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ABSTRACT

Horizontal ground heat exchanger in ground source heat pump systems is susceptible to ground surface variations thus affecting its thermal performance. However, this configuration is desirable due to low installation costs as it mainly involved burying pipes in shallow trenches. In this study, experimental investigation of thermal performance for slinky horizontal ground heat exchangers (GHEs) in several operation conditions were conducted. The slinky type horizontal ground heat exchangers (HGHEs) in two orientations were considered such as reclined (parallel to ground surface) and standing (perpendicular to ground surface). Copper tube with outer surface coated using low-density polyethylene was considered for GHEs pipes. The GHEs were buried in 1.5 m depth of the ground. Ground temperature distribution was monitored up-to 10 m depth by placing T-type thermocouples at different depth position. During the operation, performance of GHEs decreases with operation time because of ground temperature was reaching to the circulated water temperature. From the test results, the higher heat exchange rate of the standing GHE than reclined GHE is due to the greater amount of backfilled sand which has higher thermal conductivity than site soil. The dominating parameter for the performance difference between two GHEs was backfilled sand conductivity. The average heat transfer rate increased about 21.7% for standing GHE and 17.5% for reclined GHE when flow rate increases from 1 l/min to 2 l/min. The results also indicate that the seasonal change of the surrounding ground temperature of GHE has a significant effect on the overall performance of GHE. The ground temperatures very close to the ground surface is highly affected by ambient temperature and fluctuate strongly. Ground temperature fluctuation decreases with increase in depth and below a certain depth (5 m) remains relatively constant, 18 °C at 10 m depth for example.

1. INTRODUCTION

The main sources of energy for heating and cooling of a building for human comfort are different conventional forms like electricity, fossil fuels, or biomass. To reduce emissions of carbon dioxide and the other greenhouse gases all over the world, it is important to produce energy from sustainable sources such as solar, wind, biomass, hydro, and ground energy that produce low or no emissions. In contrast to many other sources of heating and cooling energy which need to be transported over long distances, earth energy is available on-site, and in massive quantities. The ground is warmer than the ambient air in the winter and cooler than the ambient air in the summer. This ground provides a free renewable source of energy that can easily provide enough energy year-round to heat and cool an average suburban residential home, for example. A Ground-Source Heat Pump (GSHP) transforms this earth energy into useful energy to heat and cool buildings. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). These geothermal heat pumps are the most efficient heating and cooling technology since they use 25% to 50% less electricity than other heating and cooling systems (Sarbu and Calin, 2014).

Ground-source heat pump is used as an all-inclusive term for a variety of systems that use the ground, groundwater, and surface water as a heat source and sink (Kavanaugh and Rafferty, 2014). These systems have been basically grouped into three categories as Ground-coupled heat pumps (GCHPs), Ground-water heat pumps (GWHPs) and Surface-water heat pumps (SWHPs). Since GSHP exchanges heat with ground, this is much more energy-efficient than air source heat pump (which exchange heat with the outside air) because underground temperatures are more stable than air temperatures through the year. In order to gain an understanding of how well GSHPs function after installation, an analysis of their performance needs to be conducted. GSHPs initially were more widely applied to residential buildings but are now increasingly being utilized in the commercial and institutional sectors. The economics of GSHPs can be very attractive in large buildings because elaborate equipment and controls are not required to provide comfort and high efficiency (Kavanaugh and Rafferty, 1997). Today, GSHP systems are one of the fastest growing applications of renewable energy in the world, with most of this growth happening in USA and Europe, but also in other countries such as Japan, China, South Korea and Turkey.

1.1 Horizontal Ground Heat Exchanger (HGHE)

GCHPs are a subset of GSHPs and often referred to as closed-loop ground-source heat pumps. GCHPs seem to be the most common GSHP type in both commercial and residential buildings where tubing buried in horizontal trenches or vertical boreholes. In a GCHP system, heat is extracted from or rejected to the ground via a closed-loop, i.e. ground heat exchanger (GHE), through which the working fluid circulates. HGHEs are the commonest form of GHEs used for GCHP systems. They are also known as shallow trench heat exchangers. The HGHEs are usually used for small buildings with large area is available since they require a larger area in comparison with vertical borehole heat exchangers. But HGHEs are less expensive than other heat exchangers. The use of ground coupled heat exchanger (GCHE) systems is increasing worldwide. Horizontal ground heat exchangers (HGHEs) are most commonly laid in trenches at a depth of 0.9 to 1.8 m (Chiasson, 2010). So HGHE includes greater adverse variations in performance because horizontal ground temperatures and thermal properties fluctuate with season, rainfall, and burial depth; slightly higher pumping energy requirements and lower system efficiency when coupled with a heat pump. Also the backfill material also plays a major part in performance.

The performance of GSHP is strongly depends on the GHE performance. So for improving the overall efficiency of GSHPs, it is needed to improve the heat transfer efficiency in the soil, adopting more advanced shapes and devices. The shallow HGHEs give lower energy output than vertical GHEs, it is best opportunity to improve the efficiency of HGHEs by selecting of different geometries from single pipe, multiple pipes, and coiled pipe that looks like a slinky toy. Since the single pipe and multiple pipes require the greatest amount of ground area and if land area is limited, slinky or spiral GHEs which can be placed vertically in a narrow trenches or laid flat at the bottom of a wide trenches may be used in order to fit more piping into a small trench area. The trench is backfilled once the pipe has been laid out. Also employing high thermal conductivity materials for HGHEs and backfilling the shallow trench by moderate sand and soli required trench lengths are only 20% to 30% of single-pipe horizontal GCHPs, but lengths may increase significantly for equivalent thermal performance (Kavanaugh and Rafferty, 1997). While this reduces the amount of land used it requires more pipes, which results in additional costs. Therefore, slinky ground heat exchangers are the subject of many studies that are both experimental as well as numerical.

Many analytical and numerical models have been developed to do thermal analyses of slinky-coil HGHEs but there is few number of experimental analyses of slinky-coil HGHEs studied. Wu *et al.* (2011) and Congedo *et al.* (2012) numerically simulated horizontal slinky heat exchangers for ground-source heat pumps. Fujii *et al.* (2012) simulate the performance of slinky-coil horizontal ground heat exchangers for optimum design of slinky-coil horizontal ground heat exchangers. Because of the complexity of slinky heat exchanger configurations, Demir *et al.* (2009) calculated heat transfer through a horizontal parallel pipe ground heat exchanger using a numerical method. Selamat *et al.* (2015a) numerically investigated the HGHE operation in different configurations to predict the outlet temperature and heat exchange rate. Thermal performance of slinky heat exchangers for GSHP systems was investigated experimentally and numerically by Wu *et al.* (2010) for UK climate. They showed that the thermal performance of slinky heat exchangers decreased with the running time.

Also due to the lack of information about the heat exchange capacity and long-term performance of the slinky coils, Fujii *et al.* (2010) experimentally performed the long term tests on two types of horizontal slinky coil GHEs and compared their results. Esen and Yuksel (2013) experimentally investigates greenhouse heating by with horizontal slinky ground heat exchanger. All of these studies have been successful in ground source heat pumps (GSHPs) system. To evaluate optimal parameters of the GHE, the performance of the GHE with different horizontal configuration was analyzed experimentally and analytically (Naili *et al*., 2013).

In the present work, an experimental investigation has been performed to analyze the performance of slinky HGHEs. To compare the thermal performance of the slinky HGHEs in field, the GHEs were installed in two orientations such as reclined (parallel to ground surface) and standing (perpendicular to ground surface). To find the ground temperature distribution, thermocouples were placed at different depth positions up-to 10m between the two orientations (reclined, standing) of GHEs. At the same time, atmospheric air temperature and ground surface heat flux were measured. Also it is possible to measure the pressure losses in GHE tube by using differential pressure sensors.

2. DESCRIPTION OF THE EXPERIMENTAL SET-UP

2.1 Material Selection

High-density polyethylene (HDPE) pipe is recommended choice in terms of performance and durability for GHEs. However, copper tubing has been successfully used in some applications. Copper tubes have a very high thermal conductivity. Therefore, tubes of copper only one-fourth to one third the lengths of plastic tubes are required. However copper pipe will not have the durability and corrosion resistance like as HDPE (Kavanaugh and Rafferty, 1997). But this copper tubing must has to be protected from corrosion. Since low-density polyethylene (LDPE) has almost similar properties of HDPE but LDPE is easy to film wrap, can be used as a surface protection. The analysis (Selamat *et al.* 2015a) shows that the effect of different tube materials is more significant in slinky configuration. Hence instead of HDPE tube which is generally used for horizontal ground heat exchanger, copper tube protected with a thin coating of LDPE was selected as tube for our slinky HGHEs.

2.2 Soil Properties

The heat transfer between the GHE and adjoining ground depends strongly on the ground type, the temperature gradient and the moisture gradient (Leong *et al*., 1998). The main thermal characteristics of soil are the thermal conductivity and thermal capacity (Hamdhan and Clarke, 2010). The thermal conductivity of the soil at the site is required to estimate the ground loop performance. The more accurate soil data will allow the designer to minimize the safety factor and reduce the trench length. This research was conducted at Saga University, Saga City, Japan. The ground sample in the Fukudomi area of Saga city consists of clay from 0 to 15 m in depth, sand and sandy-clay from 15 to 20 m, and a water content of 30 to 150% that varies with the depth (Hino *et al.*, 2007).

2.3 Details of Slinky HGHE the System

For slinky HGHEs, copper tube has outer surface coated with LDPE (corrosion resistance) were considered. Slinky HGHE loops in two orientations: reclined (parallel to ground surface) and standing (perpendicular to ground surface) were installed. The loop diameter, length of trench and number of loop for both orientations were 1.0 m, 7.0m and 7 respectively and the total length of LDPE coated copper tube was 39.5 m in each GHE. The reclined GHE was laid in the trench at a 1.50 m depth and 1.00 m wide. On the other hand the center of standing GHE was located at a depth 1.50 m and 0.50 m wide in the trench. Figure 1 shows the photograph of installation. After placing the coils inside the trenches, at first coils were covered with typical Japanese sand; water was sprayed on the sand for reducing the void space and hence thermal resistance around the coil. The remaining upper parts of the trenches were then backfilled with site soil and compressed with power shovels.

With GHE, the setup also included water bath (consists of pump, heater & cooler), flow controller, mixing chamber etc. Water bath maintains constant temperature water supply to the system. Circulation rate of water was controlled by flow controller. Inlet and outlet temperature of water for each GHE were measured by using Pt100 which were installed at close to ground surface. To monitor undisturbed ground temperature distribution, three monitoring holes between the two orientations were dug in the ground to install T-type thermocouples at various positions up to 10.0 m depth. During the installation of thermocouples, all the holes were refiled. Also T-type thermocouples were placed at near end and far end of both GHE to observe the change the ground temperature due to heat exchange between soil and circulated water. By using differential pressure sensor, it is possible to measure the pressure loss in the GHEs. At the same time digital thermometer and heat flux meter were installed to record ambient temperature and surface heat flux respectively. Figure 2 shows the complete schematic diagram of GHEs system.

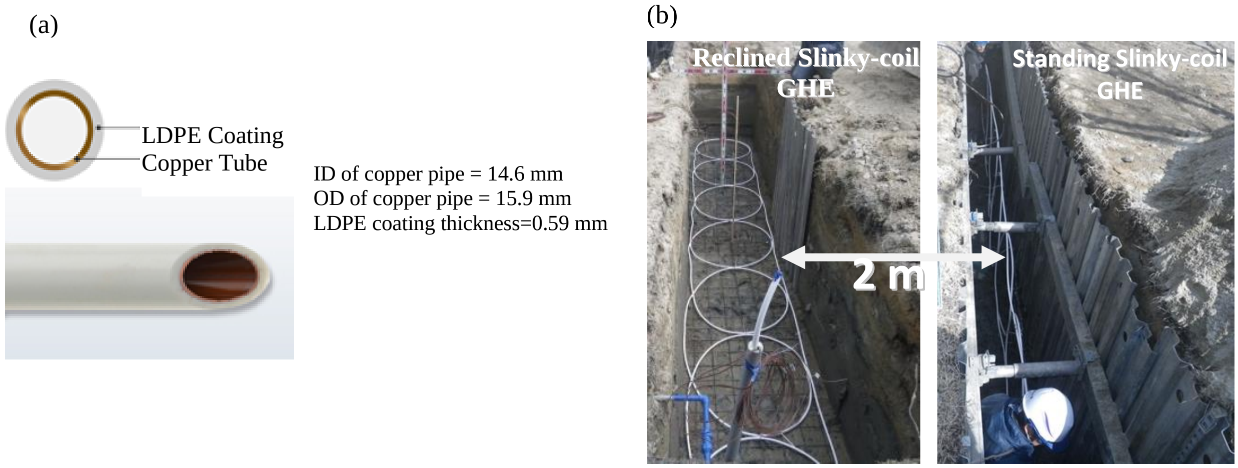
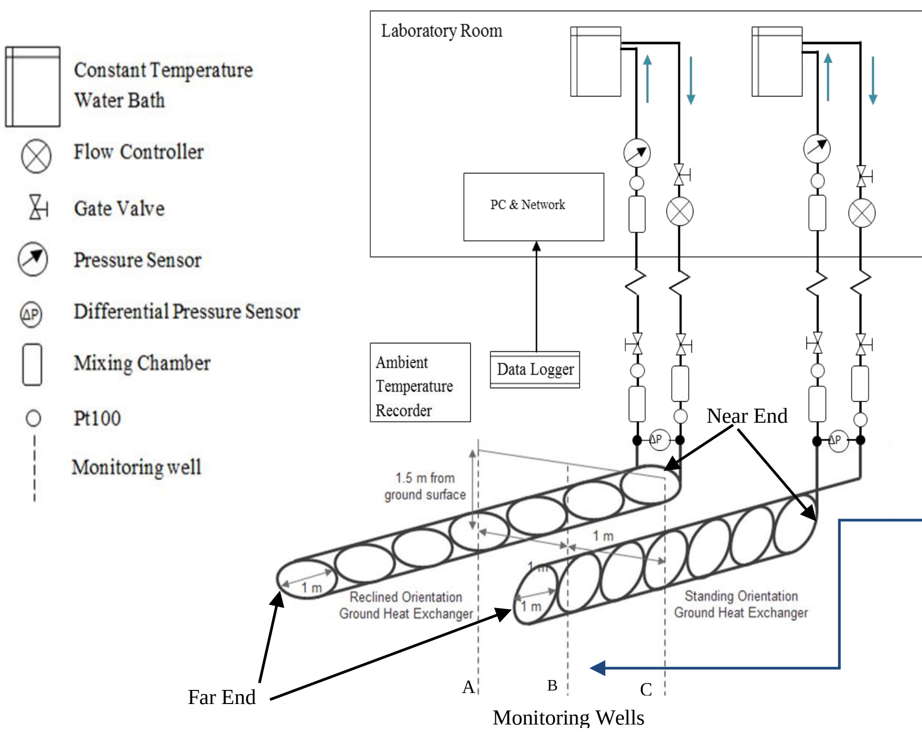


Figure 1: (a) Outer surface LDPE coated copper tube, (b) Installation of slinky-coil ground heat exchangers



Thermocouples (T type)	Monitoring well depth position (m)
A1, B1, C1	0.00
A2, B2, C2	0.02
A3, B3, C3	0.05
A4, B4, C4	0.10
A5, B5, C5	0.20
A6, B6, C6	0.30
A7, B7, C7	0.50
A8, B8, C8	0.75
A9, B9, C9	1.00
A10, B10, C10	1.50
A11, B11, C11	2.50
A12, B12, C12	3.50
A13, B13, C13	5.00
A14, B14, C14	7.50
A15, B15, C15	10.0

Figure 2: Schematic of experimental set-up of slinky horizontal ground heat exchangers

3. RESULTS AND DISCUSSION

Based on experiment of GHEs in winter season, the water temperature in the inlet and outlet, water flow rates and the ground temperature at 1.5m depth in near ends and far ends for both GHEs were measured for different intermittent heating mode. The undisturbed temperature of soil up-to 10.0m depth was also measured. All data were recorded by using a data logger connected to computer. The ambient temperature was measured by a digital thermometer. All data were recorded in 5 minute interval.

In heating mode, the experiment was conducted following conditions:

Water baths set temperatures were 7.0℃
From 23 to 26 February, 2016 the flow rate water was 2 l/min referred to case 1
From 4 to 7 March, 2016 the flow rate water was 1 l/min referred to case 2
From 17 to 21 April, 2016 the flow rate water was 1 l/min referred to case 3

3.1 Daily Average Ground Thermal Behavior (Undisturbed Ground Temperature)

The ground temperature is very important for sizing the ground heat exchanger (GHE). It is necessary to know about the minimum and maximum ground temperature at the GHE depth to decide the optimum design of GHE. The ambient climatic conditions affect the temperature profile below the ground surface and need to be considered when designing a GHE. Actually the ground temperature distribution is affected by the structure and physical properties of the ground, the ground surface cover (e.g., bare ground, lawn, snow, etc.) and the climate interaction (i.e., boundary conditions) determined by air temperature, wind, solar radiation, air humidity and rainfall (Florides, and Kalogirou, 2007). The ground temperature distribution from February 1, 2016 to April 30, 2016 at various depths is shown in Figure 3. This Figure shows that the ground temperatures very close to the ground surface have similar characteristic to ambient temperature and fluctuate strongly. Ground temperature fluctuation decreases with increase in depth and below a certain depth (5 m) remains relatively constant, 18 °C at 7.5 m and 10 m depth for example. But at the depth 1.5 m where our GHEs were installed, the ground temperature is changing seasonally which is an important parameter for GHE performance.

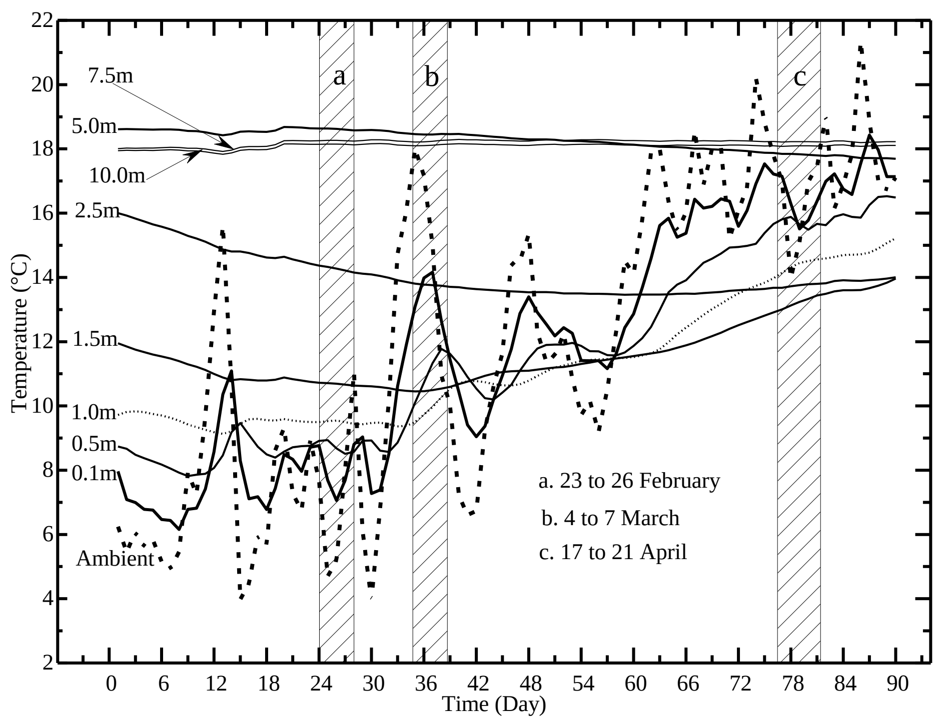


Figure 3: Daily average ground temperature and ambient temperature February 1, 2016 to April 30, 2016

3.2 Inlet and Outlet Temperatures of Circulating water

The efficiency of GSHP system depends on the inlet and outlet temperature difference of circulating fluid inside the GHE. So for higher efficiency of GSHP, it is desirable that a GHE should transfer heat to the ground as much as possible. The hourly average temperatures of circulated water at inlet and outlet and ambient temperature for both GHEs in heating mode are shown in Figure 4. After the start of the experiment, the inlet water temperatures should be quickly approach to the water bath set temperature (7℃). At the beginning of start of experiment, the temperature differences between inlet and outlet water were high for all of 3 cases of data and gradually decreases and approached to the stable value (after 24 h for case 1 &2). But during case 3, it needs more time to get stable the outlet water temperature about 48 h due to growing higher surrounding soil temperature. Then, there were no significant change in temperature differences between the inlet and outlet. The fluctuations of inlet and outlet temperatures are discussed in Figure 5 and Figure 6. Though the inlet temperatures for both GHE were almost same but standing GHE showing greater outlet temperature than reclined oriented GHE for all of 3 cases. The undisturbed ground temperatures between 1.0 m to 1.5 m depth (GHEs installed at 1.5m depth) were almost same (shown in Figure 3) during case 1 and case 2, but the inlet and outlet water temperature difference was higher for 1 l/min because of lower velocity of water through the tube for 1 l/min than 2 l/min. So for flow rate 1 l/min, water takes more time to absorb heat from surrounding soil. Again from Figure 4, during case 2 and case 3, when flow rates were same (1 l/min), the inlet and outlet water temperature difference is higher for case 3. From Figure 3, it is clear that during case 2 and case 3, the ground temperatures between 0.5m to 1.5m were almost 9.5 to 11℃ and 13.5 to 16℃ respectively. That's why more heat was absorbed by circulating water during case 3 than case 2.

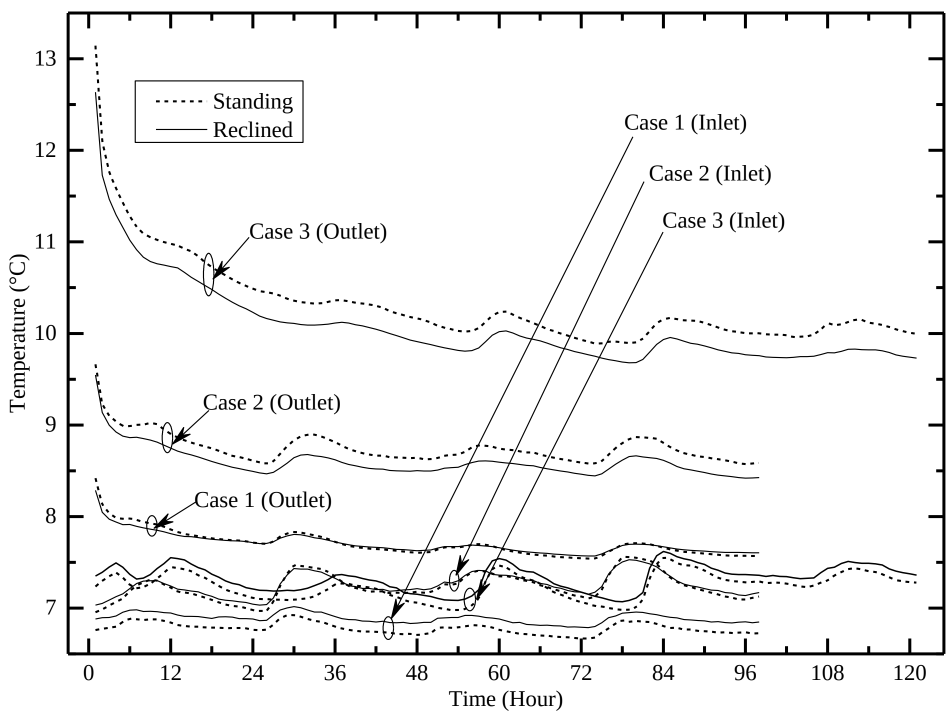


Figure 4: Hourly average inlet and outlet water temperature variation with running time in heating mode with different conditions in 2016

3.3 Effect on Ground Temperature

Figure 5 and 6 show the comparison of change of hourly average ground temperatures at 1.5 m depth due to change of circulating water temperatures for standing and reclined GHE. These two figures also show the reason of fluctuation of inlet and outlet water temperature due to change of ambient temperature. Since in heating mode of operation, the circulating water always absorb heat from higher temperature surrounding soil, hence surrounding soil temperature will gradually decreases with running time. From Figure 5 and 6, the undisturbed ground temperatures remains always constant at 1.5 m depth during case 1 and case 2. But during case 3, this temperature increases slightly due to seasonal variation of temperature. On the other hand at the 1.5 m depth the ground temperature at near end and far end started to decrease from beginning of experiments and remains almost stable after 24 h during case 1 and case 2, but during case 3 it needs approximately 48 h to approach stable. At the beginning of experiments, in the inlet side i.e. near end, the ground temperature decreases strongly than far end because in near end the temperature difference between inlet water and ground at 1.5 m depth higher than far end. So that, more heat was absorbed from near end at beginning of experiments. Due to this the ground temperature at 1.5 m depth at near end is lower than far end temperature at 1.5 m depth for all of three cases.

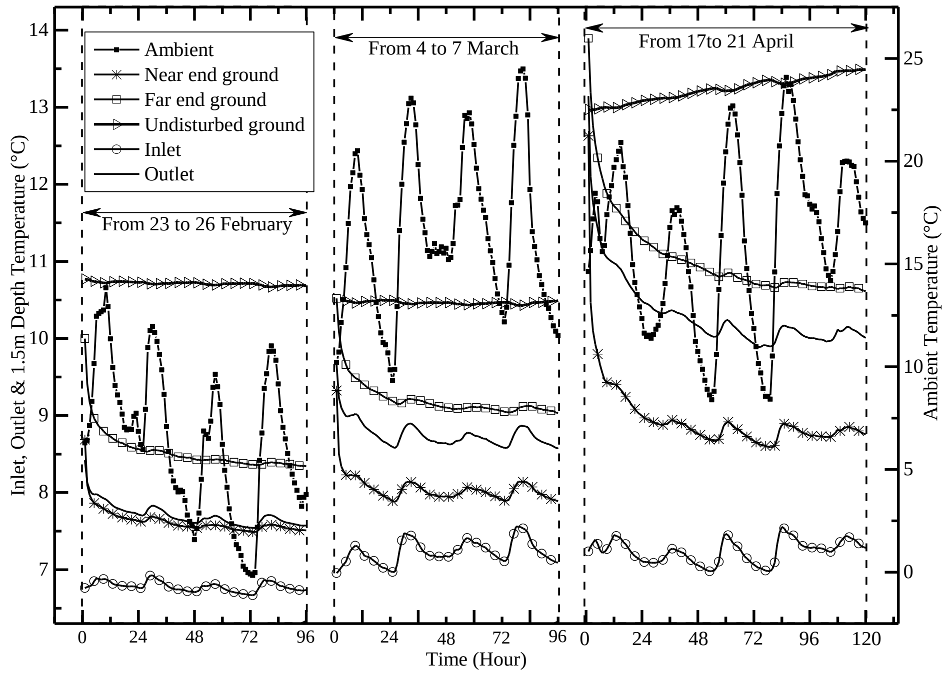


Figure 5: Comparison of hourly of change of ground temperatures at 1.5m depth due to change of circulating water temperatures and ambient temperature for standing GHE in 2016

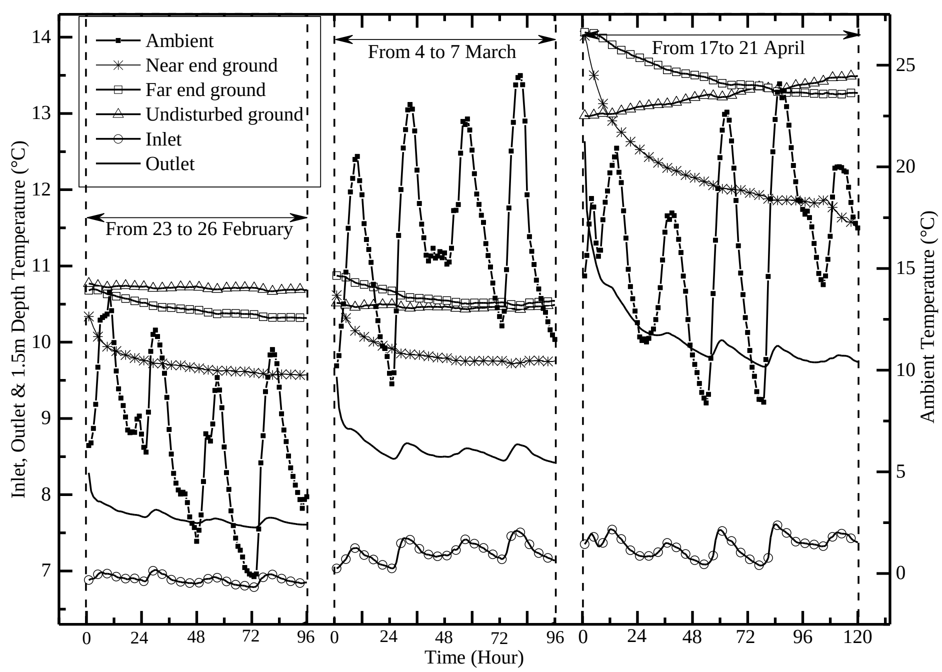


Figure 6: Comparison of hourly average change of ground temperatures at 1.5m depth due to change of circulating water temperatures and ambient temperature for Reclined GHE in 2016

Another thing, in standing GHE, the near end ground temperature at 1.5 m depth fluctuates similarly with inlet temperature because this ground temperature was measured very close to inlet and outlet tubes. But in reclined GHE, the distance between inlet and outlet tube was 1.0 m and ground temperature was measured at middle of them at 1.5 m depth. For this distance (0.5 m) between ground at 1.5 m depth and inlet/outlet, the effect of inlet and outlet temperatures on ground temperature at 1.5 m depth is lower than standing GHE and it is more stable like undisturbed ground temperature.

The water bath set temperature was 7.0℃ for both GHEs. So inlet temperature should be constant of 7.0℃ for both GHEs. But inlet temperatures for both GHEs were fluctuating in similar fashion of ambient temperature. The water baths were inside of the room and GHE inlet and outlet temperature measuring points were outside of room and about 10 m distance between them. All connecting pipes between water baths and inlet and outlet of GHEs were insulated. But it is difficult to make 100% perfect insulation. So some heat was exchanging between connecting pipes and surroundings. That's why inlet temperatures of heat exchangers are changing with ambient temperature in every day and also outlet temperatures. Similar analysis can be concluded from Figure 6.

3.4 Heat exchange rate

To investigate the performance of GHEs, heat exchange rates for both heat exchangers were calculated for each flow rate. The heat extracted/injected by GHEs from/into ground is a transient process and there is no exact mathematical or experimental approximation for GHE (Jalaluddin *et al.*, 2012). Heat exchange with the ground, Q calculated by using equation: $Q = mC_p\Delta T$, where m is flow rate, C_p is specific heat, and ΔT is the temperature difference between inlet and outlet of circulated water.
And then, heat exchange rate per unit length of GHE was simplified by, $q = Q/L$, where L is the total length of GHE.

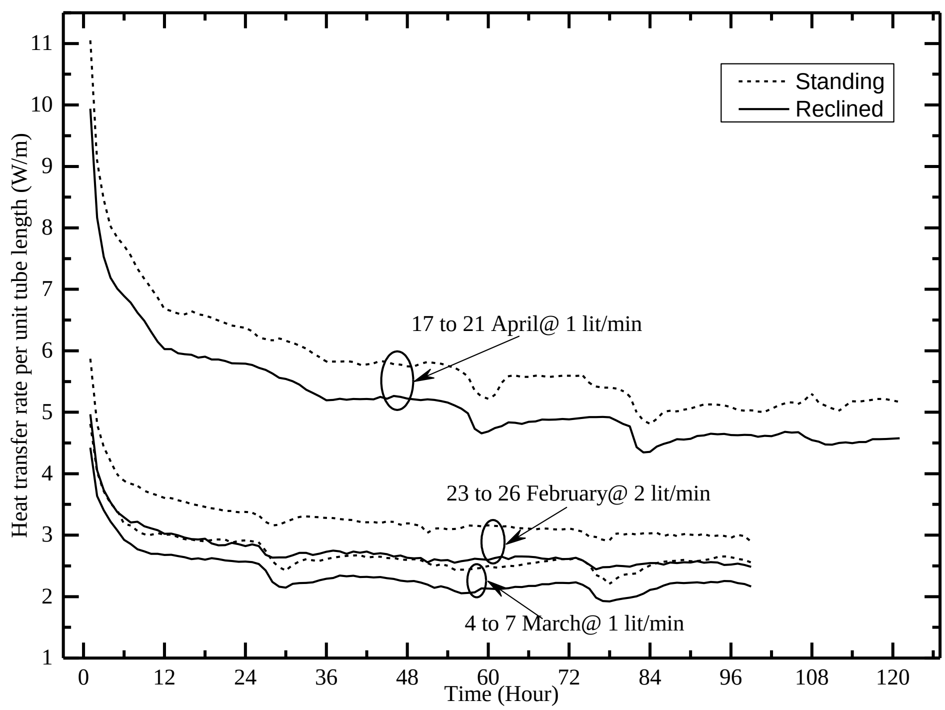


Figure 7: Comparison of hourly average heat exchange rate between standing and reclined oriented GHEs with different conditions in 2016

Figure 7 shows the hourly average heat exchange rates per unit tube length of the GHEs for continuous operation with different operation conditions (case 1, case 2 and case 3). At the beginning of operation, the heat exchange rates are high for all cases due to the higher temperature differences (Figure 4) between circulating water and ground soil. With increase of running time of experiment, heat was extracted by circulating water from the ground soil, that's why decreases the ground temperature around the trenches and then the heat exchange rate declines gradually and tends to be constant. This figure shows that, heat exchange rate per tube length of standing GHE dominates the heat exchange of reclined GHE for all three cases. From beginning of start of the experiments, the average heat extraction rates per unit tube length were calculated for 4 days for all of three cases. In case 1, the average heat extraction rate was 3.29W/m for standing GHE and 2.76 W/m for reclined GHE. In case 2 this value was 2.71 and 2.36 and in case 3 the value was 5.98 and 5.36 W/m respectively for standing and reclined GHE. The average heat extraction rate in standing GHE is 19.2% higher than reclined GHE during case 1 and 15.1% and 11.6% during case 2 and case 3 respectively. But field tests of Fujii *et al.* (2010) showed that reclined installation of slinky coils results in superior performance to standing installation in terms of energy efficiency. In our experiment, after placing the slinky coils inside the trenches, in case of standing GHE, 1.2 m × 0.5 m × 7 m = 4.2 m^3 trench volume was backfilled by typical Japanese sand. On the other hand for reclined GHE, 0.225 m × 1 m × 7 m = 1.575 m^3 volume of trench was backfilled by same type of sand. Remaining upper part of trenches was backfilled by site soil. Hamdhan and Clarke (2010) confirmed that the thermal conductivity varies with material condition and soil's thermal conductivity is significantly influenced by its saturation and dry density. The thermal conductivity of clay and sand with 20% water content are 1.17 and 1.76 and with water content 40% the conductivity values are 1.59 and 2.18 W/mK (Hillel, 1998). Since the backfill volume with sand is higher (4.2 m^3) in standing GHE than reclined (1.575 m^3) and thermal conductivity of sand is higher than soil, hence heat exchange rate is high in standing oriented GHE. Also from ground temperature distribution (Figure 3) at 1.0 m and 1.5 m depth, temperature remains almost constant for short period of time, 4-5 days for example. So in our experiment dominating parameter for the performance difference between two GHEs is backfilled sand conductivity.

Ground temperature profiles around the GHEs (between 1.0m to 2.5m) during case 1 and case 2 shown in Figure 3 were almost similar, but Figure 7 shows that heat exchange rate for case 1 is greater than for case 2. The flow rate of water for case 1 (2 l/min) was double compare to case 2 (1 l/min). Hence heat transfer rate higher with higher flow rate but not double. The average heat transfer rate increased about 21.7% for standing GHE and 17.5% for reclined GHE when flow rate increases from 1 l/min to 2 l/min. On the other hand in case 2 and case 3, flow rate was same (1 l/min) but heat exchange rate is higher for case 3. This occurred due to higher ground temperature from 0.5 m to 1.50 m depth (shown in figure) than case 2.

4. CONCLUSION

In this research, the experimental thermal performance analysis of slinky horizontal GHEs (standing and reclined orientation) has been carried out in different heating modes. For improving the overall efficiency of GSHPs, it is needed to improve the heat transfer efficiency in the soil, adopting more advanced shapes and devices. The shallow HGHEs gives lower energy output than vertical GHEs, it is best opportunity to improve the efficiency by selecting slinky type heat exchanger which occupies less space in ground. The investigation highlighted the GHEs tube orientations and the backfill sand thermal conductivity which affects the heat transfer process. For better understanding the heat transfer rate, temperature distributions of the undisturbed ground and around the GHEs were measured. Within the range of experiment the following conclusions can be drawn:

i) The outlet temperatures of the circulating water were high at the beginning of operation for both GHEs and reached almost steady state after 24 to 48 h of operation.
ii) During the operation, performance of GHEs decreases with operation time because of ground temperature was reaching to the circulated water temperature.
iii) The higher heat exchange rate of the standing GHE than reclined GHE is due to the greater amount of backfilled sand which has higher thermal conductivity than site soil. It is concluded that heat was well transferred to the sand by the standing slinky GHE.
iv) Since the orientation of HGHE loops is unimportant as it has minor effect on thermal performance (Selamat *et al.*, 2015b), slinky HGHEs either standing or reclined orientation would be practical with more backfilled material of high thermal conductivity.
v) The average heat transfer rate increased about 21.7% for standing GHE and 17.5% for reclined GHE when flow rate increases from 1 l/min to 2 l/min.
vi) The results also indicate that the seasonal change (Comparison between case 2 and case 3) of the surrounding ground temperature of GHE has a significant effect on the overall performance of GHE.
vii) The ground temperatures very close to the ground surface is highly affected by ambient temperature and fluctuate strongly. Ground temperature fluctuation decreases with increase in depth and below a certain depth (5 m) remains relatively constant, 18 °C at 10 m depth for example.

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