHP systems is that no permit is required, as is the case for open-loop GSHP systems.

1.3. Slinky-loop pipe diameter, loop diameter and loop pitch

The configuration of horizontal ground-loop heat exchangers installed commercially for GSHP systems is different in the USA and Canada compared to the UK and European countries. The pipe nominal diameters commonly used in the USA and Canada are DN15 (i.e., 1/2 in. or 15 mm), DN20 (i.e., 3/4 in. or 20 mm) and DN32 (i.e., 1–1/4 in. or 32 mm), while the standard pipe diameters used in the UK and Europe are DN25 (i.e., 25 mm), DN32 (i.e., 32 mm) and DN40 (i.e., 40 mm). Among them, DN40 is the most common pipe diameter used in the UK [21]. DN32 is widely used in Ireland [30].

The most common loop diameters installed in the USA and Canada are 0.762 m (i.e., 30 in.), 0.813 m (i.e., 32 in.), 0.609 m (i.e., 34 in.) and 0.914 m (i.e., 36 in.), with the latter the most common loop diameter installed. Meanwhile, the loop diameters of horizontal ground-loop heat exchangers installed in the UK and Europe are 0.8 m, 1.0 m, and 1.2 m. Among these, 1.0 m is the most common loop diameter installed [29,31,32]. Typical loop pitches used in the USA and Canada range from 0.254 m to 1.422 m (i.e., 10–56 in.). The loop pitch used in the UK and Europe is normally equal to the slinky-loop's loop diameter [29,31,32].

1.4. The textural composition of the soil

The thermal performance of horizontal ground-loop heat exchangers very much depends on the composition of the local soil, and also on the effect of soil moisture content and possibly groundwater flows on the thermal properties. UK soil thermal diffusivities have been reported to vary from 1.37×10^{-7} m^2/s to 4.33×10^{-6} m^2/s. The common range is between 4.0×10^{-7} m^2/s and 8.0×10^{-7} m^2/s [14,33].

2. Computer modelling of horizontal slinky-loop heat exchanger

The thermal performance of a horizontal slinky-loop heat exchanger was analysed using commercial Computational Fluid Dynamics (CFDs) software, FLUENT 13.0 [16]. The investigation of the thermal performance of the slinky-loop heat exchanger included five loop pitch configurations with a loop diameter of