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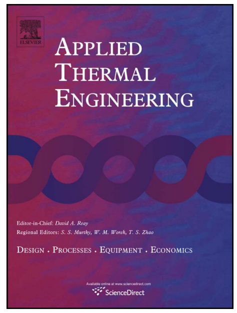

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Experimental measurement and numerical simulation of horizontal-coupled Slinky Ground Source Heat Exchangers

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Abstract

Results from both experimental measurements and 3D numerical simulations of Ground Source Heat Pump systems (GSHP) at a UK climate are presented. Experimental measurements of a horizontal coupled slinky GSHP were undertaken in Talbot Cottage at Drayton St Leonard site, Oxfordshire, UK. The measured thermophysical properties of in-situ soil were used in the CFD model. The thermal performance of slinky heat exchangers for the horizontal-coupled GSHP system for different coil diameters and slinky interval distances was investigated using a validated 3D model. Results from a two month period of monitoring the performance of the GSHP system showed that the COP decreased with the running time. The average COP of the horizontal coupled GSHP was 2.5. The numerical prediction showed that there was no significant difference in the specific heat extraction of the slinky heat exchanger at different coil diameters. However, the larger the diameter of coil, the higher the heat extraction per meter length of soil. The specific heat extraction also increased, but the heat extraction per meter length of soil decreased with the increase of coil central interval distance.

Key words: Ground source heat pump; horizontal-coupled; slinky; specific heat extraction

1. Introduction

To reduce dependence on fossil fuel energy resources and environmental degradation resulting from their combustion, renewable energy sources must play an increasingly significant role. Geothermal energy, one of the renewable energy resources, can be used to provide electricity, heating and cooling for buildings. Shallow Ground Source Heat Pump systems (GSHP) which make use of the relatively constant temperature of the earth are mainly used for space conditioning. However, the installation of the ground Heat Exchanger (HE) is costly, which is one of the main causes preventing the wide adoption of the GSHPs in the UK. Therefore, the horizontal-coupled ground source heat pump has become increasingly important. It can reduce installation cost compared to that of other GSHP systems as no drilling is necessary and only a trench 1 to 2 m in depth is required. Nevertheless, A single tier ground loop requires a large area of ground to lay the pipe network. This problem can be alleviated to some extent by employing double tier pipe arrangement or slinky ground loop. A slinky ground loop requires horizontal trench lengths of 20-30% of those for a horizontal coupled single pipe configuration, however the thermal performance of the slinky ground loop may be doubled. A first recorded slinky heat exchanger coupled GSHP system was developed by Bose and Smith [1] at Oklahoma State University. They indicated that the slinky heat exchanger enhanced the heat transfer area within a limited space when compared to a horizontal buried heat exchanger.

The performance of a heat pump is usually expressed in terms of its Coefficient Of Performance (COP) which is the ratio of energy output to supplied energy (electricity for the compressor, pump etc) of GSHP. COPs in the heating and cooling mode are indentified by COP_h and COP_c, respectively. A typical heat pump has a COP of around 4 which indicates that the heat pump produces four units of heating energy for every unit of electrical energy input. The COP of the GSHP depends on the soil type at the installation, etc. Research has been carried out to determine the performance of horizontal-coupled GSHP. Metz [2] used a horizontal-coupled GSHP to provide heating and cooling for a $104m^2$ house in Long Island, New York. During a period of one year monitoring, the obtained average COP_h and COP_c of the GSHP system were 2.46 and 1.91, respectively. İnallı and Esen [3] carried out experimental measurements of a GSHP system with horizontal-coupled heat exchanger in selected depths of 1 and 2m in Elaziğ, Turkey. After running the GSHP for heating from November 2002 to April 2003 for a room with $16.24m^2$ floor area, the obtained average COP_h of the GSHP system was 2.66 and 2.81 for the heat exchanger buried at depths of 1m and 2m, respectively. Doherty et al [4] installed and undertook experimental measurements of a horizontal slinky GSHP system in the University of Nottingham, UK. An average COP_h of approximately 2.7 was reported. Coşkun et al [5] studied the performance of a horizontal ground source compression refrigeration system in Bursa city, Turkey. The horizontal coupled heat exchanger was buried at a depth of 2.0m. The COP_c of the overall system varied between 2 and 2.5.

Research has also been undertaken for the horizontal-coupled GSHP systems by other investigators including the experimental characterisations of the thermal performance of the horizontal coupled heat exchanger and different approaches to enhance the heat transfer between the heat exchanger and the soil [6-11]. Florides and Kalogirou [12] reviewed the performance and numerical model of ground-coupled heat exchangers. They indicated that the ambient climatic conditions would affect the temperature profile below the ground surface and this should be considered when designing a horizontal coupled heat exchanger. In the UK, most of the recent studies of the horizontal coupled GSHP were focused on the heat pump output to maintain daily indoor air temperature [13-16]. Few studied the long term effect of horizontal-coupled heat exchanger on the ground temperature, which is vital for correct sizing of heat pumps to achieve an accurate prediction of their long term performance over their useful working life. In this work, the performance of a horizontal coupled slinky GSHP installed in the UK was monitored and measured results were used to validate a CFD model. The validated model was then used to predict the thermal performance of ground coupled slinky heat exchangers for different slinky diameters and slinky interval distances.

2. Experimental measurements

2.1 Experimental apparatus installation

Experimental measurements were carried out at Talbot Cottage, Drayton St Leonard site, Oxfordshire, UK where 4 parallel horizontal-coupled slinky Heat Exchanger loops were installed in a 80m long by 20m wide paddock area at a depth of around 1.2m below the ground surface. Figure 1 shows an image for one of the loops. The fluid in the heat exchanger was water-ethylene glycol (30% by weight) mixture. The ground surface was overgrown with wild flowers. Soft sand was used below and on top of the slinky heat exchanger.

To monitor the soil temperature distribution and also the performance of the horizontal-coupled heat exchanger, two holes were dug in the ground to install thermistors at various depths. One hole was dug above a portion of the ground coupled heat exchanger, the second hole served as a reference hole dug at a distance of around 2m from the other hole and with no heat exchanger installed around it. After installing the sensors, all the holes were refilled with the original soil. Monitoring started 1 month after switching on the GSHP system. A sketch of the positions of the sensors used to monitor the soil and the heat exchanger thermal performance with detailed sensor positions is shown in Figure 2. T-type thermocouples were installed at the inlet and outlet of the ground coupled heat exchangers to monitor the thermal energy extracted by the ground coupled slinky heat exchanger. Simultaneously, a mini weather station was installed to monitor the ambient air temperature, wind speed, global solar radiation, relative humidity and rain fall. All the sensors were calibrated before installation.

2.2 Analysis of experimental results

The sensor readings were taken every 30mins. Ambient air temperature and soil temperatures above a portion of heat exchanger and in the reference hole for a period of around two months from 6th Nov 2009 to 31st Dec 2009 are shown in Figures 3. The measured soil temperature at a depth of 0.25m had a similar characteristic to ambient air temperature. There were short term strong and irregular fluctuations of temperature, caused by the daily change of weather conditions. However, the temperature fluctuation ceased at a larger depth, below the depth of 0.5m, the temperature fluctuations were hardly discernible. It can be seen that soil with and without heat exchanger below had a similar temperature variation pattern at the same depth. However, the soil temperatures with a heat exchanger installed below were lower than those of the soil in the reference hole without heat exchanger under it. With the soil depth increase, the soil temperature increased without heat exchanger below it, whereas the soil temperature decreased where the heat exchanger was installed below it. This is due to the thermal energy being extracted by the heat exchanger. At a depth of 0.02m below the ground surface, there were no significant temperature differences for the soil with and without heat exchanger below them. Around 20th Dec 2009, the soil without heat exchanger installed below had a higher temperature of around 2°C than that with heat exchanger installed below. This deviation may be caused by the different soil physical properties or the heat exchanger. At a larger depth, the temperature difference between the soil with and without heat exchanger installed was larger. The temperature difference at a depth of 0.5m was around 1.5°C, and 3°C at a depth of 1m.

The ground temperature distribution was analysed in more detail for two different days-7th Nov and 28th Dec 2009. It was sunny on 7th Nov 2009, and a partly cloudy day and the ground was covered by snow on 28th Dec 2009. The measured solar radiation intensity, ambient air temperature and wind speed for the two days are shown in Figure 4(a). The measured solar radiation intensity on 7th Nov. 2009 was significantly higher than that on 28th Dec. 2009. The highest solar radiation intensity was around 350W/m^2 on 7th Nov 2009 and approximately 150W/m^2 on 28th Dec 2009. The measured ambient temperature was also higher on 7th Nov 2009. The measured average wind speed was around 1 and 2m/s on 7th Nov and 28th Dec 2009, respectively.

The various ground surface temperatures with ambient air temperature are shown in Figure 4(b), and the ground temperature distribution above the heat exchanger and without heat exchanger installed below on 7th Nov 2009 is illustrated in Figure 5. From Figures 4(b) and 5, it can be seen that the soil with and without heat exchanger installed, their surface temperature had a similar characteristic to the ambient air temperature on that day, however, the ground surface temperature was slightly higher with no heat exchanger installed below. This might be caused by different soil physical properties. They all decreased in the night from 00:00 to 8:00 due to convective and long wave radiative heat losses, and reached the lowest value of around 3℃ of the day at 8:00 in the morning, and then increased to around 13.5℃ (no HE) and 11.5℃(HE installed), respectively at noon. After 13:30 they all began to decrease due to the reduced solar radiation intensity. Because the thermal energy in the ground was extracted by the heat exchanger, the soil temperature varied between 7 and 8℃ at a depth of around 1.14m below the ground. The environmental conditions influenced the soil temperature up to a depth of around 0.5m. It can also be seen that at the same depth of around 1m from the ground surface, the soil with no heat exchanger installed below had a constant temperature around 11℃ for the whole day, which was over 3℃ higher than the soil temperature with heat exchanger installed below. At a depth of 0.25m from the ground surface, the soil without heat exchanger installed below had a temperature around 1℃ higher than that with heat exchanger installed below. It can be concluded that the extraction of thermal energy by the heat exchanger affected the soil temperature at a distance of around 0.9m from the heat exchanger during the operation period.

Figure 6 illustrates ground temperature distribution above the heat exchanger and ground temperature distribution in the reference hole on 28th Dec 2009. From Figures 4(b) and 6, it can be seen that the soil at a depth of 0.02m had a temperature around 0°C for the whole day, because the ground surface was covered with approximately 0.05m thick snow, which prevented the radiative and convective heat loss, and also the chance to absorb the diffused solar radiation at the ground surface. Its temperature was higher than the ambient air temperature at the same time. At a depth of around 1.0 m from the ground surface, the soil with no heat exchanger below had a constant temperature around 5℃ for the whole day, it was approximately 2.5℃ higher than that of the soil with heat exchanger installed below. At a depth of 0.1m from the ground surface, the soil with no heat exchanger below had a temperature around 0.5°C higher than that with heat exchanger installed below, similar to characteristics of the soil temperature distribution found on 7th Nov 2009.

Figure 7 illustrates the measured inlet and outlet fluid temperatures of the ground coupled heat exchanger. The temperatures of the inlet and outlet of the heat exchanger significantly decreased with time. However, there were no significant change in temperature difference between the inlet and outlet. The GSHP system had been continuously running for nearly two month by the time (nearly 24 hours a day). Only for a few hours (less than 1 hour a week), the temperature difference dropped to approximately 1°C from 2°C during a two month operation, because the GSHP system stopped running, and the inlet temperature for the heat exchanger began to increase for a short period. The calculated COP of the ground source heat pump system is shown in Figure 8. It can be seen that the system COP decreased slightly with the time from 6th Nov 2009 to 31st Dec 2009. It was around 2.7 on 6th Nov 2009, and decreased to approximately 2.5 on 31st Dec 2009.

2.3 Measurement of site soil properties

Three soil samples at depths of around 0.2, 0.8 and 1m below the ground surface at the test site were taken to the lab at the Department of Built Environment, University of Nottingham using 50mm deep by 50mm inner diameter aluminium cylinder tins. The thermal conductivity, thermal capacity, density and volumetric moisture content of the in situ undisturbed soil were measured using the following facilities

- KD2 pro used to measure the thermal conductivity and capacity,
- A thermostatically controlled oven, capable of maintaining a temperature between 105 and 110°C,
- A balance readable and accurate of 0.01g

The measured thermophysical properties of the soil samples are shown in Table 1. The measured thermophysical properties varied at different depths. The thermal conductivity and density were higher for the soil near the ground surface and heat exchanger than in the middle but the soil thermal capacity and the volumetric moisture content decreased with the depth. Average thermophysical properties were used in the numerical prediction.

3. Numerical prediction

A commercial CFD software package FLUENT was used to predict the thermal performance of a portion of the horizontal coupled slinky and straight heat exchangers. The transient 3 dimensional sensible heat transfer model for the ground coupled heat exchanger is as follows:

$$\frac{\partial(\rho T)}{\partial t} + \nabla \bullet (\rho \vec{V} T - \frac{k}{c} \nabla T) = \frac{q}{c} \quad (1)$$

where ρ is the density (kg/m^3), t is the time (s), T is the temperature (K), V is the fluid flow velocity (m/s), k is the thermal conductivity (W/mK), c is the specific heat (J/kgK) and q is the heat source (W/m^3).

The model was validated using the experimentally measured results using the method described below. The measured environmental conditions at 00:00 7th Nov 2009 were used as the initial conditions for the model. The predicted and the measured soil temperature distributions at selected times are shown in Figure 9. It can be seen that the predictions generally agreed with the experimental measurements. The maximum difference between the predicted and measured soil temperatures was less than 1°C, which was found near the ground surface. This might be the result of using constant and uniform soil thermophysical properties in the model, whereas the soil thermophysical properties might not be uniform particularly near the surface.

The thermal performance of a portion of a horizontal coupled slinky and straight heat exchangers was predicted using the validated CFD model. Comparisons of thermal performances of the slinky heat exchanger at different slinky (coil) diameters and different slinky (coil) interval distance were also conducted. The measured average thermophysical properties of the in situ soil detailed in section 2.3 were used in the numerical model. In the predictions, it was assumed that the horizontal-coupled straight and slinky heat exchangers were buried at a depth of 1.2m in the ground as illustrated in Figure 10. Due to a large number of meshes required to model the 3D transient heat transfer, only half of the slinky heat exchanger was applied in the model and a symmetric surface was defined at the vertical central surface as shown in Figure 10(b).

Further assumptions used to simplify the model were as follows,

- For a short length of the heat exchanger, the pipe outer surface temperature was assumed constant at 1°C for heating mode. Prediction of the thermal performance of the heat exchanger with similar dimension and environmental conditions with 1°C refrigerant fluid flow at the inlet of the heat exchanger was also undertaken, and the results showed that after running the system for more than 140 hours, there was no significant difference in the temperature distribution in the soil or the specific heat extraction between the conditions with fixed pipe temperature and fluid flow inside the heat exchanger,
- A constant temperature of 10°C was utilised at a depth of 4m from the ground surface for a short period of operating the GSHP,
- The soil thermal properties (soil thermal conductivity and diffusivity) were constant and uniform,
- The wind speed was 3m/s on the ground surface with an ambient air temperature of 5°C.

3.1 Predicted thermal performance of the horizontal-coupled straight and slinky heat exchanger

Isotherms generated from prediction for the horizontal-coupled straight and slinky heat exchanger at the elapsed time of 1 and 50hours are shown in Figures 11 and 12, respectively. For the horizontal-coupled straight heat exchanger, after running the system for 1 hour, the temperature of the soil around the heat exchanger decreased to 1°C. The temperature of the soil decreased at a distance within 0.1m from the central long axis of the heat exchanger, due to the thermal energy being extracted by the heat exchanger. At 50 hours, the heat exchanger affected the temperature of the soil within a distance of around 0.6m from the central long axis of the heat exchanger. With further running of the system, the soil temperature continuously decreased, due to the convective heat loss from the soil to the ambient air and heat extraction by the heat exchanger. The slinky heat exchanger and its surrounding soil had similar thermal characteristics as that for the straight heat exchanger under similar conditions. However, the temperature of the soil within a distance of around 0.8m from the central long axis of the heat exchanger was influenced by the heat exchanger, it was larger than that of the single straight heat exchanger system. This is because the slinky system comprised of a straight and coil heat exchangers with a small portion of the heat exchanger being in parallel located.

A parameter used to calculate the required length of borehole heat exchangers is the specific heat extraction, expressed in Watt per meter length. Typical values are in the range from 40 to 70W/m for borehole heat exchangers, dependent on soil thermal conductivity, heat pump annual operation hours, number of neighbouring boreholes, etc [17]. The variation of the predicted specific heat extraction with time for a portion of the horizontal-coupled straight and slinky heat exchangers, and the difference of the specific heat extraction between the two systems are illustrated in Figure 13. It can be seen that the specific heat extraction for both the horizontal-coupled straight and slinky heat exchangers was approximately at 46W/m initially, decreased to approximately 33 and 30W/m respectively after continuously running the GSHP system for 10hours, and further decreased to around 18 and 15W/m after running the GSHP system for 140hours. Thus, it can be concluded that the difference of the specific heat extraction between the straight and the slinky heat exchangers increased with running time. It was around 1.5W/m for the first hour, and increased to around 3W/m at 140hour. The predicted specific heat extraction was lower than that commonly used for designing GSHPs. If the total length of the heat exchanger was estimated from the over optimistic value of the specific heat extraction, the output and COP of the heat pump would be lower than expected.

The variation of the heat extraction per meter length of the soil occupied by heat exchangers is illustrated in Figure 14. Although the specific heat extraction of the slinky heat exchanger was lower than that of the straight one, the heat extraction per meter length of the soil for the slinky heat exchanger was significantly higher than that of the straight heat exchanger. At the beginning, the difference between the slinky and straight heat exchanger was about 45W per meter length of soil, and decreased to approximately 12W per meter length of soil after running the simulation for 140hours.

3.2 Effect of the coil diameter on the thermal performance of the slinky heat exchangers

The thermal characteristics of the ground coupled slinky heat exchangers at different coil diameters of 0.6, 0.8 and 1.0m were determined by running the transient state simulation for the similar environmental conditions used in section 3.1. The dimensions of the domain and the heat exchangers are shown in Table 2.

From the prediction, it was found that there was no significant difference of the specific heat extraction of the slinky heat exchanger at different coil diameters of 0.6, 0.8 and 1.0m. This might be because the horizontal-coupled straight part of the heat exchanger occupied over 50% of the total length in the simulated slinky heat exchanger. Thus by changing the diameters of the coil, there was no obvious differences of the specific heat extraction. However, the larger the diameter of the coil, the higher the heat extraction per meter length of soil. The variation of the heat extraction per meter length of the soil occupied by heat exchangers at different coil diameters are illustrated Figure 15. At the beginning, the heat extraction per meter length of soil was around 91W/m for the coil diameter of 1m, approximately 82W/m for the coil diameter of 0.8m and 72W/m for the coil diameter of 0.6m. It decreased to approximately 30W/m with a coil diameter of 1m, around 27W/m with a coil diameter of 0.8m and 24.6W/m with a coil diameter of 0.6m at 140 hours.

3.3 Effect of coil central interval distance on the thermal performance of the slinky heat exchangers

The thermal characteristics of the ground coupled slinky heat exchangers at different coil central interval distance of 1.2, 1.6, 2.0 and 3.0m were predicted using the similar environmental conditions used in sections 3.1 and 3.2.

The variation of the specific heat extraction for the slinky heat exchangers and the variation of the heat extraction per meter length of the soil occupied by heat exchangers at different coil central interval distances are illustrated Figures 16 and 17, respectively. From the prediction, it was observed that the specific heat extraction increased with the increase in the coil central interval distance. At the beginning, the specific heat extraction was 44.6W/m for a slinky with coil central interval distance of 3m, 44.2W/m for that at 2m, 44.0W/m at 1.6m and 43.8W/m at 1.2m. At 140hours, the specific heat extraction decreased to 14.9W/m for a slinky with coil central interval distance at 3m, 14.0W/m for that at 2m, 13.3W/m at 1.6m and 11.8W/m at 1.2m. However, the heat extraction per meter length of soil for a slinky decreased with the increase of coil central interval distance. At the beginning, the heat extraction per meter length of soil was 158.4W/m for a slinky with coil central interval distance of 1.2m, 130.5W/m for that at 1.6m, 113.7W/m at 2.0m and 91.3W/m at 3.0m. At 140hours, the heat extraction per meter length of soil decreased to 42.5W/m for a slinky with coil central interval distance of 1.2m, 39.3W/m for that at 1.6m, 36.1W/m for that at 2.0m and 30.5W/m at 3.0m

4. Conclusions

The thermal performance of horizontal-coupled slinky GSHP was determined both experimentally and numerically in a UK climate. During a two month period of monitoring the performance of the GSHP system, the COP of the GSHP decreased with the running time. The average COP of the horizontal coupled GSHP was 2.5. To increase the COP of the system, it required longer heat exchanger and a larger land area for heat exchanger installation.

The thermal performance of a portion of slinky GSHP at different coil diameters and different coil central interval distances was predicted using a validated 3D model. The performance of slinky heat exchangers was also compared with that of straight heat exchangers. The specific heat extraction for both the straight and slinky heat exchangers initially at 46W/m decreased with increasing system running time but at different rates. After running the systems for 140hours, the specific heat extraction of the straight pipe would be 3.5W/m higher than that of the slinky pipe. However, the heat extraction per meter length of soil for the slinky heat exchanger was significantly higher than of the straight system. There was no significant difference in the specific heat extraction of the slinky heat exchanger at different coil diameters of 0.6, 0.8 and 1.0m. However, the larger the diameter of coil, the higher the heat extraction per meter length of soil. The specific heat extraction also increased with the increase in the coil central interval distances. On the other hand, the heat extraction per meter length of soil for a slinky decreased with the increase of coil central interval distance.

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Table 1 Measured thermophysical properties of the undisturbed soil samples from the site

	Sample 1 (Depth at 1m)	**Sample 2** (Depth at 0.6m)	**Sample 3** (Depth at 0.2m)	**Average**
Soil thermal conductivity (W/m K)	1.37	1.02	1.32	1.24
Soil thermal capacity (J/kg K)	1383.32	1420.27	1591.07	1464.88
Soil density (kg/m^3)	1598.70	1431.15	1733.01	1587.62
Soil volumetric moisture content (%)	22.69	24.79	30.74	26.07

Table 2 Dimensions of domain for selected models

Model dimension	**Slinky (d=1m)**	**Slinky (d=0.8m)**	**Slinky (d=0.6m)**
Width (m)	3	2.8	2.6
Length (m)	1.5	1.5	1.5
Depth (m)	4	4	4
Diameter of the heat exchanger(m)	0.04	0.04	0.04
Total length of the heat exchanger (m)	1.5(straight part) +1.57(coil part)	1.5(straight part) +1.256(coil part)	1.5(straight part) +0.942(coil part)

Figure(s)

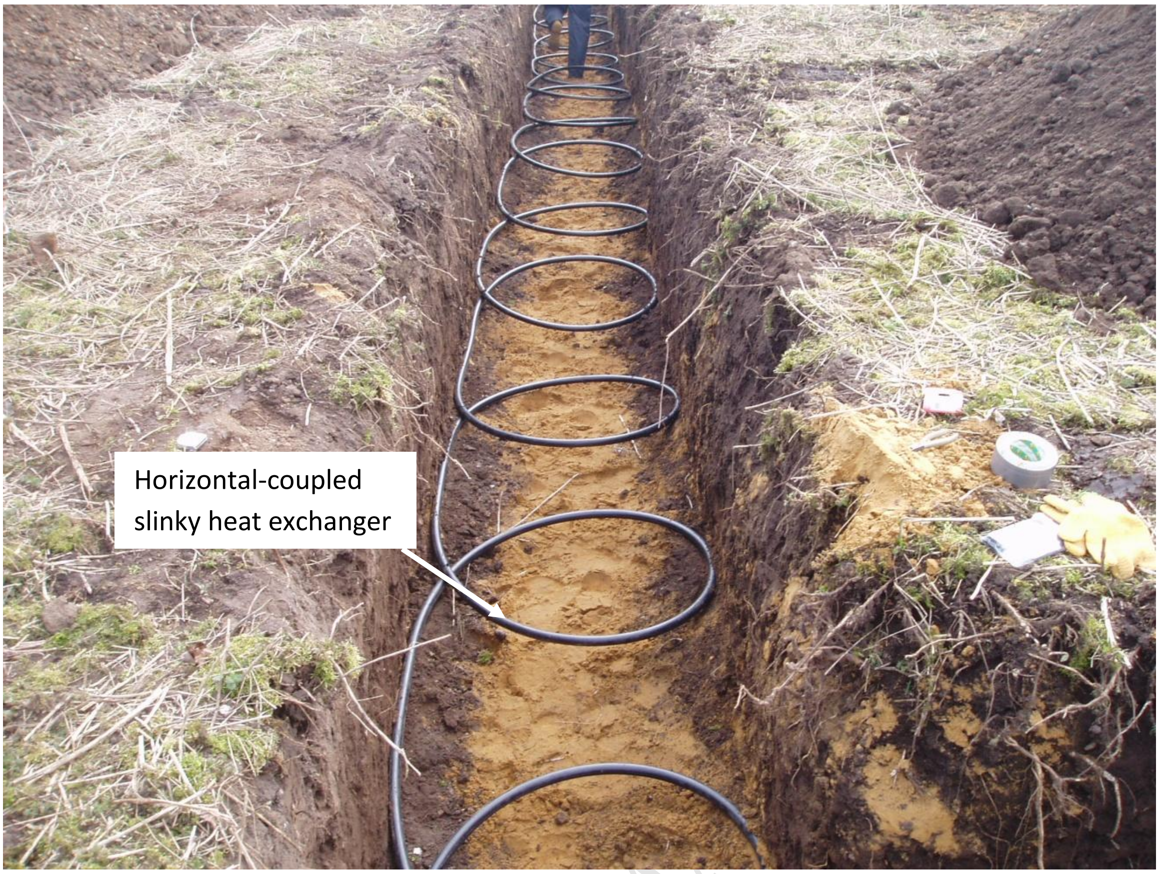
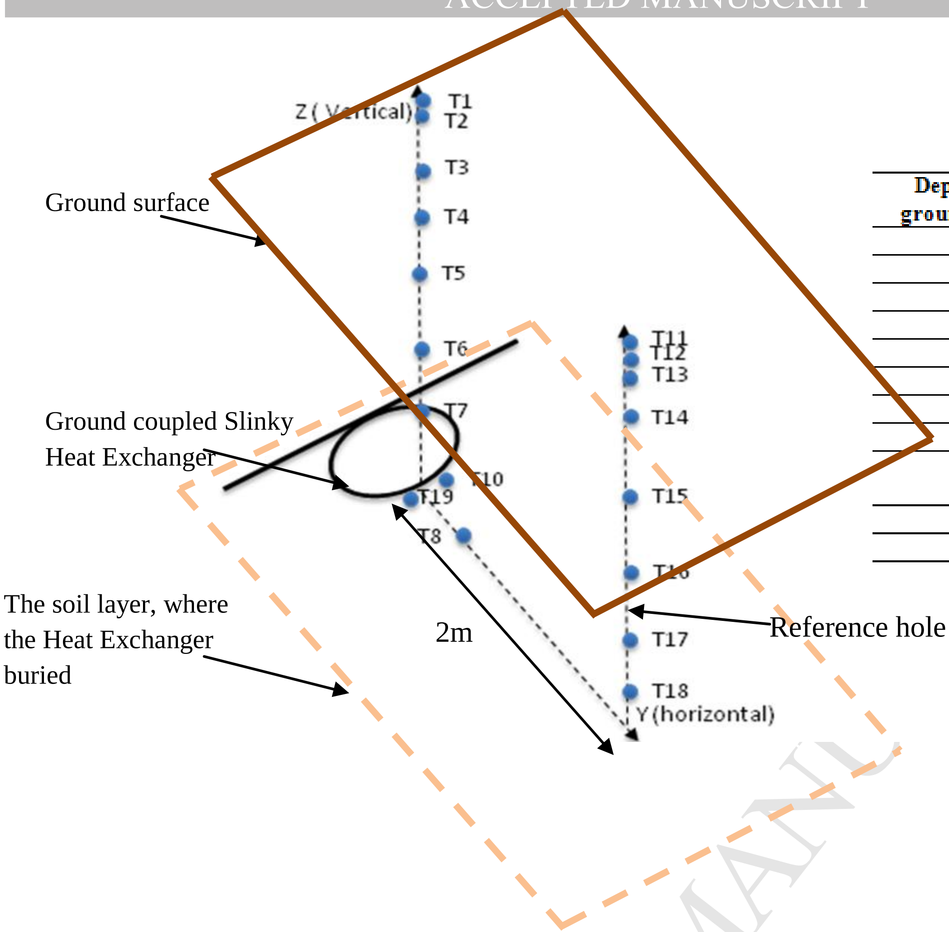
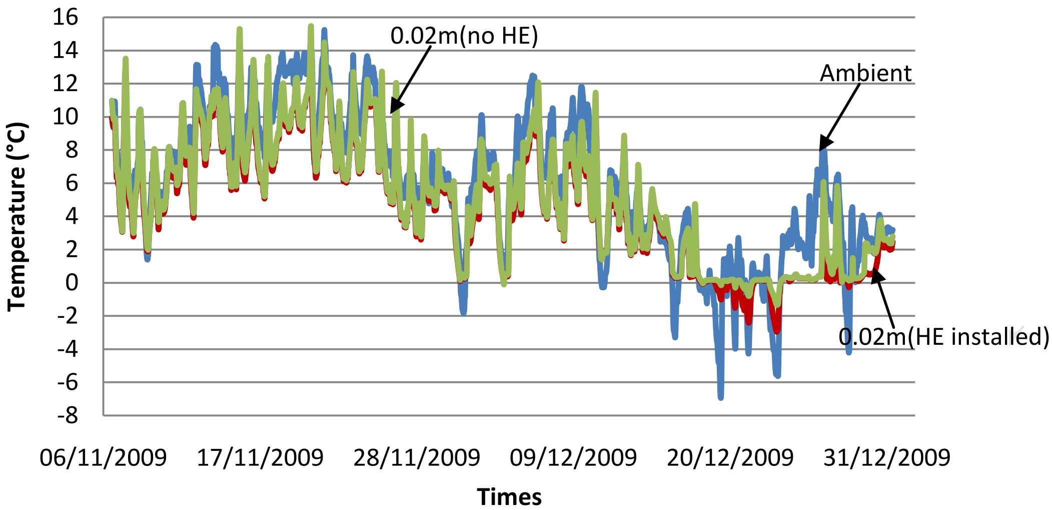


Figure 1 Image of the horizontal-coupled ground source heat exchanger at Talbot Cottage, Drayton St Leonard site, Oxfordshire, UK

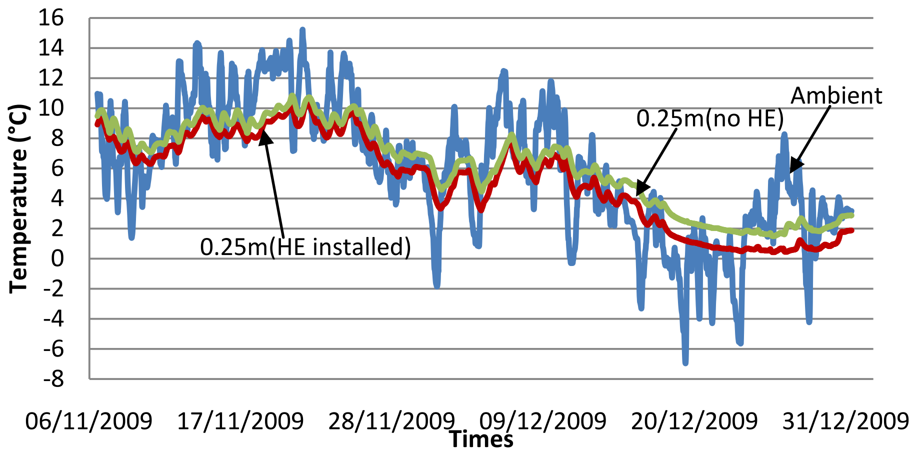


Depth below the ground surface (m)	Thermistors
0.02	T1, T11
0.05	T2, T12
0.1	T3, T13
0.25	T4, T14
0.5	T5, T15
0.75	T6, T16
1.0	T7, T17
1.05	T18
1.1	T8 24cm away from slinky
1.14	T9
1.14	T10

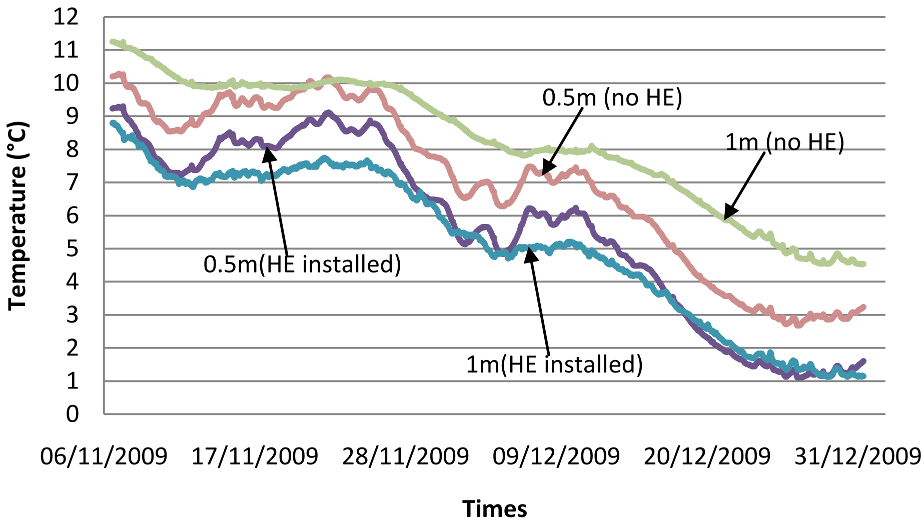
Figure 2 3D sketch of the sensor positions used to measured the slinky and the soil thermal performance



(a) At a depth of 0.02m below the ground surface

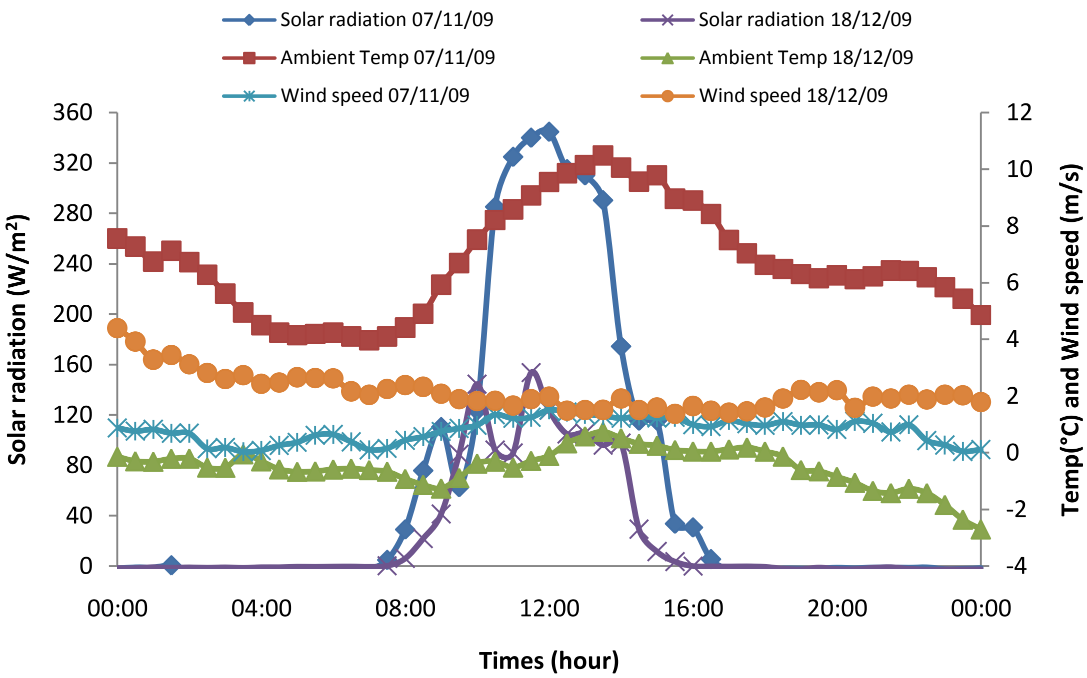


(b) At a depth of 0.25m below the ground surface

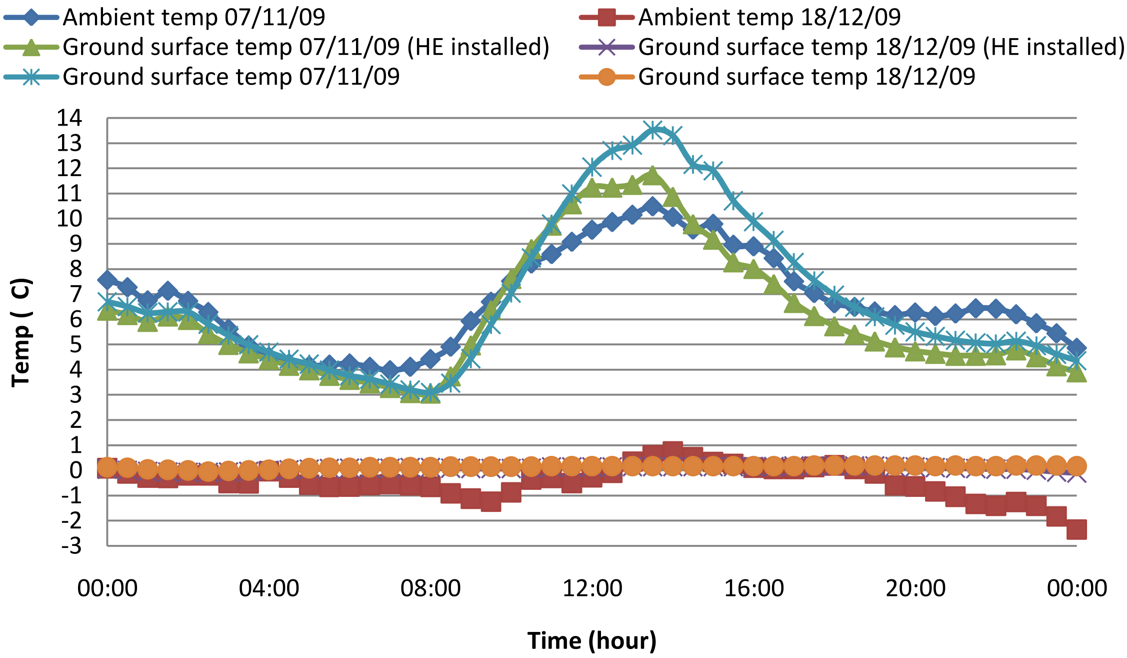


(c) At a depth of 0.5 and 1m below the ground surface

Figure 3 Measured ambient air and soil temperatures from 6th Nov 2009 to 31st Dec 2009

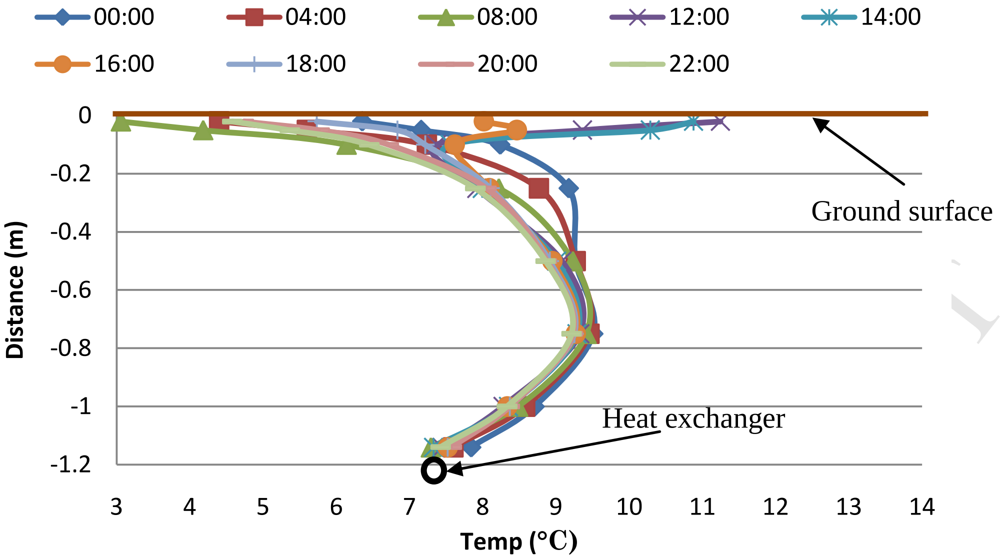


(a) Ambient air temperature, solar radiation and wind speed

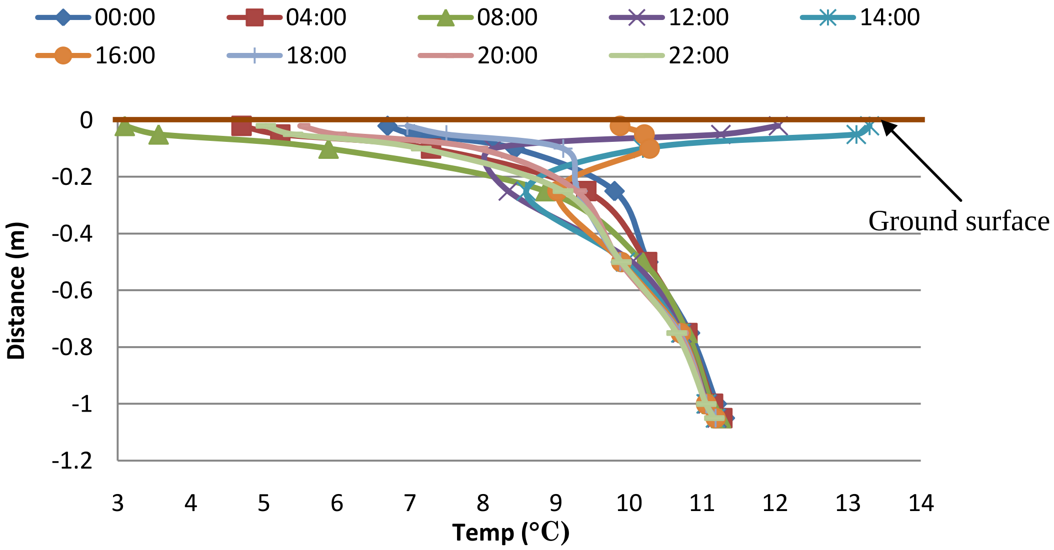


(b) Ambient air temperature and ground surface temperature

Figure 4 Measured ambient air temperature, ground surface temperature, solar radiation and wind speed on 7th Nov. and 28th Dec 2009

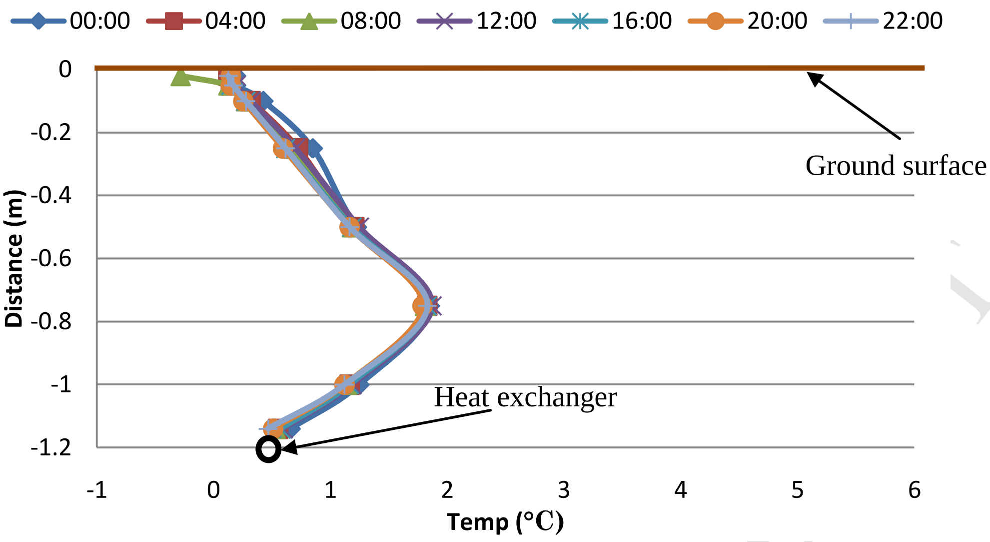


(a) Above the heat exchanger

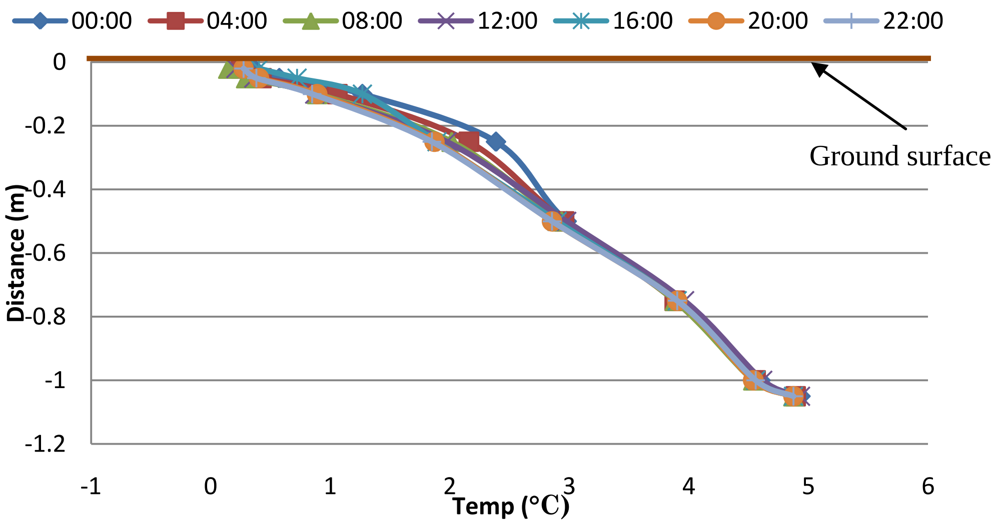


(b) In the reference hole

Figure 5 Measured soil temperature variation on 7th Nov. 2009



(a) Above the heat exchanger



(b) In the reference hole

Figure 6 Measured soil temperature variation on 28th Dec. 2009

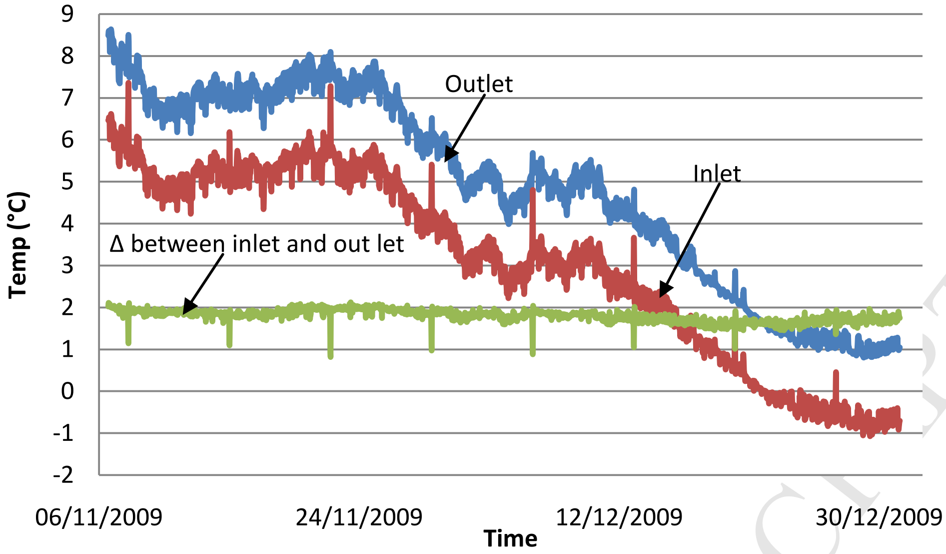


Figure 7 Measured variation of inlet and outlet temperatures of heat exchanger

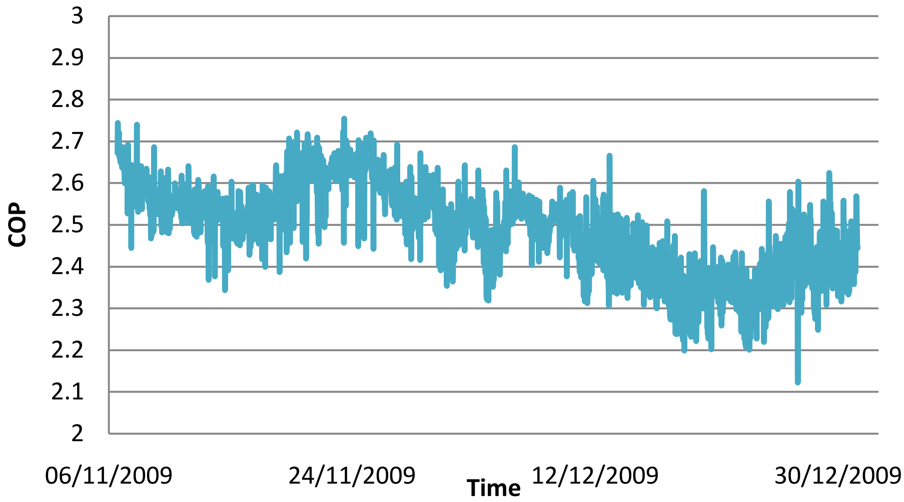


Figure 8 Measured variation of COP of the GSHP system

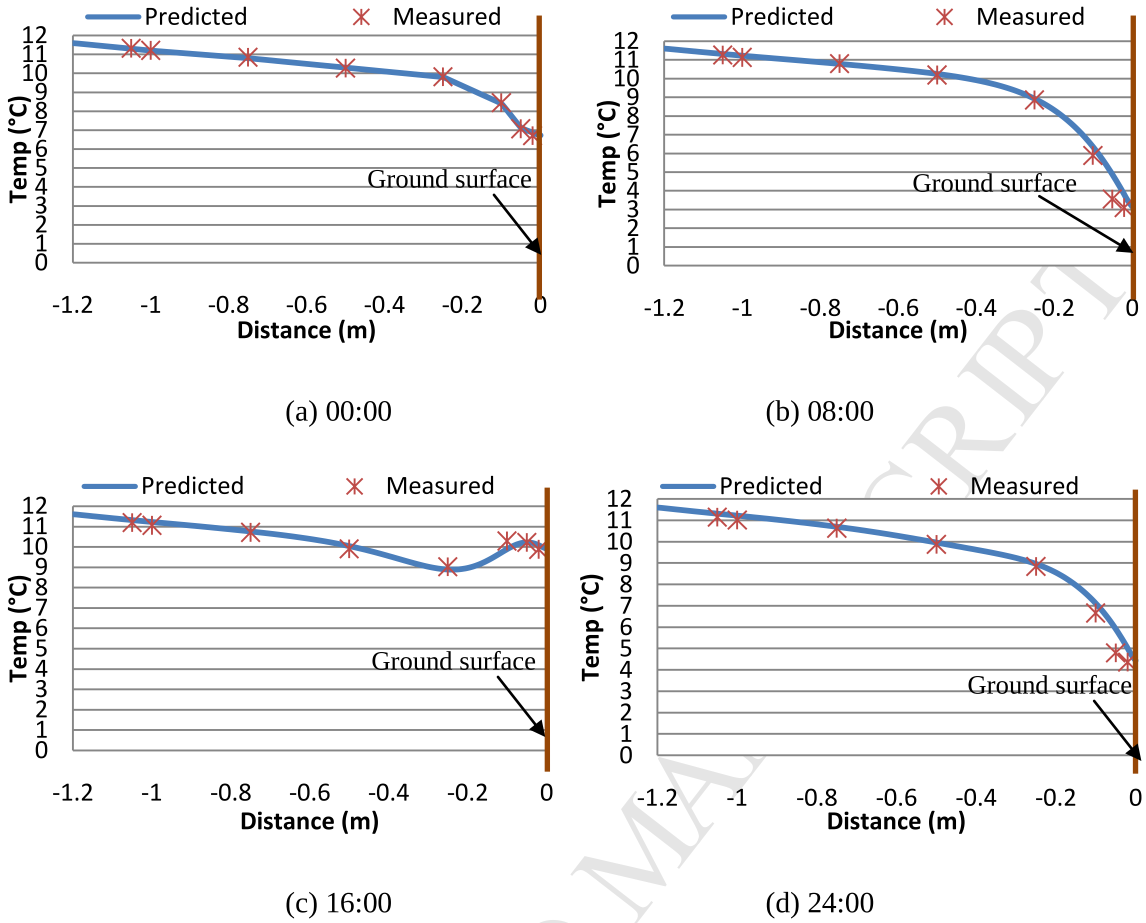


Figure 9 Predicted and measured soil temperatures at selected times on 07th Nov. 2009

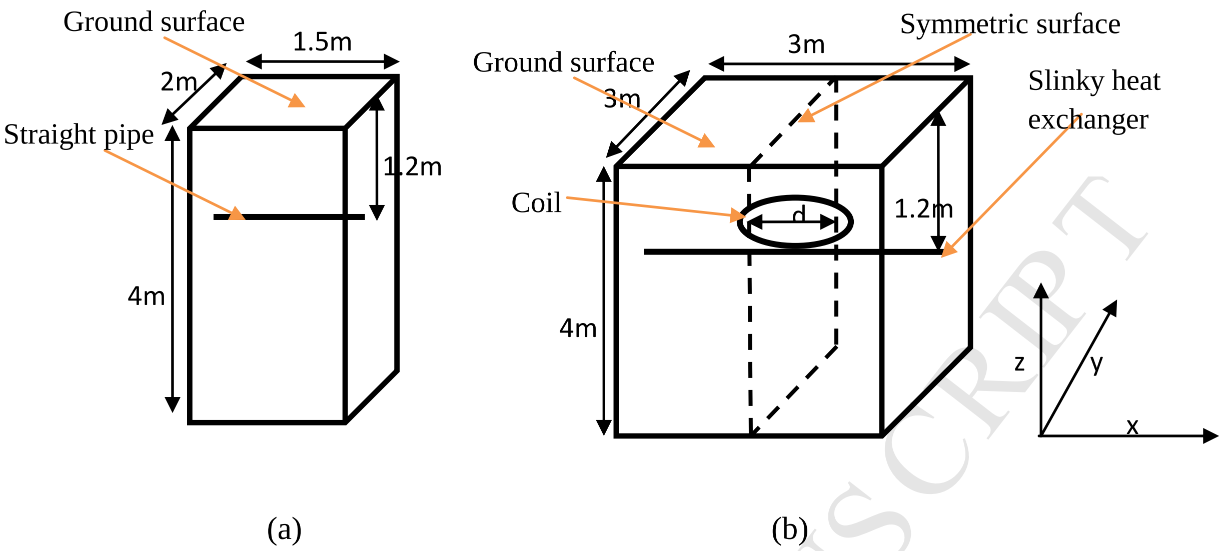
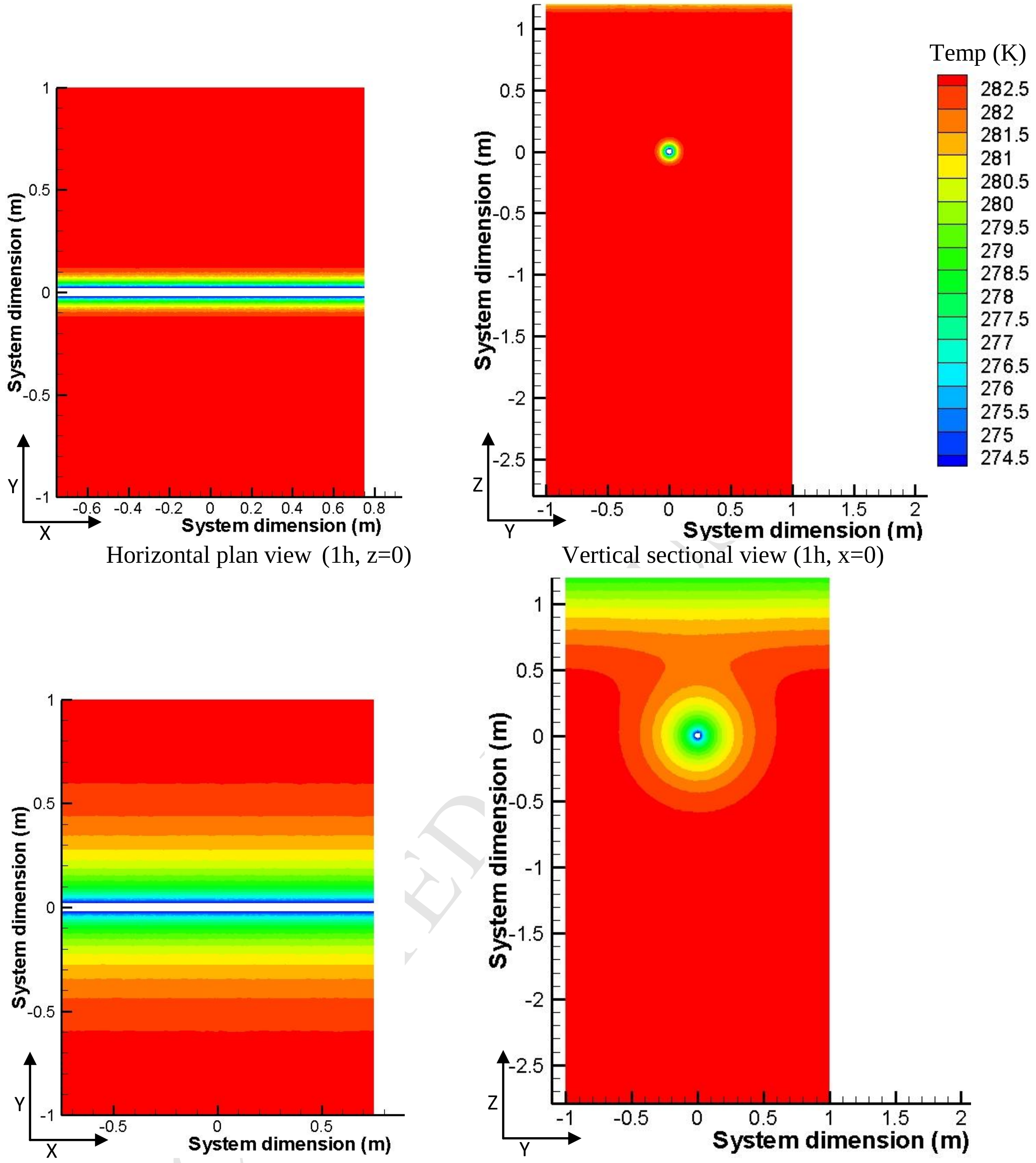


Figure 10 Sketch of a portion of horizontal coupled pipe (a) Straight pipe, (b) Slinky pipe



Horizontal plan view (1h, z=0)

Vertical sectional view (1h, x=0)

Horizontal plan view (50h, z=0)

Vertical sectional view (50h, x=0)

Figure 11 Isotherm generated from prediction for the straight heat exchanger at 1 and 50 hours

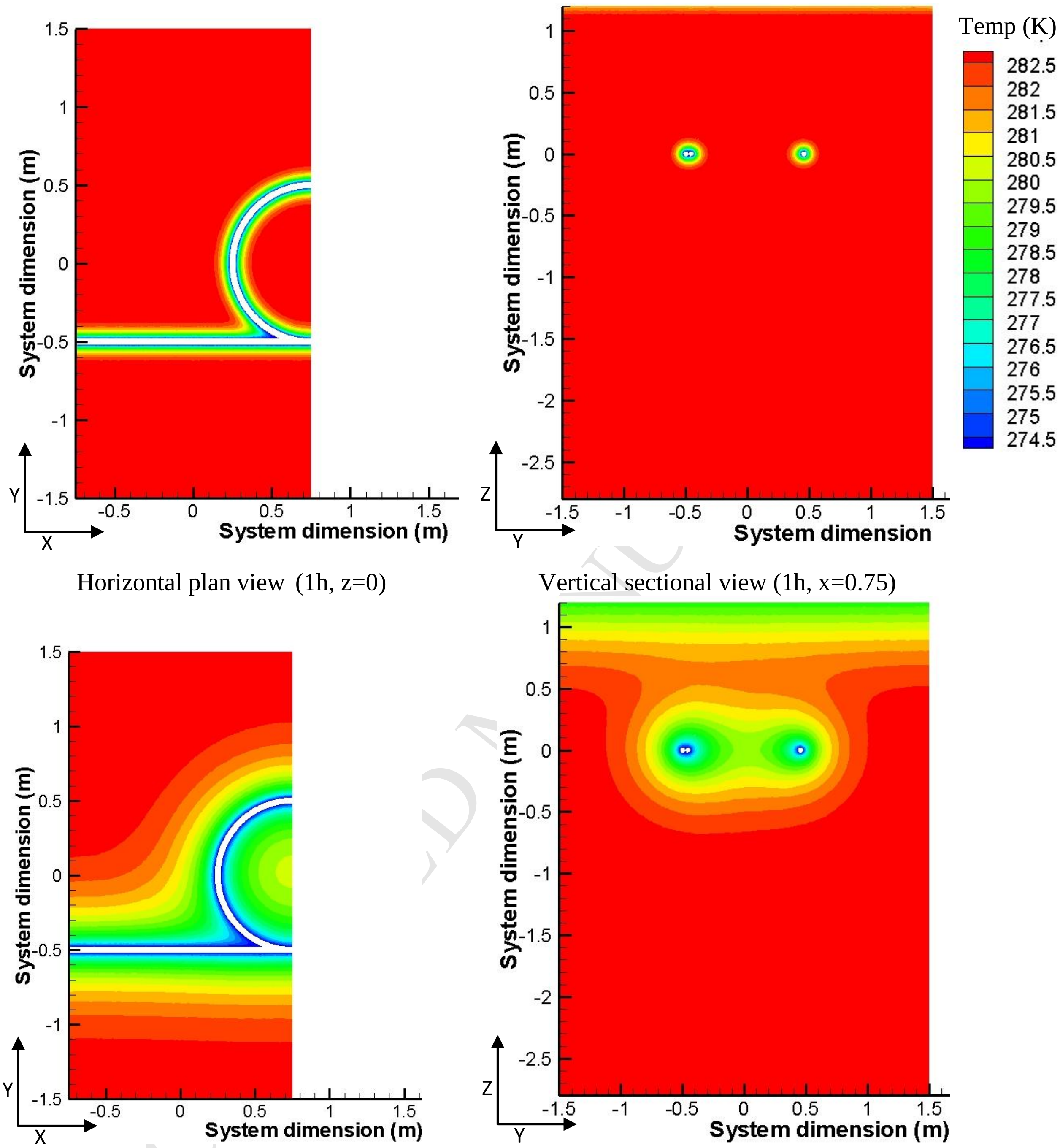


Figure 12 Isotherm generated from prediction for the slinky heat exchanger at 1 and 50 hours

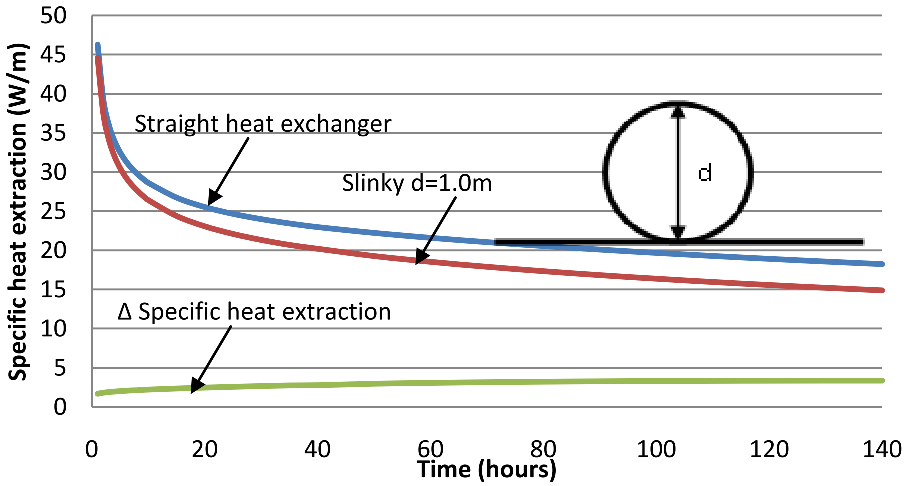


Figure 13 Predicted variation of specific heat extraction with time for the horizontal coupled straight and slinky heat exchangers

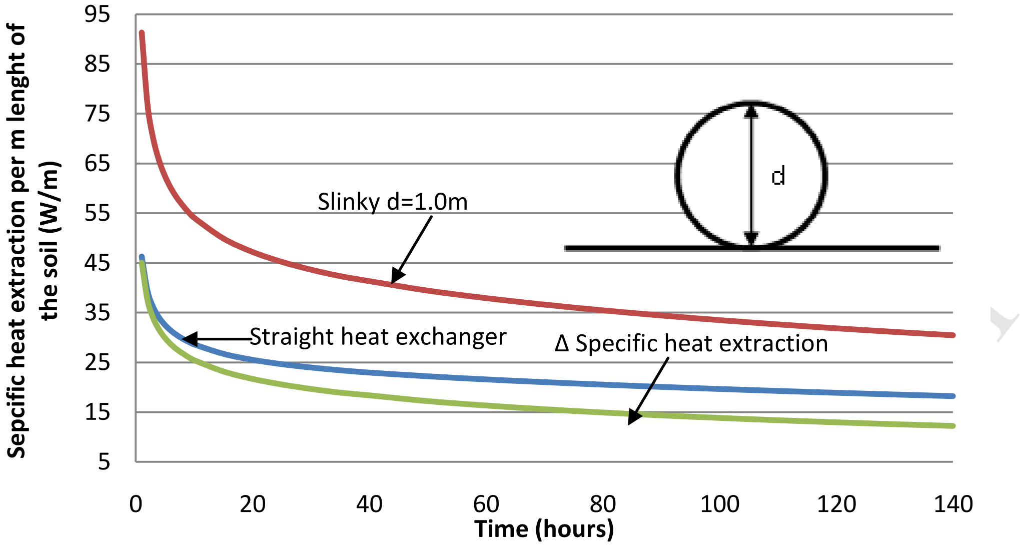


Figure 14 Predicted variation of the heat extraction per meter length of soil by straight and slinky heat exchanger with time

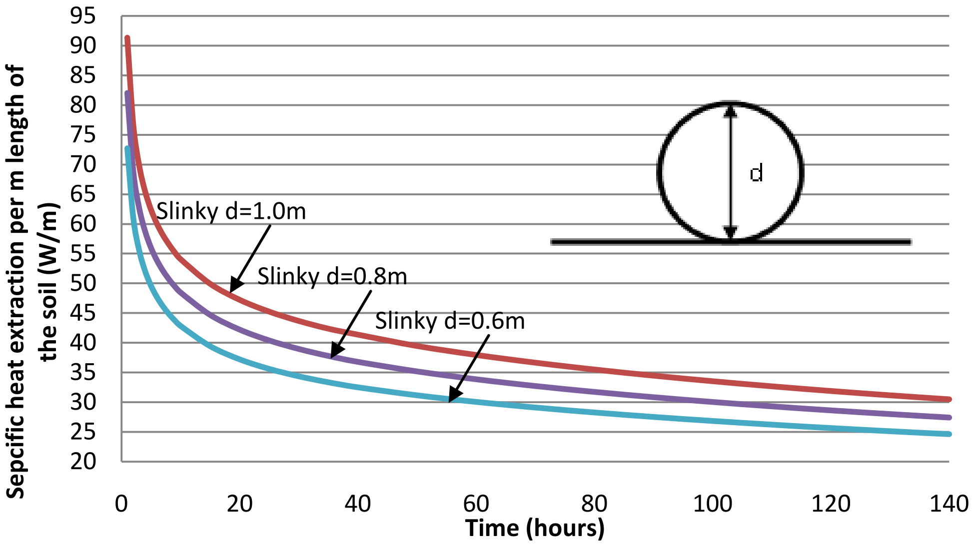


Figure 15 Predicted variation of the heat extraction per meter length of soil for slinky heat exchanger at different coil diameter

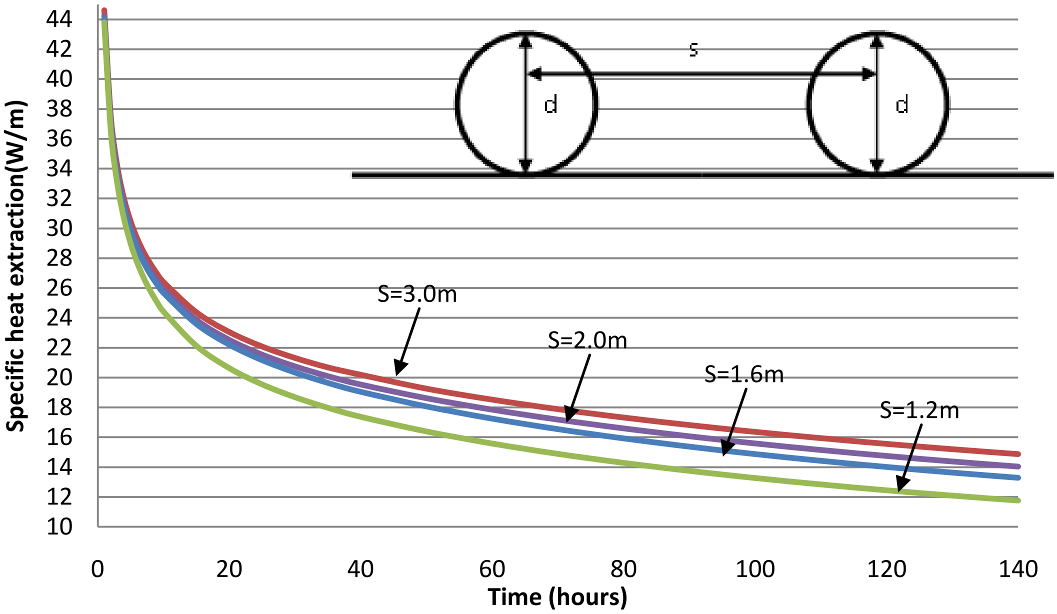


Figure 16 Predicted variation of specific heat extraction with time for slinky heat exchangers at different coil interval distances

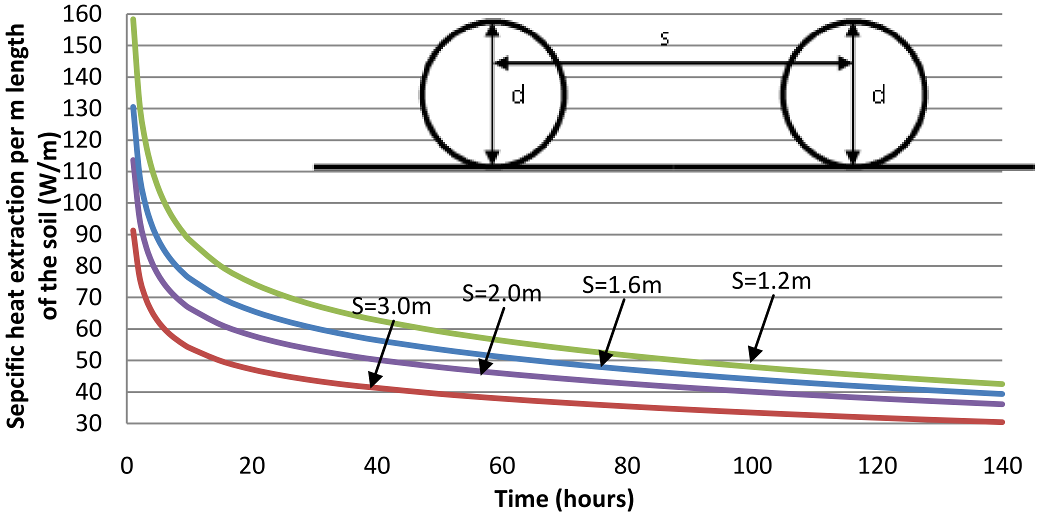


Figure 17 Predicted variation of the heat extraction per meter length of soil for slinky heat exchanger at different coil interval distances