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Research Paper

# Numerical investigation into the thermal interference of slinky ground heat exchangers

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ABSTRACT

The thermal performance of a slinky ground heat exchanger has been investigated using a validated transient 3D model for different trench separations, installation depths, soil properties, and daily operation hours. The effect of trench separation on thermal interference was analysed. The centre-to-centre distances between parallel trenches range from 1.5 m to 11 m. The initial soil temperature was found to have a significant effect on the predicted thermal performance. The predicted heat extraction using a varying initial soil temperature for a heating season would decrease with the increasing depth of installation, whereas using a uniform initial temperature would lead to increasing heat extraction with installation depth. It has also been found that soil with a high thermal conductivity would exacerbate the thermal interference between trenches with a small separation and that the thermal interference in continuous operation would be more than that in intermittent operation as a result of heat depletion in the ground. The effect of installation depth depended on the initial soil temperature for the first three months of continuous operation, but the effect decreased with operating time.

## 1. Introduction

The ground source heat pump (GSHP) market has expanded rapidly in recent years, owing to ongoing efforts to reduce installation costs and growing energy bills. In the year 2022, gas prices in the UK grew by 129 %, while electricity costs rose by 67 % [1]. Therefore, geothermal energy has gained popularity for use in commercial and residential buildings for space heating, cooling, and hot water. As stated in the European Heat Pump Association (EHPA) report of 2021, Norway topped the rankings with 49.77 installations per 1,000 households, while the UK installed the fewest heat pumps per household in all of Europe, with only 1.5 heat pumps installed for every 1,000 houses [2]. The independent Climate Change Committee pointed out that the UK must reach 15.3 installations per 1,000 households in order to achieve the nation's 2050 net-zero goal [3]. An ambition to lower heat pump expenses by 25–50 % before 2025 will go a long way towards making heat pumps a compelling alternative [4]. The UK government launched the Boiler Upgrade Scheme to take on the role of the Domestic Renewable Heat Incentive (RHI) and offer subsidies of £5,000 and £6,000, respectively, to encourage the use of air source and ground source heat pumps from 2022. According to government statistics, around 90,000 residences are anticipated to benefit from it [5]. Domestic heating accounts for 14 % of the UK's carbon dioxide emissions, based on the report from the Committee on Climate Change (CCC) [3]. The Boiler Upgrade Scheme will play a significant role in guaranteeing that all new heating system installations are low carbon by 2035 [6]. By 2028, the government hopes to have installed 600,000 heat pump systems annually [7].

The Ground Heat Exchanger (GHE) is one of the key components of a ground source heat pump system. GHEs are classified as vertical or horizontal according to their placement orientation. Vertical GHE pipes are installed vertically in deep boreholes with varying depths from 15.2 to 183 m [8]. Deep vertical pipes give the heat exchanger a greater energy extraction amount and require less land than horizontal GHE. However, the widespread adoption of this technology is mainly limited by the high initial installation drilling cost. Horizontal ground heat exchangers (HGHE) are placed underground, typically at a depth of 1 m to 2 m. Horizontal trenches require far less excavation costs than vertical boreholes and can be a cost-effective option for the installation of ground heat exchangers in situations where surrounding land space is available.

The installation costs can be further reduced using slinky ground heat exchanger [9], making HGHE an attractive technology for house and small office building applications [10]. Slinky GHE can obtain more heat transfer per unit soil length than straight pipe because of its longer

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pipe length per soil length [11]. Therefore, the use of slinky GHE can minimize the need for land area, making it possible to apply heat pump systems with HGHEs even in situations where the available land for installation is not substantial.

In the design stage of horizontal ground source heat pump system, it is useful to predict the HGHE's performance as accurately as possible. Several numerical studies have been carried out to investigate the thermal performance of HGHE under various conditions.

Selamat et al. [11] conducted a parameter study for a HGHE using various GHE configurations and pipe materials using CFD simulation. Their results showed that the slinky GHE outperformed the straight GHE per unit length of trench. Besides, a copper pipe could increase the energy efficiency by 16 % compared with a high-density polyethylene (HDPE) pipe.

Chong et al. [12] investigated the influence of soil type, loop pitch, and diameter on the thermal behaviour of a slinky GHE using CFD. The simulations included five loop pitch configurations and three loop diameters. The effect of loop pitch was found to be greater than that of diameter. The heat exchange rate of intermittent operation was higher than that of continuous operation. In addition, it was found that local soil conditions were essential for an accurate prediction of the GHE thermal performance. However, these findings were based on 60-day simulation time with uniform initial soil temperature conditions, which might deviate from real operation conditions.

Congedo et al. [13] also used CFD to study the effect of different configurations of horizontal GHEs over a year. It was demonstrated that soil type and the carrying fluid velocity were critical factors influencing the energy behaviour of the GHE. However, the sizes of loop diameter and pitch in their simulation were much smaller than those for real design.

Wu et al. [14] investigated the thermal performance of a slinky GHE system in a UK climate using both experimental and numerical methods. The experimental measurements revealed that the system's average COP was 2.5 with a falling trend over the two-month period. The CFD modelling revealed that changing the diameter of the slinky coils had no significant effect on the total amount of heat transfer, whereas the heat extraction per metre length of trench increased as the loop diameter increased. However, the simulation of the system operation lasted for less than one week without considering the thermal equilibrium. Simulation of a longer operation time would provide more useful thermal performance for a slinky ground heat exchanger.

Yu et al. [15] conducted a 3D numerical model for horizontal GHEs and compared it with the experiment in the countryside conditions in NSW, Australia. The results showed that as the distance of trench separation decreased, the carrier fluid temperature increased slightly (0.5 °C). In terms of configuration, the dense slinky loop averaged 1.5 °C lower than the horizontal straight and slinky loop.

Asgari et al. [16] developed a 3D numerical model through the finite-element method to investigate the thermal behaviour of different GHE pipe arrangements for three various types (linear, spiral and slinky) of horizontal GHEs. It was found that linear GHE with a quadruple layer arrangement has better performance. The staggered double-layer layout enhanced the energy performance for slinky and spiral GHE types, with around 22 and 7 % higher heat exchange rates per unit area of ground, respectively, than the standard single-layer system.

Yuan et al. [17] created a mixed numerical method to study the thermal performance and thermal interference of multiple vertical GHEs. They found that increasing the intermittent ratio from 0.5 to 2 could enhance the heat exchange rate, while increasing the separation distance between adjacent pipes has a little improvement in overall heat flux. When compared to a continuous operation, an intermittent mode can reduce the thermal interference coefficient by roughly 1/3–1/2.

Dasare et al. [18] performed a parametric study through a validated numerical model to identify the key elements influencing the thermal performance of the ground heat exchanger. They found that soil thermal conductivity and fluid velocity were critical parameters to enhance the heat transfer amount with soil. Pu et al. [19] illustrated that the buried depth has a negligible effect on the thermal behaviour of horizontal ground heat exchangers. They also found that the spacing distance of adjacent buried pipes is an important factor causing thermal interference between heat exchangers. The buried depth, inlet temperature, and Reynolds number all influence critical pipe spacing. Fujii et al. [20] created a full-field numerical simulation model of double-layer slinky-coil GHE in Fukuoka, Japan, from December 2010 to February 2011. The optimal depth of the upper layer was found to be 1.5 m when the depth of the lower layer was set at 2.0 m. It was found that circulation from the upper layer to the bottom layer is more efficient.

Despite such numerical studies, there is still a lack of comprehensive numerical investigation that would allow practical performance prediction and design of slinky-loop heat exchangers, particularly on the energy output efficiency for the whole heating season and intermittent operation. It has also been shown that the impacts of varied trench separations under diverse circumstances have not been investigated thoroughly, which makes it difficult to determine the size of slinky-loop heat exchangers and the system efficiency accurately. As main conclusion, it will be demonstrated that the thermal performance of slinky GHE and thermal interference between parallel heat exchanger pipes vary with trench separation, installation depth, soil properties and daily operation duration.

## 2. Description of the numerical model

Philip and de Vries [21] developed the general equations for heat and moisture flow in porous materials like soil under combined temperature and moisture gradients, and these equations serve as the basis for the governing equation here.:

$$\dot{q} = -\left(k + L_{water}\rho_l D_{T,v}\right)\nabla T - L_{water}\rho_l D_{\theta,v}\nabla\theta \tag{1}$$

where k is the thermal conductivity of soil (W/mK), the product $L\rho_l D_{T,v}$ is the contribution to the apparent thermal conductivity by latent heat transfer from vapour movement due to the temperature gradient, and $L_{water}$ is the latent heat (for evaporation/condensation) or fusion of water (for freezing/thawing) (J/kg).

According to the principle of energy balance, it is necessary for the rate at which heat is gained or lost in a control volume to be equal to the total of net rate of heat flow into the volume and the rate of heat generation or dissipation occurring in the volume. For this study, the heat transfer equation in soil containing a slinky loop ground heat exchanger is derived with the following assumptions:

- Thermal properties ( heat capacity, density and thermal conductivity ) of soil were constant and uniform [12,13,22].
- The moisture transfer, the movement of solutes in the soil and rain infiltration during heating season was ignored [12,14].

With these assumptions, the above general equation can be simplified for the conduction heat transfer in soil surrounding a heat exchanger as follows:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla(k\nabla T) = H \tag{2}$$

where $\rho$ is the density of the soil (kg/m$^3$), $C_p$ is the specific heat (J/kg K), $T$ is the temperature (K), $t$ is the time (s), $k$ is the thermal conductivity (W/mK) and $H$ is the heat generation or extraction (W/m$^3$).

For the present study, commercial CFD software package ANSYS FLUENT [23] is used to solve the above equation for transient 3D model with the complex heat exchanger configuration.

In order to avoid potential freezing problems, water-ethylene glycol (30 % by weight) mixture is used as a typical antifreeze solution [11,24,25]. For given operating conditions of water-ethylene glycol (30 % by weight) mixture in the GHE pipe, the heat transfer rate between the pipe and the surrounding soil (W) and the surface heat flux ($W/m^2$) can be obtained from CFD simulation. The surface heat flux is the ratio of the heat transfer rate to the total pipe surface area. These together with the total heat transfer for a period of operation (kWh) were used to evaluate the performance of HGHE.

The amount of heat extraction from slinky GHE is influenced by the local soil composition, soil moisture content and groundwater flow. Soil thermal diffusivities in the United Kingdom have been reported to range from $1.37 \times 10^{-7}\ m^2/s$ to $4.33 \times 10^{-6}\ m^2/s$ [12]. The thermal properties of three representative types of soil (loamy, clayey and sandy), as shown in Table 1, were used in the simulation based on the data recommended for the determination of thermal properties for horizontal ground collector loops [26].

In the UK and Europe, the commonly used pipe diameters are DN25 (i.e., 25 mm), DN32 (i.e., 32 mm), and DN40 (i.e., 40 mm). DN40 is the most frequently utilized pipe diameter in the United Kingdom [27]. The main part of the horizontal heat exchanger consisted of a circular HDPE pipe with a 40 mm diameter. The installation depth ($Z_1$) of 1.2 m under the soil surface was selected as a base case since the most common commercial installation depth for slinky GHE within the UK is 1.2 m [28]. The impact of thermal interference was simulated for different distances (separations) between adjacent trenches (defined as the distance between the centers of two trenches) ranging from 1.5 m to 11 m and for different soil types, installation depths and daily operation hours. Fig. 1 shows a schematic of a slinky-loop ground heat pump system. The CFD solution domain is shown in Fig. 2. The total depth $Z_d$ ($=Z_1 + Z_2$) of the computational domain was 10 m. For the purpose of reducing the amount of computing power that was required, a symmetrical slinky-loop heat exchanger was taken into consideration, and one half of the slinky-loop heat exchanger was modelled. The vertical boundary was defined as symmetrical surfaces, assuming the domain was part of a larger volume of soil buried with the same configuration of GHE loops. A symmetric boundary condition was applied at the planes of symmetry, which indicated zero heat flux through the symmetric plane.

The simulations were conducted for the heating season in the UK from 1st September 2022 to 31st March 2023. The simulation results are presented in terms of monthly or seasonally total heat transfer in kWh. The daily operating time for the simulations includes 24-hour continuous operation and 12-hour-on and 12-hour-off intermittent operation.

### 2.1. Initial and boundary conditions

Since the ambient temperature continuously varies and is influenced by a degree of solar radiation, this study is not focused on the diurnal variation. The top surface of the model was assumed to vary monthly with a monthly average ambient air temperature and a monthly average wind speed to avoid short-term temperature perturbations resulting from day and night radiation, precipitation, condensation, and evaporation heat transfer under vegetation in heating seasons.

The outdoor ambient air temperature influences the soil surface temperature by natural convection. The convection heat transfer coefficient between the topsoil and ambient air varies with wind speed as follows [29]:

$$h_c = 5.8 + 3.9v \quad (v < 5m/s) \tag{3}$$

$$h_c = 7.1v^{0.78} \quad (v > 5m/s) \tag{4}$$

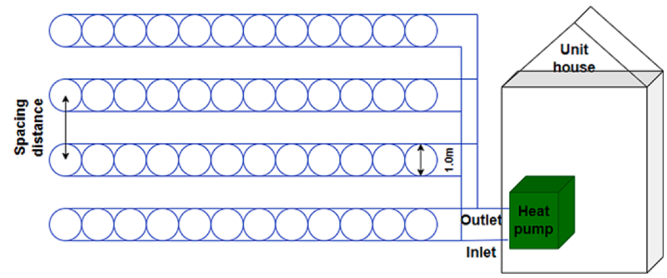



**Fig. 1.** Schematic of slinky GHE system.

Where $h_c$ is the convective heat transfer coefficient at the topsoil surface ($W/m^2K$) and $v$ is the wind speed (m/s).

The vertical boundary was defined as symmetrical surfaces, assuming the domain was part of a larger volume of soil buried with the same configuration of GHE loops. The temperature of the bottom boundary was set at 10 °C, the annual mean temperature of the deep soil in the UK [12].

During operation times, water-ethylene glycol (30 % by weight) mixture with a constant inlet temperature of 1 °C was assumed to circulate through the heat exchanger at a fluid velocity of 0.4 m/s. The single pipe mass flow rate is 0.36 kg/s. The selection of this velocity was based on the requirement of turbulent fluid flow in the pipes ($Re \approx 4000$) for efficient heat transfer but not too high to avoid excessive pressure loss. Based on these assumptions, the calculated difference between pipe temperature and fluid temperature would be less than 0.05 °C. As a result, in practical simulation, the pipe temperature (=fluid temperature) could replace the fluid convection boundary condition without much loss of accuracy. The impact of pipe thermal resistance mainly occurred at the beginning of the operation. The difference between the simulations with and without considering pipe thermal resistance was less than 5 % at the end of the first week and gradually decreased with the operation time. Thus, the thermal resistance of the pipe was ignored in this study.

The initial soil temperature is another essential set of data for the simulation and design optimization of GHE. However, it is challenging to find published data for a specific microenvironment. Measuring locally unique data is also not always feasible due to time and budget constraints. In order to understand the variation, greater depth data must be collected and monitored for at least a year. Even if the situation permits data collection, there is no guarantee that the data will not fluctuate due to changing environmental events such as rainfall, water table movement, or the possible installation of energy systems in the surrounding area. The initial soil temperature depends on the time $t$ (day) and lag$t_0$, which is from the beginning date to the day with the lowest temperature in a year (day). The initial soil temperature of different depths Z (m) for simulation at the start of the heating season was calculated with the following empirical equation for soil with homogeneous properties [30]:

$$T = T_a + T_{amp}e^{-\frac{Z}{D}}\sin\left((t - t_0)\frac{2\pi}{365} - \frac{Z}{D} - \frac{\pi}{2}\right) \tag{5}$$

where $T$ is the initial soil temperature (°C), $T_a$ is the yearly average temperature of soil (°C), $T_{amp}$ represents the yearly amplitude of surface

**Table 1**
Soil properties for simulation.

| Soil Type | Soil Name | Density ($kg/m^3$) | Specific Heat (kJ/kgK) | Thermal conductivity (W/mK) | Diffusivity ($\times 10^{-6} m^2/s$) | Location |
|---|---|---|---|---|---|---|
| Loamy | A | 1470 | 1.039 | 1.5 | 0.982 | Coventry |
| Clayey | B | 1520 | 1.014 | 0.62 | 0.402 | Mylnefield |
| Sandy | C | 1250 | 1.398 | 2.79 | 1.597 | Wellesbourne |

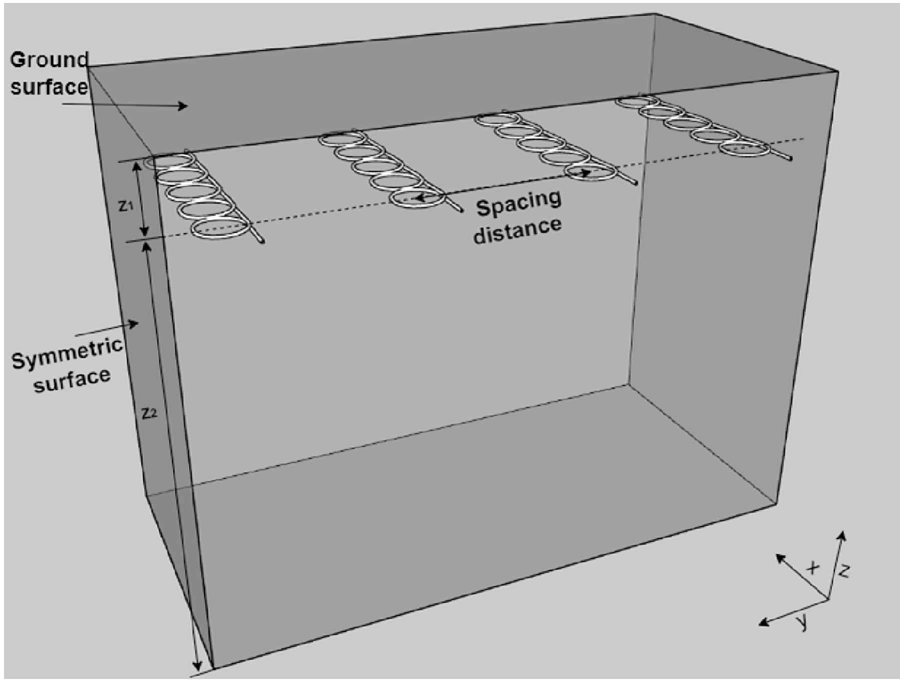



**Fig. 2.** Computational domain for soil with slinky ground heat exchanger.

temperature (°C) and D is the annual fluctuation damping depth (m).

This equation requires yearly data of ambient temperature and thermal properties of soil. The climatic data utilized for the simulation were from a weather station in the Midlands (city of Coventry) UK, in the year 2020, at the coordinates: Latitude 52° 24′ 24″ North and Longitude −2° 29′ 16″ East. The values used for this estimation are listed in Table 2 [31].

Fig. 3 depicts an example of the calculated soil temperature variation with depth for the site at the beginning of September. The variation of temperature at the time is close to linear up to 5 m deep. The calculated temperature data served as the initial conditions.

### 2.2. Mesh independence and time step size

The mesh size could have a big impact on the numerical simulation's accuracy. To obtain accurate simulation results, the grid independence study was explored by changing the mesh size until an appropriate one was found. Take a base case as an example, the time step was first set at 60 s for the first day. Four mesh sizes were considered, as shown in Table 3. The computational mesh was refined in areas where the heat transfer would be highest, i.e., near the GHE.

The heat exchange rates for four mesh sizes at the 1st, 6th, 12th and 24th hour were selected for comparison. Fig. 4 depicts the heat transfer rates per unit trench length of the slinky-loop GHE for various mesh sizes. It is noticeable that the difference in the predicted heat transfer decreases with the increase in cell number. The relative difference between the two finest mesh sizes is lower than 0.1 %; mesh size iii was therefore chosen for the CFD simulation. It is concluded that the soil domain element size can be set at 0.08 m, and the size near the pipe surface can be taken at 0.006 m. A total cell number of 1,478,186 shows a good balance between calculation time and accuracy.

The time step independence study was then performed with grid size iii. Different time step sizes were used, ranging from 60 s to 3600 s. The

**Table 2**
Data for estimating ground temperature variation at the beginning of September.

| Mean ground temperature, $T_a$ (°C) | 10 |
|---|---|
| Maximum average air temperature, $T_{max}$(°C) | 17 |
| Minimum average air temperature, $T_{min}$ (°C) | 4 |
| Temperature amplitude of air, $T_{amp}$ (°C) | 6.5 |
| Day of $T_{min}$, $t_0$ | 37 |
| Soil diffusivity, $\alpha$ ($m^2$/day) | 0.085 (for loam) |

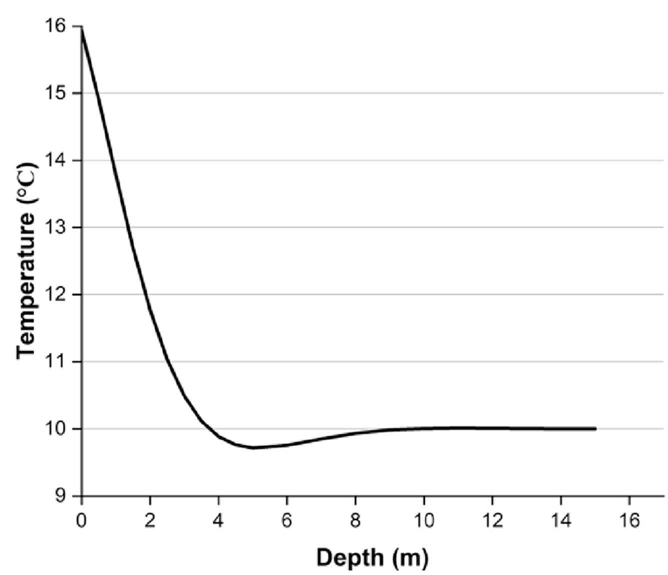



**Fig. 3.** Initial ground temperature profile.

**Table 3**
Mesh sizes for mesh independence study.

| Mesh size number | Cell size near pipe | Cells away from pipe | Total cell number |
|---|---|---|---|
| i | 0.02 $m$ | 0.2 $m$ | 240,168 |
| ii | 0.01 $m$ | 0.1 $m$ | 819,486 |
| iii | 0.006 $m$ | 0.08 $m$ | 1,478,186 |
| iv | 0.006 $m$ | 0.06 $m$ | 2,307,900 |

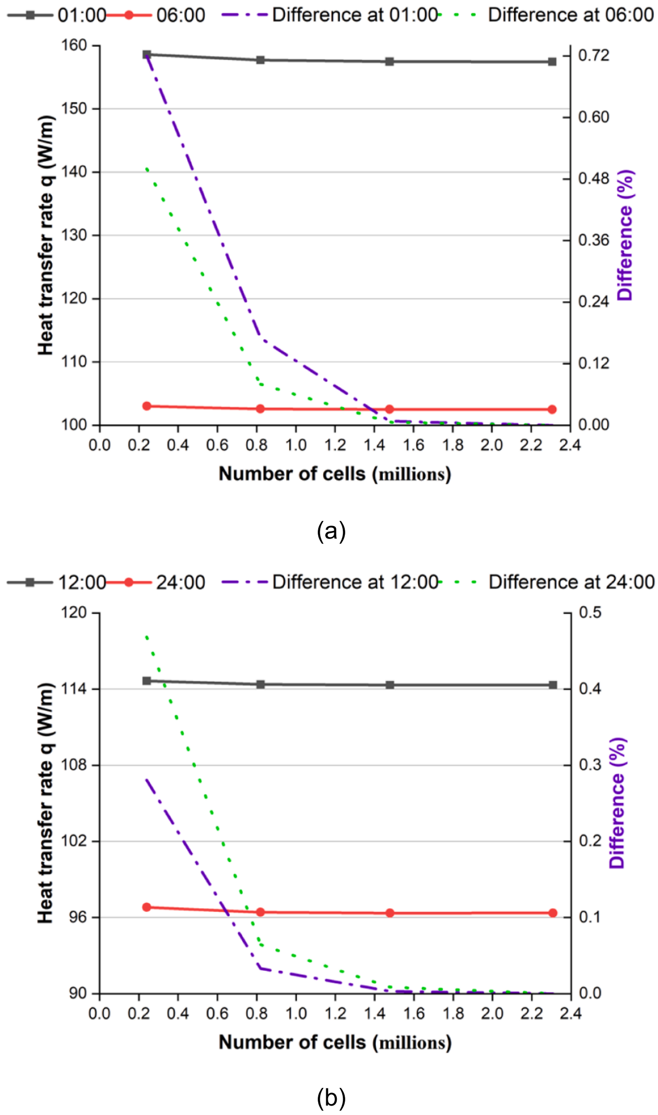



**Fig. 4.** Mesh independence study.

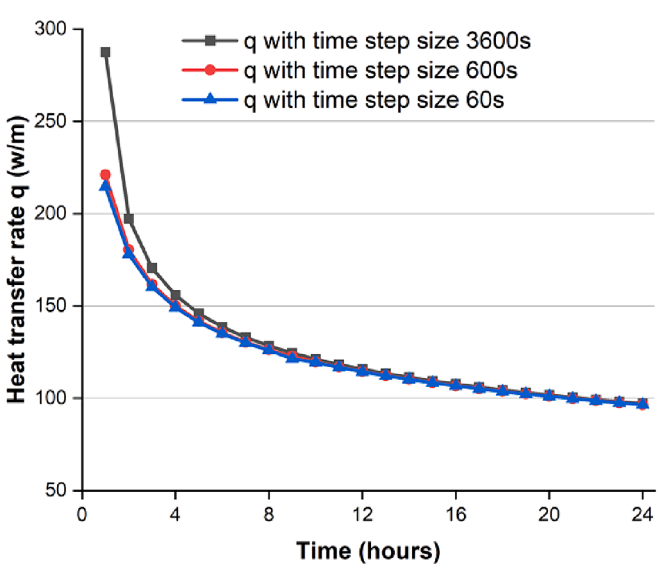



**Fig. 5.** Heat transfer rate for various time step size on the first day.

simulation results in Fig. 5 show that for the first hour, the time step significantly affects calculation accuracy, with a difference of about 30 % in the heat transfer rate (q) with 600 s and 3600 s time steps. The difference decreased with time but was still 5 % by the end of the third hour.

Table 4 compares the simulation results for the heat transfer rate with three time steps at different times. At the end of the first hour, the difference in the simulated heat transfer rate between 60 s and 3600 s time steps was approximately 34 %, while the difference between 60 s and 600 s time steps was around 3 %. The difference between the time steps of 60 s and 600 s was less than 1 % after the third hour. The difference in the simulated heat transfer rate at the end of the first day was about 0.5 % between the 600 s and 3600 s time steps, and the difference was negligible between the smaller time steps of 60 s and 600 s.

It can be seen from Fig. 6 that the difference in the simulated heat transfer rate between the larger time steps of 3600 s and 60 s was around 6 % at the end of the third hour and then decreased to 3 % at the end of the 6th hour. The difference decreased with time, and at the end of the first day, it was less than 0.59 % and became lower than 0.07 % after 10 days of operation.

Fig. 7 shows the heat transfer amount for three-time step sizes during different periods. For the predicted amount of heat extraction on the first day, the difference between time step sizes of 60 s and 3600 s was approximately 9 % and became negligible on the second day. Therefore, the time step was taken as 60 s for the first day prediction, and a time step size of 3600 s was used in the rest of the heating season simulation.

### 2.3. Validation of CFD model

The present simulation model was validated against the published experimental data measured by Wu et al. [14]. Wu et al. investigated the performance of a slinky GHE by placing four parallel slinky GHE loops in an 80 m long by 20 m wide paddock area at a depth of approximately 1.2 m beneath the ground surface. The soil temperature distribution at various times was recorded. For the validation, the measured climatic data and topsoil temperature at 00:00 on November 7, 2009, were set as the initial conditions. Fig. 8 shows that the predicted soil temperature profiles agree very well with the experimental results 14]. The maximum difference between predicted and measured soil temperatures was 0.6 °C at a depth of 0.02 m in the middle of the day (12:00). This could be due to the model's assumption of constant and homogeneous soil thermophysical parameters; however, real soil properties might not be uniform, especially around the surface. For example, there was some vegetation, and the soil surface would not be as flat as assumed, with an unevenness likely to be 0.02 m or more. When the depth is greater than 0.1 m, the predicted temperature has the same trend as the measurement, indicating a good agreement between the current work and experimental measurements.

## 3. Results and discussion

Thermal interference among adjacent parallel pipes has a large impact on overall thermal performance. Simulations were conducted to determine the interference in terms of the effect of the spacing distance between adjacent loops on heat exchange. The simulation was also investigated for the effects of initial soil temperature, installation depth,

**Table 4**
Time step size study.

| Time step size (s) | Heat transfer rate at the end of each hour/day (W/m) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1st hour | 3rd hour | 6th hour | Day 1 | Day 2 | Day 3 | Day 10 |
| 60 | 214.64 | 160.30 | 134.93 | 96.47 | 80.37 | 72.04 | 54.89 |
| 600 | 221.11 | 161.68 | 135.47 | 96.55 | 80.41 | 72.06 | 54.89 |
| 3600 | 287.51 | 170.50 | 138.65 | 97.04 | 80.63 | 72.21 | 54.85 |

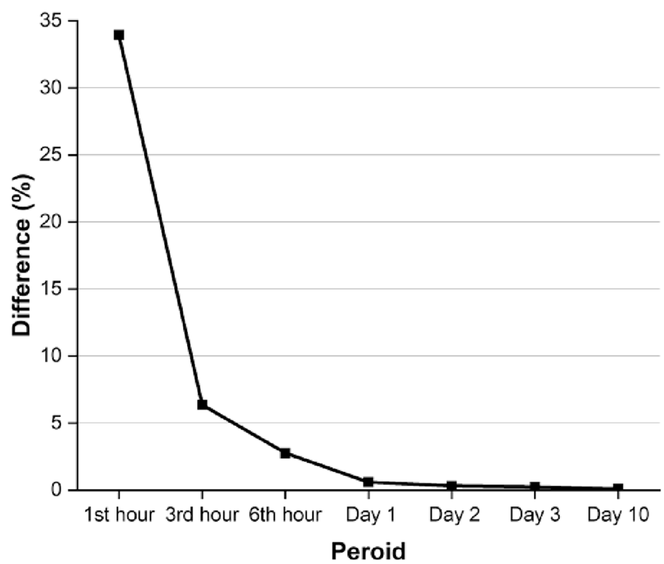



**Fig. 6.** The difference between time step size 60 s and 3600 s at selected time.

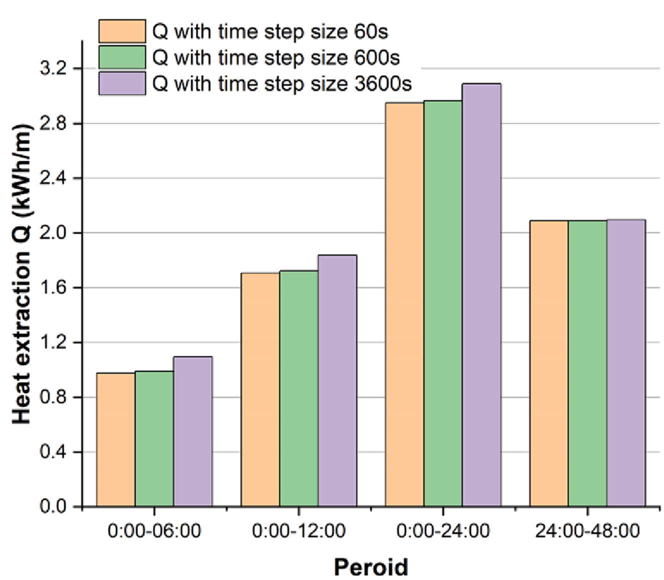



**Fig. 7.** Heat transfer amount for various time step size during different period.

soil thermal properties, loop trench spacing distance, continuous heating operation and intermittent operation on GHE performance. The results are presented as the amount of heat transfer per meter of trench length for a given period (in kWh/m).

### 3.1. The effect of the interference of different slinky loops for a base case

To study the thermal interference in terms of the effect of spacing between adjacent loops on heat exchange, different cases have been simulated under the same boundary conditions with loamy soil. The centre-to-centre distances of 1.5 m, 2.0 m, 2.5 m, 3.5 m, 4.5 m, 6.0 m, 8.5 m, and 11.0 m were considered. The base case was mentioned in the model description section, with the heat exchanger 1.2 m deep from the top surface. Fig. 9 shows the variation in monthly heat extraction per metre length of the trench occupied by heat exchangers at various loop spacing distances.

The thermal interference between parallel pipe loops decreased from September to March. The heat extraction amount decreased from September to February and then increased during March. When the spacing distance between heat exchangers is greater than 6 m, the difference of the heat extraction amount is much less than in short distance cases. For example, in September, the heat extraction is 41.39 kWh/m, 41.42 kWh/m, and 41.43 kWh/m, respectively, at 6.0 m, 8.5 m and 11 m. By contrast, for spacing distances at 1.5 m, 2.5 m and 4.5 m, the heat transfer amount in September is 28.54 kWh/m, 37.31 kWh/m and 41.12 kWh/m, respectively. The difference between the spacing distances of 1.5 m and 6 m was 31 % in September and then increased to 42 % in March. The total amount of heat extraction from the slinky loop is compared under different spacing distances in Fig. 10 (a).

Fig. 10 (b) shows that by increasing the distance between slinky GHE trench, annual energy output approaches the single loop operation, i.e., no thermal interference. Energy output efficiency η is calculated based on the 7-month heat extraction values for the slinky GHE using the following expression:

$$\eta = \frac{Q_d}{Q_s} \times 100\% \tag{6}$$

Where $Q_S$ is the heat extraction of a single loop slinky GHE without considering multiple trench loop thermal interaction, and $Q_d$ is the heat extraction from one of the loops of slinky GHE under different trench separation distances.

From this figure, a nearly perfect polynomial correlation can be obtained between energy output efficiency and spacing distance.

$$\eta = -0.03L^4 + 1.01L^3 - 11.17L^2 + 54.68L - 3.28 \tag{7}$$

Where η is energy output efficiency (%), $L$ is the distance of trench separation (m).

This correlation could be used to estimate the thermal performance of other different spacing distances. The thermal performance is greatly enhanced when the minimum is increased to 3.5 m. Further improvement is seen at 4.5 m spacing, while the benefit of increasing spacing beyond 6 m becomes negligible. As a result, considering the practical construction of the HGHE, the spacing distance between 5–6 m is suggested compared with ideal (no interference) conditions, since further increasing the distance leads to less improvement of heat extraction rate and a higher installation cost but little gain in total energy output for a given land area. Considering the limit of the land area, if the spacing distance is less than 5 m, the following simpler correlation can be used to predict the energy output efficiency:

$$\eta = 0.82L^3 - 11.63L^2 + 58.36L - 7.56 \tag{8}$$

To further simplify the expression for the separation distance of not more than 5 m, a quadratic equation can be used with a loss of accuracy of less than 3 %:

$$\eta = -3.69L^2 + 34.75L + 13.68 \tag{9}$$

### 3.2. The effect of initial soil temperature

Fig. 11 depicts the simulation results of heat transfer amount through the slinky-loop heat exchanger at a depth of 1.2 m in loamy soil with two types of initial soil temperature – constant soil temperature of 10 °C and varying temperature with the depth at the beginning of the heating season. The centre-to-centre distance of 11 m was considered for this comparison. The calculated temperature at 1.2 m deep, for instance, was 14.3 °C instead of the constant value of 10 °C, and the resulting discrepancy in soil temperature would have a significant impact on the heat transfer rate in the first few heating months. The difference for the first month was 16 %, and then decreased to 6 % and 2 % at the end of the second and third month, respectively. The effect of the initial soil temperature decreased further and became negligible at the end of the heating season.

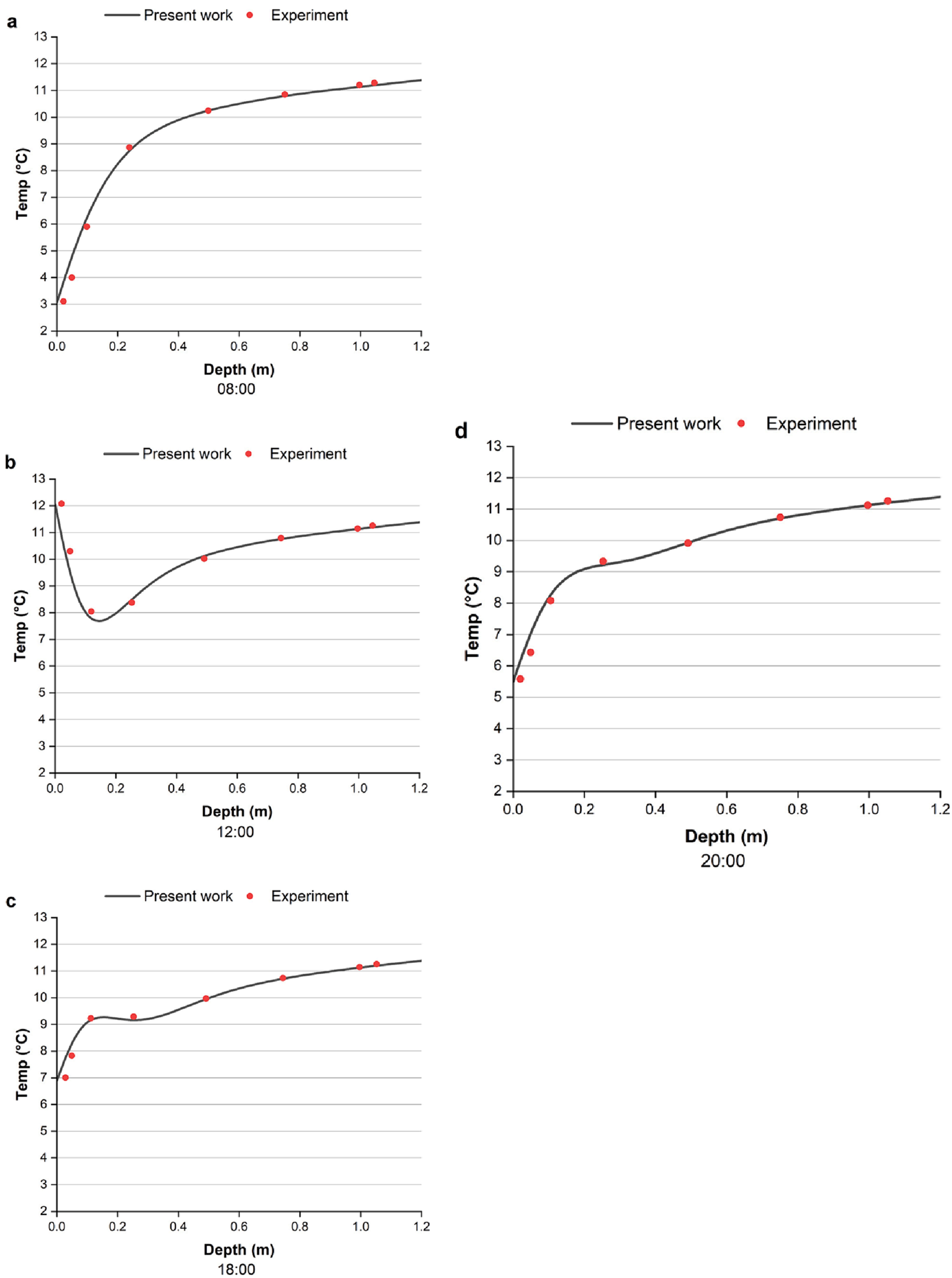



**Fig. 8.** Comparison of the soil temperature between the present numerical model and the experimental results of Wu et al. [14].

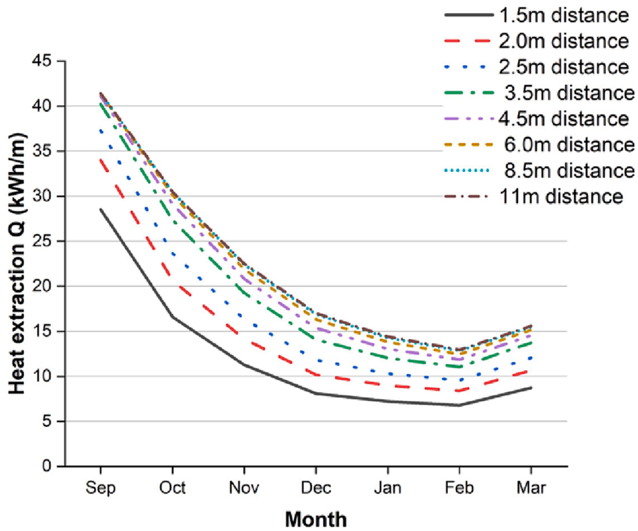



**Fig. 9.** Monthly heat extraction under different spacing distances.

### 3.3. *The effect of the soil thermal conductivity on the interference of different slinky loops*

To investigate the impact of trench spacing distance and soil texture on the performance of the slinky ground heat exchanger, further simulation was carried out using three types of soil with different thermal conductivities: 0.62 W/mK, 1.5 W/mK and 2.79 W/mK as shown in Table 1. The installation depth was 1.2 m. The centre-to-centre distance of adjacent loops for simulation was from 1.5 m to 11 m.

Fig. 12 (a) depicts that the amount of heat extraction for horizontal slinky-loop ground heat exchangers increases with the thermal conductivity of the soil. The annual heat extraction with a high soil thermal conductivity of 2.79 W/mK was around 260 % higher than that with a low thermal conductivity (0.62 W/mK). The total heat extraction from soil B (clayey) during the heating season increased from 45 kWh/m for the GHE separated at 1.5 m distance to 75 kWh/m at 11 m distance. The mean heat transfer rate of the GHE separated at 6 m is 29 W/m for soil A (loamy), 14 W/m for soil B (clayey), and 51 W/m for soil C (sandy). The total heat extraction from soil A (loamy) (87–154 kWh/m) and soil C (sandy) (148–267 kWh/m) was on average 123 % and 297 %, respectively, higher than that from soil B (clayey). Thus, soil with higher thermal conductivity would allow more heat to be extracted from the surrounding soil, especially when the distance of trench separations increased. Therefore, the thermal conductivity of the soil surrounding the pipe is a very important parameter for the overall thermal performance of the GHE.

The decrease in heat extraction was significant with a very small spacing distance of 1.5 m. This size of spacing would degrade overall thermal performance by 40–45 %, as demonstrated in Fig. 12 (b). The results show that thermal interactions between slinky GHE would have a larger impact at a smaller distance. At the end of seven months of non-stop operation, the energy output efficiency at a spacing distance of 1.5 m was 60 %, 57 %, and 55 % for the soil thermal conductivity of 0.62 W/mK (clayey), 1.5 W/mK (loamy) and 2.79 W/mK (sandy) respectively. Moreover, the results indicate that by increasing the distance between slinky GHE, the difference in efficiency among the three types of soil decreased.

For sandy soil with a thermal conductivity of 2.79 W/mK within a separation distance of 5 m, the relationship between energy output efficiency and spacing distance can be expressed as a simplified quadratic equation:

$$\eta = -4.12L^2 + 37.34L + 8.9 \tag{10}$$

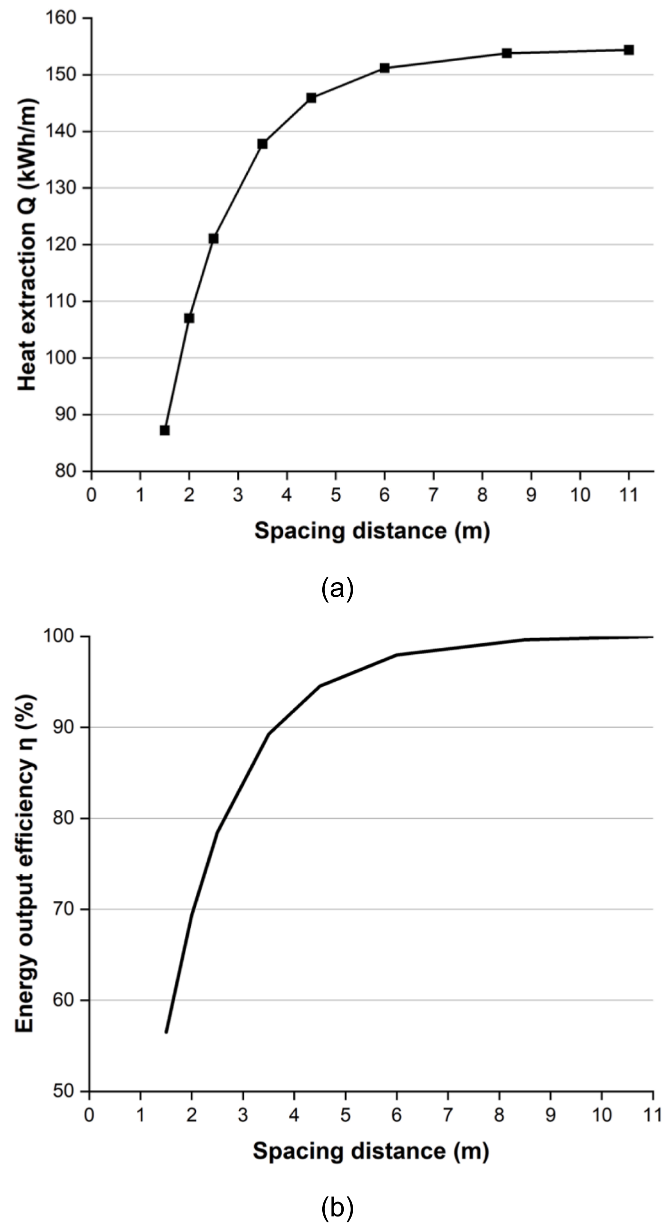



**Fig. 10.** Effect of spacing distance between adjacent trenches on heat extraction through the slinky-loop heat exchanger (Base case).

For clayey soil with a thermal conductivity of 0.62 W/mK and a maximum separation distance of 5 m, a simplified quadratic equation between energy output efficiency and spacing distance can be derived:

$$\eta = -4.36L^2 + 37.94L + 13.69 \tag{11}$$

It can be concluded that soil with high thermal conductivity would exacerbate the phenomenon of thermal interference between parallel pipes with a small separation distance. The rate of heat transfer was greater in soil with a higher thermal conductivity, resulting in a more rapid decrease in soil temperature between adjacent trenches during the same period. When installing horizontal slinky heat exchangers in soil with high thermal conductivity, the spacing between pipes should be given consideration. However, in soil with low thermal conductivity, the impact of different spacing between pipes was relatively small compared to soil with high thermal conductivity.

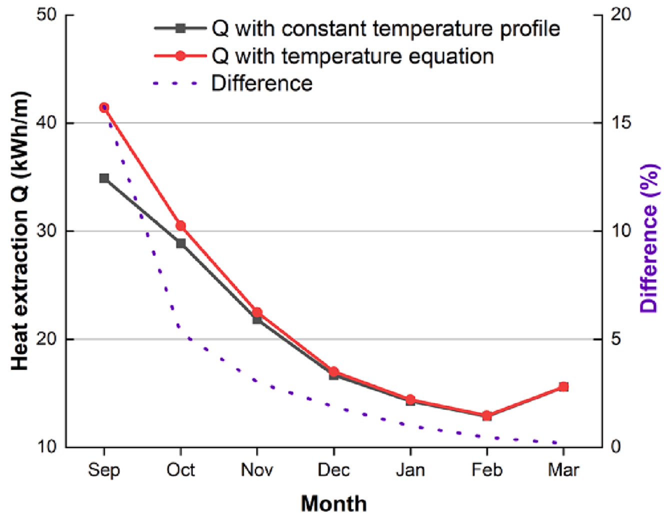
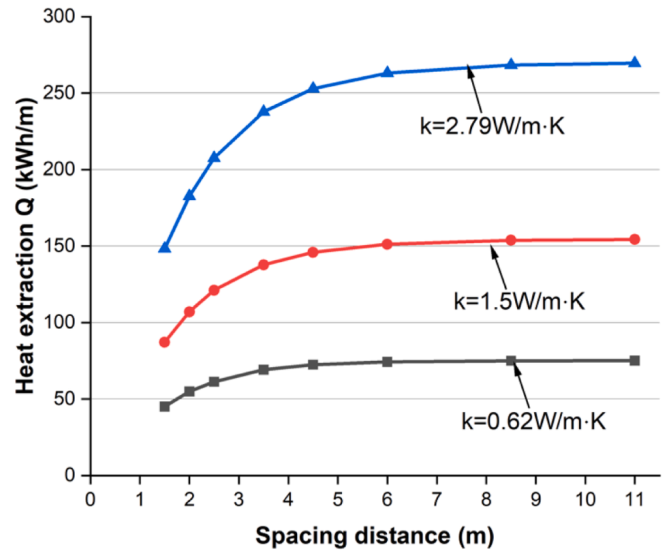



**Fig. 11.** Effect of initial soil temperature on the predicted heat extraction through the heat exchanger.

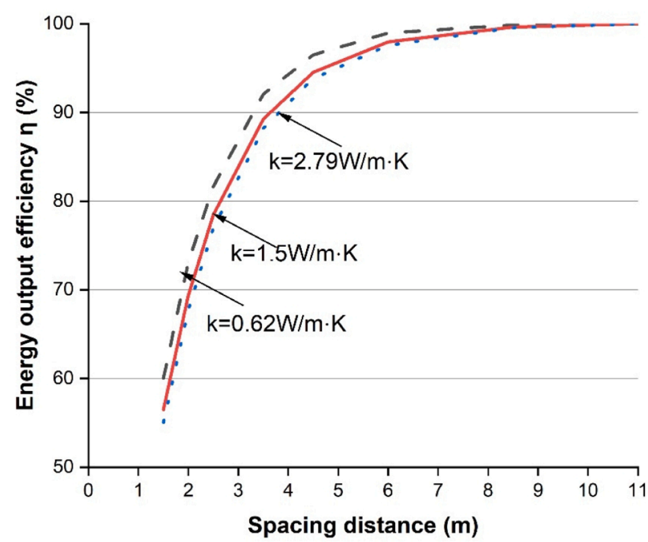
### 3.4. The effect of installation depth on the interference of different slinky loops

Fig. 13 depicts the total heat extraction per unit length of trench for the heating season of seven months for three installation depths. The soil type for simulation is loamy. The energy extracted from the surrounding ground increased from 100 kWh/m to 162 kWh/m at a depth of 0.9 m as the trench spacing distance increased from 1.5 m to 11 m. When the heat exchanger was installed at 1.2 m and 1.5 m, the heat extraction varied from 87 kWh/m to 154 kWh/m and 80 kWh/m to 150 kWh/m, respectively, under increasing trench separation distance. The mean heat transfer rate of the GHE for the spacing distance of 6 m was 31 W/m at 0.9 m depth, 29 W/m (1.2 m depth), and 28 W/m (1.5 m depth). Contrary to conventional understanding (based on a constant and uniform initial soil temperature), the results indicated that the total heat extraction during seven months decreased with increasing installation depth of the heat exchanger because of the higher initial soil temperature at shallower depth at the beginning of September. The topsoil was heated in the summer by solar radiation and warm air during the initial operating time, as shown in Fig. 3. In March, heat transfer amount through the heat exchanger in relatively shallow ground also increased due to the warming of the soil near the top surface by the surrounding air. However, the effect of depth depends on when the operation begins. If heating starts later from a cold month like December, when the topsoil is cooler, the heat extraction for December would increase with the installation depth, as shown in Fig. 14. The heat extraction amount in December for the spacing distance of 6 m was 18.5 kWh/m at 0.9 m depth, 18.9 kWh/m (1.2 m depth) and 19.5 kWh/m (1.5 m depth). The difference between varying depths is lower in the shorter spacing distance between adjacent trenches. For example, the heat extraction amount for 2 m spacing distance is 15.2 kWh/m at 0.9 m depth, 15.4 kWh/m at 1.2 m depth, and 15.6 kWh/m at 1.5 m depth. Because of this, the slinky heat exchanger of the ground source heat pump that is designed to provide space heat during the winter months should be located at a deeper position in order to achieve maximum efficiency. Installing the heat exchanger in a shallow trench, on the other hand, could be advantageous for a short period of operation in the autumn (or in the spring, if there is a requirement for heating, such as hot water).

For trench spacing differences from 1.5 m to 6 m, the energy output efficiency at 0.9 m depth increased from 62 % to 99 %, while the energy output efficiency for the depth of 1.2 m and 1.5 m changed from 57 % to 98 % and 53 % to 97 %, respectively. The changes of energy output at 0.9 m depth were less than those of the heat exchangers buried deeper




(a)




(b)

**Fig. 12.** Effect of soil type on variations in heat extraction through the slinky-loop heat exchanger.

(1.2 m and 1.5 m). This can be explained by the fact that the performance of a heat exchanger is affected by both climatic conditions and thermal interference, but the effect of the climatic conditions is greater in shallower soil. As a result, the spacing distance between parallel pipes affects deeper installation more.

When the separation distance is less than 5 m and the installation depth is 0.9 m, a simplified quadratic equation between energy output efficiency and spacing distance can be established:

$$\eta = -4.34L^2 + 37.04L + 16.8 \quad (12)$$

When the separation distance is no more than 5 m and the installation depth is 1.5 m, the relationship between energy output efficiency and spacing distance can be described as:

$$\eta = -4L^2 + 37.09L + 6.9 \quad (13)$$

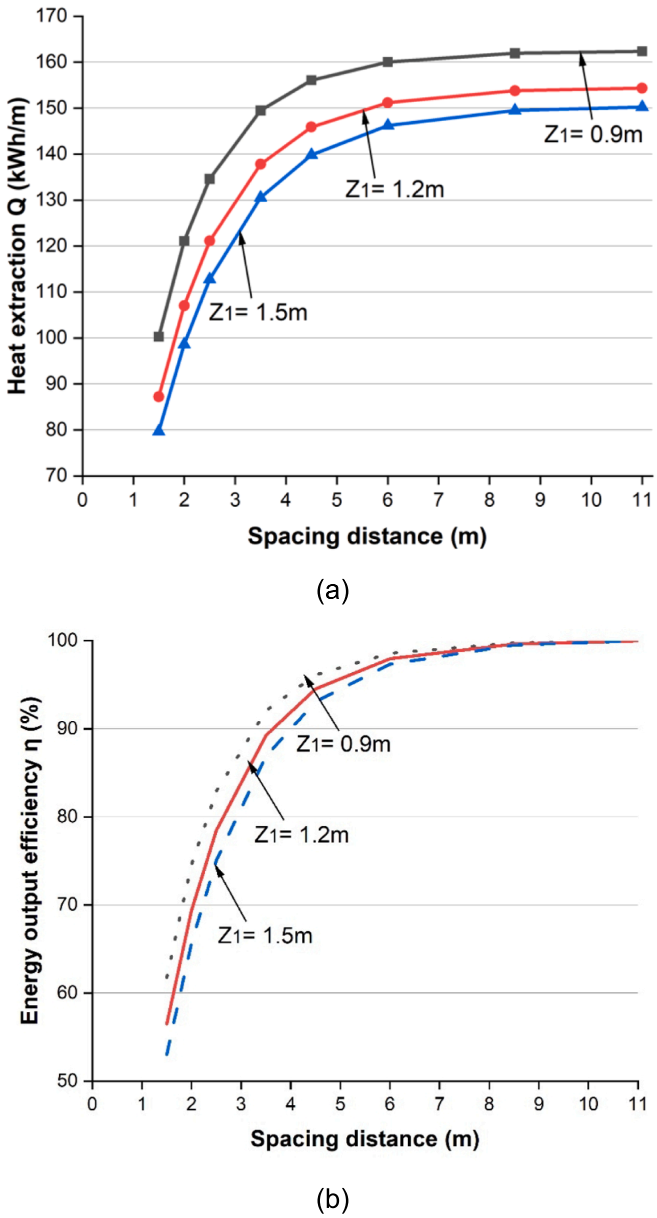



**Fig. 13.** Effect of installation depth on variations in heat extraction through the slinky-loop heat exchanger (heating season ) .

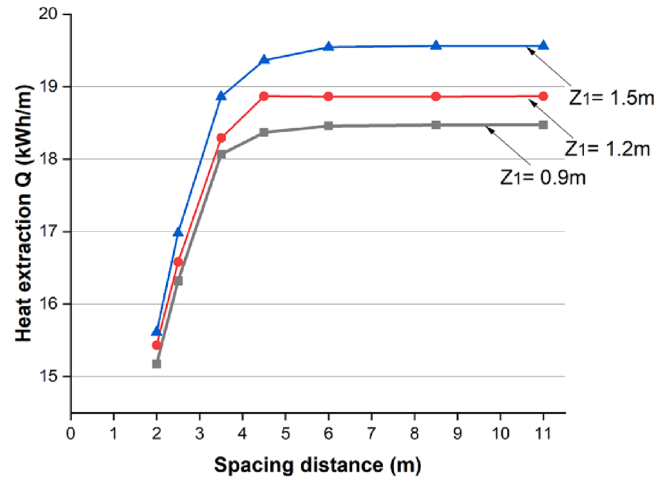



**Fig. 14.** Effect of installation depth on variations in heat extraction through the slinky-loop heat exchanger in December.

The results indicate that there was a similar variation trend with the separation distance for the three installation depths. Again, when the separation distance was greater than 6 m, the variation in spacing distance had only a small change in energy output. By comparison, when the distance was much less than 6 m, the dependency of energy output on the pipe spacing distance would be considerable. Installation depth has less influence than trench separations on the thermal performance.

### 3.5. *The effect of intermittent operation on the interference of different slinky loops*

Fig. 15 shows the heat extraction under different spacing distances for two operation modes. One is continuous running for the entire heating season, while the other is intermittent operation with 12-hour-on (heating operation) and 12-hour-off (heat recovery). For these simulations, the installation depth is 1.2 m, and the soil type is loamy. It can be observed that for continuous operation, heat transfer increased with spacing distance by 43 %, from 87 kWh/m at 1.5 m to 154 kWh/m at 11 m, but for intermittent operation, the increase was about 38 % (from 76 kWh/m to 124 kWh/m). The mean heat transfer rate of the GHE separated at 6 m is 29 W/m for continuous operation and 47 W/m for intermittent 12 h operation. It also shows that total heat extraction in the intermittent operation mode was lower because of less total operating time than that for continuous operation for a seven-month heating season. Although the heat transfer time of continuous mode was twice than that of intermittent mode, the difference in heat extraction amount between two modes was less than 25 %. This is because heat extraction amount is limited by the thermal capacity of the surrounding soil.

As discussed earlier, heat transfer between adjacent parallel pipes interfered with each other, resulting in a reduction in overall thermal performance. As demonstrated in Fig. 14 (b), the performance of the horizontal slinky GHE is highly affected by the spacing distance under 4 m. As the spacing distance increased, the energy output increased to 95 %, 98 % and 99 % of full capacity when the spacing distance between GHE loops was 4.5 m, 6 m and 8.5 m, respectively.

It also indicates that energy output efficiency with continuous operation increased by 38 % from spacing distance of 1.5 m to 4.5 m, while the increase with the intermittent operation mode was 33 %. This is because the thermal interference for a short distance in continuous operation would be greater than that in intermittent operation as a result of heat depletion in the ground with operating time. The off period in the intermittent operation lessened the effects of heat depletion. It would enable the ground to partially recover thermal condition before the next cycle begins, improving thermal performance for the subsequent heating cycle. When the spacing distance between trenches was larger than 4.5 m, the two operation modes would have almost the same trend in the correlation between spacing distance and energy output.

For intermittent operation, when the separation distance is not more than 5 m, a simplified quadratic equation can be obtained between energy output efficiency and spacing distance:

$$\eta = -4.38L^2 + 36.71L + 17.63 \quad (14)$$

It was found that the most influential parameter on thermal performance is the thermal conductivity of the soil surrounding the heat exchanger pipe. The total heat extraction amount of GHE in sandy soil with higher soil thermal conductivity is almost 3.6 times higher than that installed in clayey soil. The variation in spacing distance between adjacent trenches also has an important impact on thermal performance. The total heat extraction amount for the single-loop heat exchanger is 1.8 times greater than the 1.5 m short spacing distance between parallel trenches. The difference in total heat extraction amount between continuous operation and intermittent operation for various spacing distances ranges from 14

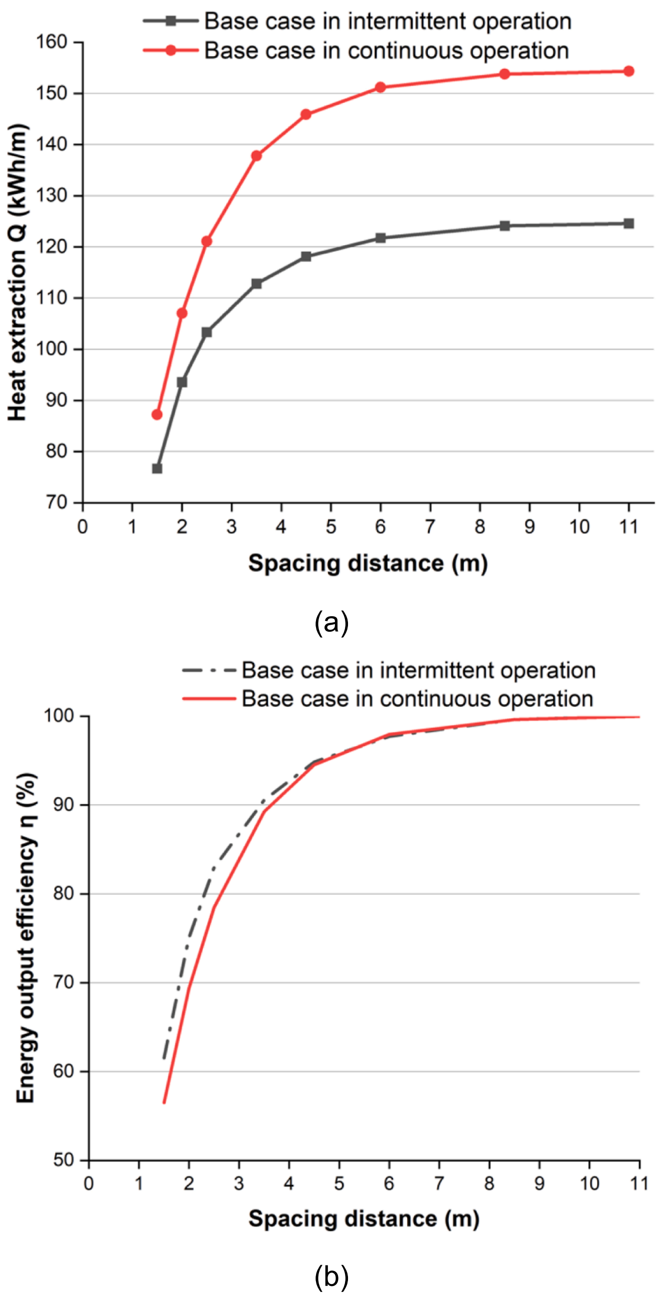



**Fig. 15.** Variations in heat extraction by slinky-loop heat exchangers (in continuous and intermittent operation).

% to 22 %. In addition, the installation depth has minimal impact compared to the other operation conditions.

## 4. Conclusion

A 3D CFD model has been developed for dynamic thermal performance simulation of the horizontal slinky-loop ground heat exchangers with different trench separations for different installation depths, soil properties and daily operation hours. The effect of trench separation was analysed for separation distances from 1.5 to 11 m. The numerical model was validated using measured data from literature.

The thermal performance of a slinky-loop heat exchanger was predicted with two types of initial soil temperature – constant and varying with depth. The discrepancy in predicted heat transfer through a 1.2 m deep heat exchanger in loamy soil using a constant temperature profile compared with that with varying temperatures would be up to 16 % at the end of the first month's operation and then drop to 6 % and 2 % in the second and third months, respectively. The heat transfer difference for the first month would be far greater for a heat exchanger placed at shallower depths because of a larger temperature difference between the constant value and varying profile.

Heat transfer between parallel pipes would interfere with each other, resulting in a reduction in overall thermal performance if the separation distance is too small. Correlations have been developed from the numerical simulation to estimate the thermal performance of different spacing distances. It is suggested that the centre-to-centre trench separation distance should be between 5 m and 6 m to achieve good thermal performance while making use of the available land.

The heat transfer amount through a heat exchanger is dependent on the depth of installation and the composition of the soil. The predicted total heat extraction for a heating season would decrease with the increasing depth of installation. This is because the topsoil was heated in the summer by solar radiation and warm air in the early period of the heating season while the rising air and soil temperatures in the later part of the heating season led to a higher temperature in the shallower soil. However, if heating starts later from a cold month like December, when the topsoil is cooler, the total heat extraction would increase with the installation depth. The results of the simulation also indicated that the effect of the trench separation would increase with the installation depth. However, installation depth has less influence than trench separations on thermal performance.

The simulation results showed that the increase in soil thermal conductivity would greatly improve the overall performance during a seven-month heat extraction for a heat exchanger installed at 1.2 m depth, with 297 % and 123 % higher in sandy and loam soil, respectively, than in clayey soil. Besides, soil with a higher thermal conductivity will exacerbate the phenomenon of thermal interference between parallel pipes with a shorter separation distance. The reason is that soil types with higher thermal conductivity exhibited a higher heat transfer rate, which led to a more accelerated reduction in soil temperature between adjacent trenches during the same period.

The results also revealed that intermittent operation would reduce the effects of heat depletion and thermal interference from adjacent parallel pipes. Due to the system's off period, the effects of heat depletion would be mitigated. It would allow the ground to recover its temperature before the next heating cycle, thus improving its thermal performance.

## CRediT authorship contribution statement

**Man Luo:** Data curation, Investigation, Methodology, Software, Validation, Writing – original draft. **Guohui Gan:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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