International High Performance Buildings Conference

School of Mechanical Engineering

2014

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Selamat, Salsuwanda and Miyara, Akio, "The Effect Of Seasonal Variation On Thermal Performance Of Horizontal Slinky-Loop Ground Heat Exchanger" (2014). *International High Performance Buildings Conference.* Paper 126.
http://docs.lib.purdue.edu/ihpbc/126

The Effect of Seasonal Variation on Thermal Performance of Horizontal Slinky-Loop Ground Heat Exchanger

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ABSTRACT

For ground-source heat pump (GSHP) installations, it is important to predict the thermal performance and economic feasibility prior to the introduction of the system. Numerical modelling can be used as an analytical method to accurately predict the thermal performance of such system. It is desirable that the modelling to incorporate seasonal variation during long period of operation, which would lead to a better understanding of the overall performance and provide more reliable results. In this work, numerical modelling performed using computational fluid dynamic software presented the heat exchange rate for different operation of slinky loop ground heat exchanger (GHE) using time- and position-varying parameters. Each operation were carried out in short and long simulation periods during winter and summer conditions of southwest of Japan, specifically in Saga City. This analysis suggested that heat flow in GHE operation was more dominant along vertical axis. It also supports the common claim that heat exchange rate is predominantly limited by the thermal conductivity of the ground. Spaced loops in multiple parallel GHE helped to minimize the interference of heat flow that would penalize the overall thermal performance.

1. INTRODUCTION

Heating, ventilation and air conditioning (HVAC) of buildings have benefited greatly from the development of geothermal technology. Geothermal heat pump is also known as ground source heat pump (GSHP), provides high efficiency and eco-friendly solution for space heating and cooling applications. GSHP systems use less energy than conventional air source heat pump (ASHP) systems thus helps conserving natural resources. GSHP installations do not require large cooling towers or coupled with one for greater efficiency. Their running costs are lower than ASHP systems. In GSHP systems, heat is rejected from an enclosed space to ground or extracted from ground to an enclosed space using ground heat exchangers (GHE).

GHE could be installed in two configurations, which are vertically and horizontally. This provides an option for users depending on availability of land area and capital investment. While vertical GHE has been recognized as highly efficient and provides steady thermal performance, the high initial costs could be a hindrance for such installations. Horizontal GHE on the other hand, provided that land area is abundant, are seen as a tool to promote geothermal technologies in HVAC systems due to the relatively lower installation costs. GHE are one of the crucial components in GSHP systems that would largely determine its thermal performance. The design of GHE should take into account important parameters at the installation sites which include thermal properties of the ground, underground water flow and climate conditions.

The thermal performance of GHE has to be accurately predicted prior to the introduction to safeguard an optimum compromise between design and economic feasibility. Numerical modelling has been applied in many research studies to predict the thermal performance of GHE. Nam et *al.* (2008) have developed a numerical modelling for predicting the thermal performance of vertical GHE by combining a heat transport model with ground water flow. The numerical analysis was validated with experimental results where the conditions imposed on the model were based on. The proposed model was later used to predict the thermal performance for an actual GHE installation in Japan. Jalaluddin and Miyara (2012) have investigated the thermal performance of several types of vertical GHE in different operation mode. The GHE were simulated in short time period of operation, discontinuous 6 h and 12 h operation a day and continuous operation mode. Discontinuous operation and alternate operation between cooling and heating mode were found to increase the heat exchange rate in GHE. The effect of different pipe materials was examined and found that thermal performance increases with higher thermal conductivity materials.

Research studies on numerical modelling of horizontal GHE are recently increasing due to the renewed interest in the less expensive GSHP systems. Congedo *et al.* (2012) have suggested that slinky-loop pipes in horizontal GHE configuration would provide greater heat exchange area compared to straight pipes, thus allowing the length of trenches hence the required land area to be reduced. Their simulation covered for system operation in both summer and winter. It was found that the key factors that affect thermal performance are the thermal conductivity of the ground and the velocity of working fluid inside the GHE. Chong *et al.* (2013) have further investigated the effect of loop pitch and loop diameter on the thermal performance of slinky-loop GHE. Comparisons were later made against the required amount of pipe material and excavation costs to evaluate the effect financially. By setting loop diameter and loop pitch to be equal, a reasonable compromise between thermal performance and installation costs was assumed. Fujii *et al.* (2012) performed simulation of slinky-loop GHE by using time-varying parameter as surface boundary condition to improve the analysis accuracy. In their model, the geometry of the slinky-loop was simplified to a thin plate. The simulation results were found agreeable with the experimental thermal response tests and long-term air-conditioning tests.

In this work, the numerical modelling of horizontal slinky-loop GHE in several operations was performed to predict the heat exchange rate. The simulation incorporated seasonal variations during short and long periods of operation, which would lead to a better understanding of the overall performance and provide reliable results. The modelling of the exact shape of slinky-loop pipe was performed using computational fluid dynamic software using time- and position-varying parameters. Each operation were covered for both summer and winter conditions of southwest of Japan, specifically in Saga City.

2. DESCRIPTION OF NUMERICAL MODEL

Three-dimensional horizontal slinky-loop GHE models were developed and the operation were simulated using a commercial computational fluid dynamics software, FLUENT. Thermal performance in term of heat exchange rate between GHE and ground were predicted in FLUENT using a finite volume method by solving governing equations pertaining conservation of mass or continuity, momentum and energy. The time frames of the simulation include continuous operation for 5-day and discontinuous operation for 90-day periods in heating mode during winter and cooling mode during summer. For discontinuous operation, the GHE were operated for 9 h from 09:00 to 18:00 daily to mimic a typical commercial building working hours. Seasonal variations were incorporated as boundary conditions to obtain realistic simulation where actual data from 1 January to 31 March 2013 were used for operation during winter and from 1 June to 28 August 2013 during summer. Hourly time step was used with gradually increasing shorter intervals within the first hour after flow startup or shutdown.

2.1 Simulation Model

The numerical modelling involved investigating thermal performance of GHE in single and multi-parallel configurations. The analysis domain dimension was 20 m x 1.1 m x 20 m as illustrated in Figure 1. Three main geometries developed as shown in Figure 2(a)–(d) were reclined orientation referred as Case 1, standing (Case 2), double parallel (Case 3) and triple parallel (Case 4). In order to reduce the computational requirements to run the simulation, only a single unit of each configuration was modelled. The pipe material used in Case 1–4 was DN40 size high density polyethylene pipe (HDPE), typically used in GHE installations, with density of 955 kg/m^3, specific heat of 2300 J/kg·K and thermal conductivity of 0.461 W/m·K. For comparison of different pipe materials, same dimension copper pipe with density of 8978 kg/m^3, specific heat of 381 J/kg·K and thermal conductivity of 387.6 W/m·K was also tested and referred as Case 5.

The 1 m loop diameter GHE was placed 1.5 m below the ground surface with working fluid flows from one side of the wall and exit through the other. The composition of ground was clay to the depth of 15 m and sandy-clay below 15 m (Jalaluddin and Miyara, 2012). The properties of ground according to the type of soils are presented in Table 1.

The dimension of analysis domain was considered adequate that any possible interference from ground could be safely eliminated. Underground water flow and rain infiltration were assumed to have no influence on the analysis domain.

2.2 Initial and Boundary Conditions

Time- and position varying parameters were defined as initial and boundary conditions to achieve realistic simulation. It is worth noting that ground temperature varies along the depth and ground heat flux has strong influence on GHE due to its shallow position (Fujii *et al*., 2008). The boundary conditions vary throughout the day and prone to fluctuation due to meteorological conditions. Data obtained using GLDAS-1 CLM Model from Goddard Earth Sciences (GES) Data and Information Services Center (DISC) as shown in Figure 3(a) and (b) were used to define initial ground temperature profile and ground surface flux. All vertical walls and bottom were considered to have no influence on the analysis domain thus defined as adiabatic boundaries. Comparison of average 83–138 cm deep ground temperature between GLDAS data and simulation result under undisturbed condition is presented in Figure 4. Although the simulation result was slightly higher than the GLDAS data, the comparison showed a reasonable agreement between the two curves.

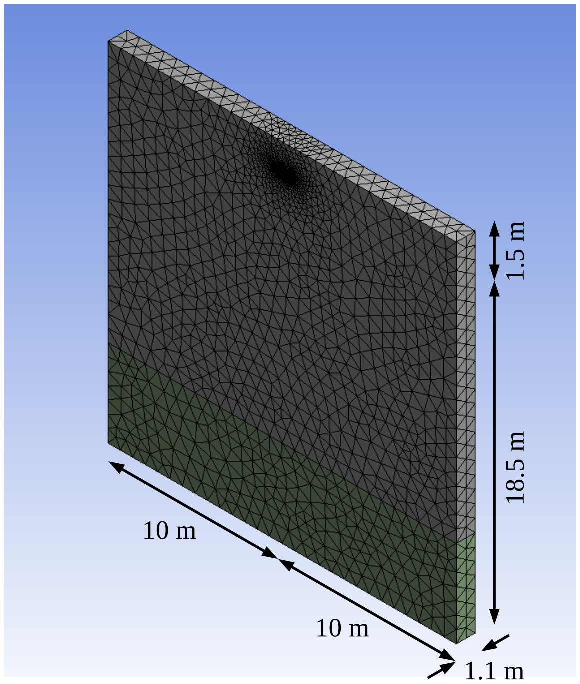
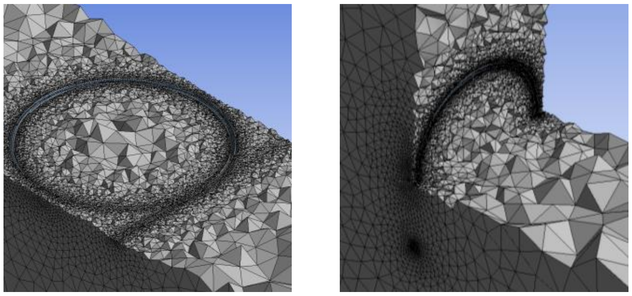
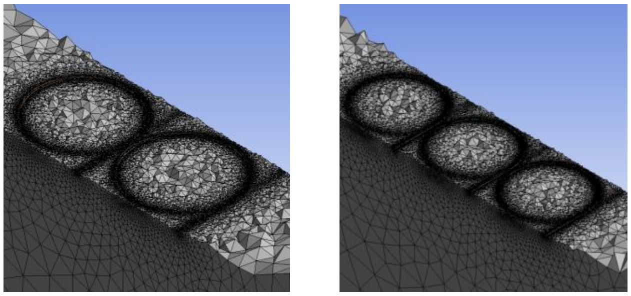


Figure 1: Analysis domain for the simulation models



(a) Reclined orientation (Case 1 and Case 5)

(b) Standing orientation (Case 2)



(c) Double parallel (Case 3)

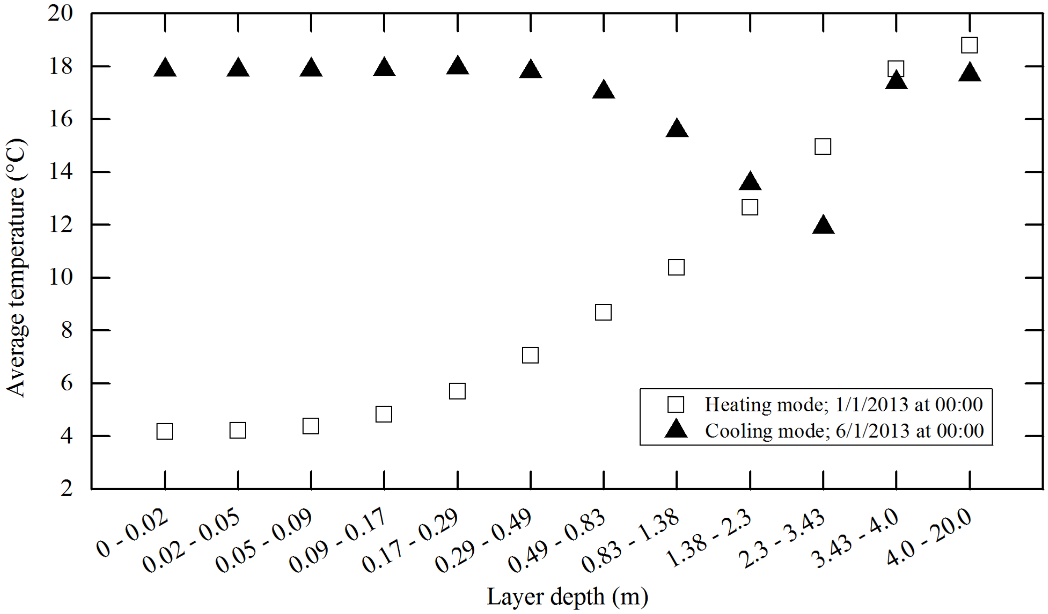
(d) Triple parallel (Case 4)

Figure 2: Section view of detailed meshing of GHE at 1.5 m deep

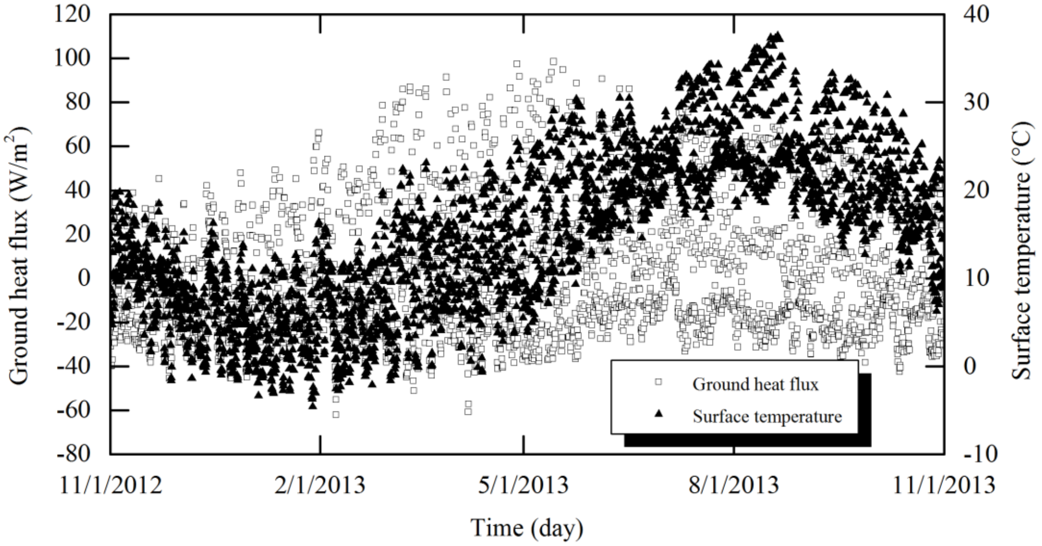
Table 1: The properties of ground (The Japanese Society of Mechanical Engineers, 2009)

Parameters	**Value**
Clay (temperature: 293 K; water content: 27.7%)	
Density	1700 kg/m^3
Specific heat	1800 J/kg·K
Thermal conductivity	1.2 W/m·K
Sandy-clay (temperature: 293 K; water content: 21.6%)	
Density	1960 kg/m^3
Specific heat	1200 J/kg·K
Thermal conductivity	2.1 W/m·K

Water was used as working fluid inside the pipe with a constant inlet flow rate of 4 L/min. This was the total flow rate in case of multiple parallel operations. The initial inlet temperature was set as same as the air temperature near the surface when the flow starts at 09:00 on the first day for continuous operation or every day in case of discontinuous operation. Heat buildup during cooling mode and reduction during heating mode would occur around the GHE along with operating time thus causing the coefficient of performance of the heat pump to significantly drop. A dynamic control was implemented to counter this occurrence (Nam *et al*., 2008 and Congedo *et al*., 2012). The boundary condition for the inlet temperature was set a constant difference, ΔT of 2°C from the outlet temperature. Limits were also imposed so that the inlet temperature would not drop below 4°C during heating mode and exceed 35°C during cooling mode.



(a) Initial ground temperature profile; data beyond 3.43 m were taken from recorded data at Saga University



(b) 3-hourly ground heat flux and surface temperature

Figure 3: Data used as initial and boundary conditions for a location at Saga University, Japan (Source: GES DISC)

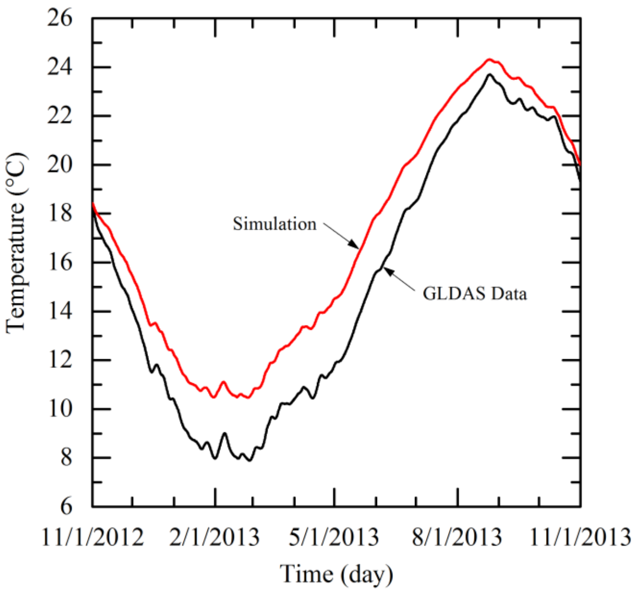


Figure 4: Comparison average 83–138 cm deep ground temperature between GLDAS data and simulation results under undisturbed condition

3. RESULTS AND DISCUSSION

Thermal performance was assessed by heat exchange rate between GHE and ground. The total surface heat flux along the slinky-loop pipe, $\bar{q}$ were solved in FLUENT and used to calculate the heat exchange rate per unit length, $\bar{Q}$ using Equation (1)

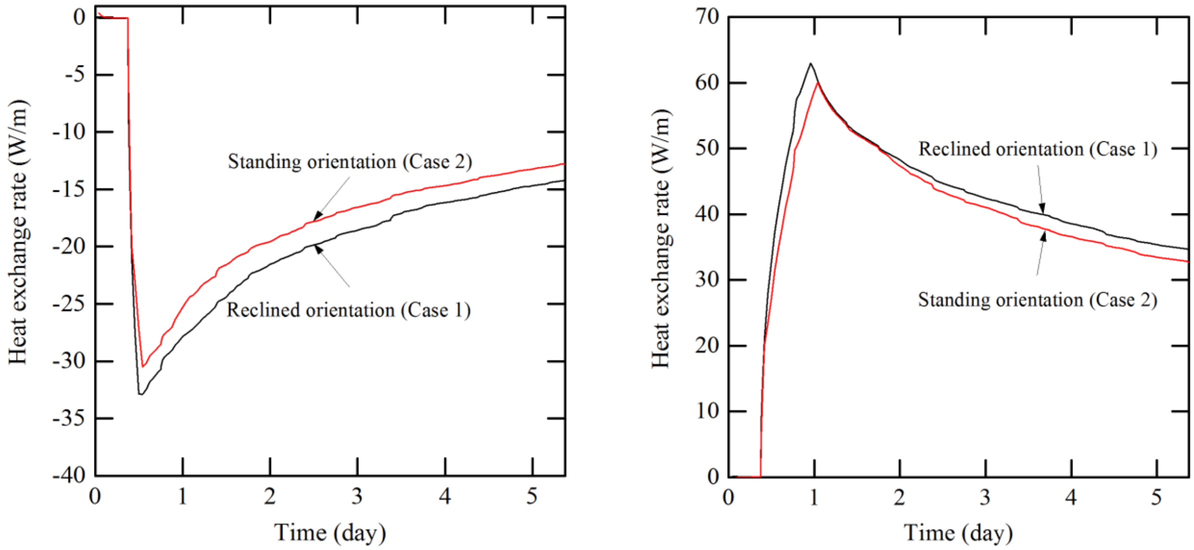
$$\bar{Q} = \bar{q}A/L \tag{1}$$

where A is the surface area and L is the length of the slinky pipe.

3.1 Continuous Operation

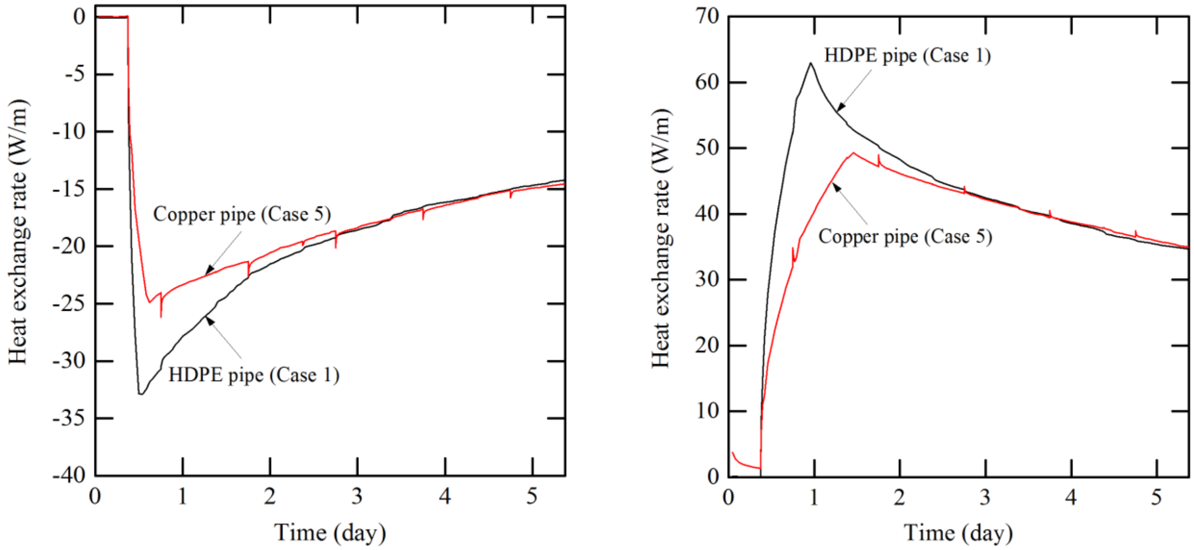
In this work, continuous operation was investigated similar to the method in conducting thermal response test with the exception of dynamic control imposed on inlet temperature. Figure 5(a) and (b) shows comparisons between the orientations of GHE on heat exchange rate during 5-day operation periods. The heat exchange rate of GHE in Case 1 was slightly higher than in Case 2 in term of in both heating and cooling mode. The mean heat exchange rate for Case 1 was 19.0 W/m, while 17.1 W/m for Case 2 in heating mode. Meanwhile in cooling mode, the mean heat exchange rate was 41.0 W/m and 39.2 W/m for Case 1 and Case 2 respectively. The mean heat exchange rate for Case 1 increased 11.1% and 4.6% compared to that in Case 2 in heating and cooling mode respectively. This suggests that heat flow in GHE operation was more dominant along vertical axis. Further simulation of GHE operation beyond this was assumed in reclined orientation unless otherwise stated.

Heat exchange rate for both heating and cooling mode using different pipe materials were compared as shown in Figure 6(a) and (b). The mean heat exchange rate for Case 5 was 17.8 W/m and 37.8 W/m in heating and cooling mode respectively. The heat exchange rate in Case 1 increased 6.7% and 8.5% in heating and cooling mode respectively compared to that in Case 5. However, the heat exchange rate was about the same at the end of operation with result in Case 5 were slightly higher than in Case 1. The prospect of using higher thermal conductivity materials such copper become viable as coating could be applied on the outer surface of the pipe as protection from the elements. Although pipe material with higher thermal conductivity suggests higher heat exchange rate, this analysis supports the common claim that heat exchange rate is predominantly limited by the thermal conductivity of the ground.



(a) Heating operation (b) Cooling operation

Figure 5: Comparisons between the orientations of GHE on heat exchange rate



(a) Heating operation (b) Cooling operation

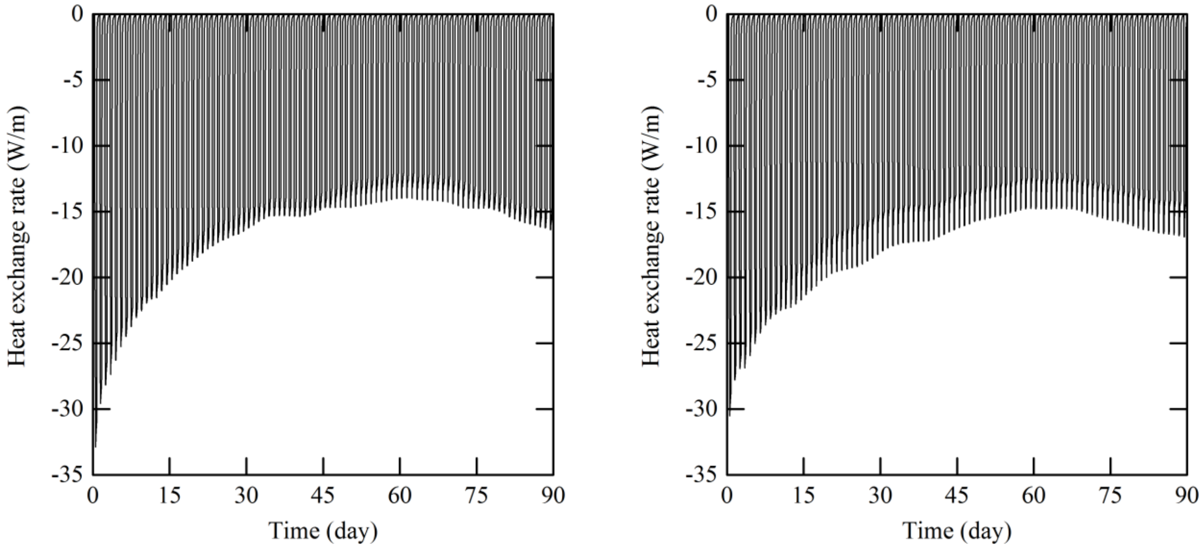
Figure 6: Comparisons between different pipe materials of GHE on heat exchange rate

3.2 Discontinuous Operation

Comparison of heat exchange rate between continuous and discontinuous operation in different cases are summarized in Table 2. Heat exchange rate in Case 1 and Case 2 increased significantly when operated in discontinuous operation. For example, the heat exchange rate at 4.75 day or 18:00 on day-5 increased by 59.3% and 51.7% in heating and cooling mode respectively in Case 1 compared to that in continuous operation. Meanwhile, the increase in Case 2 was 70.6% and 36.2% in heating and cooling mode respectively. In Case 5 however, a decrease of 0.7% in heating mode and a slight increase of 8.5% in cooling mode was observed. This was due to the maximum heat exchange rate in discontinuous operation were far less than they were able to achieve in continuous operation. Case 5 took longer time to reach the maximum heat exchange rate compared to that in Case 1 and Case 2. This suggests that pipe material with higher thermal conductivity prolonged the time before the effect of heat buildup or reduction around the GHE became influential.

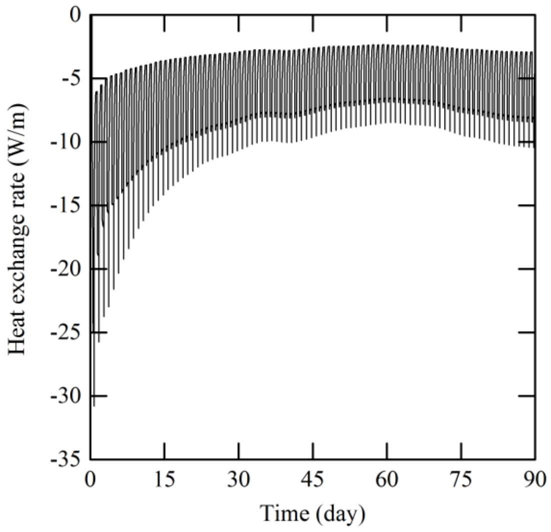
Table 2: Comparison of heat exchange rate between continuous and discontinuous operation

Heat exchange rate (W/m)										
Operation time (day)	*Heating mode*					*Cooling mode*				
	0.75	*1.75*	*2.75*	*3.75*	*4.75*	*0.75*	*1.75*	*2.75*	*3.75*	*4.75*
Continuous operation										
Case 1	30.7	22.7	19.2	16.6	15.0	52.4	50.4	43.7	39.8	36.0
Case 2	28.5	20.4	17.1	15.0	13.6	46.4	50.1	42.1	37.6	34.3
Case 5	24.0	21.3	18.7	16.8	15.1	32.0	47.2	43.1	39.4	36.5
Discontinuous operation										
Case 1	30.7	27.4	26.2	24.9	23.9	52.4	53.8	54.2	54.5	54.6
Case 2	28.5	26.4	25.7	24.4	23.2	46.4	46.6	46.8	46.6	46.7
Case 5	24.0	18.9	16.7	15.7	15.0	32.0	37.9	40.7	42.3	39.6



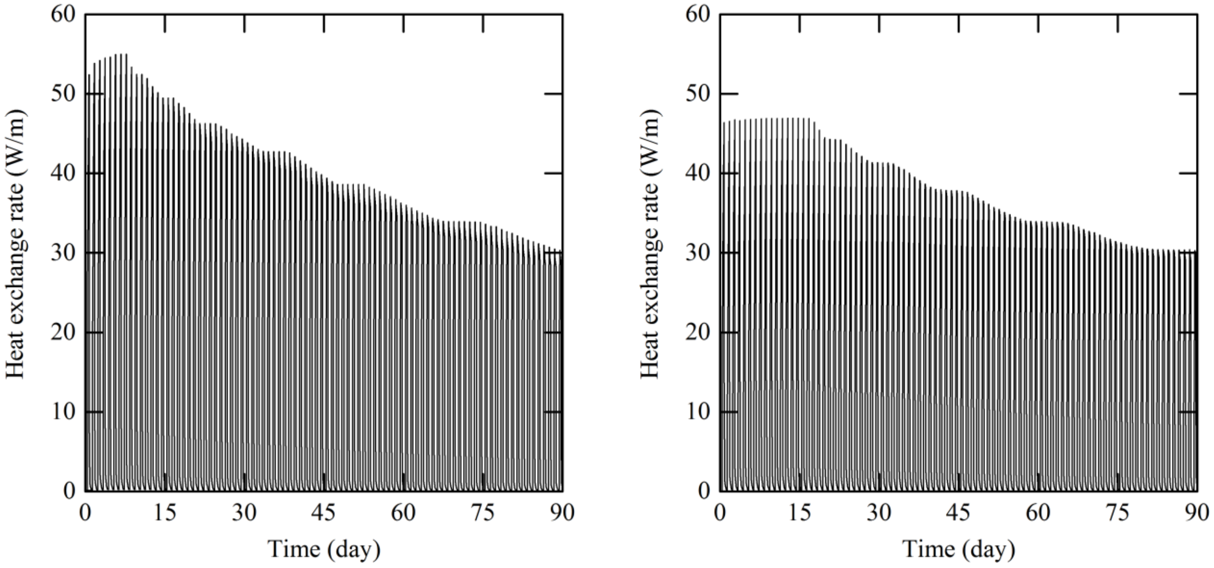
(a) Reclined orientation (Case 1)

(b) Standing orientation (Case 2)



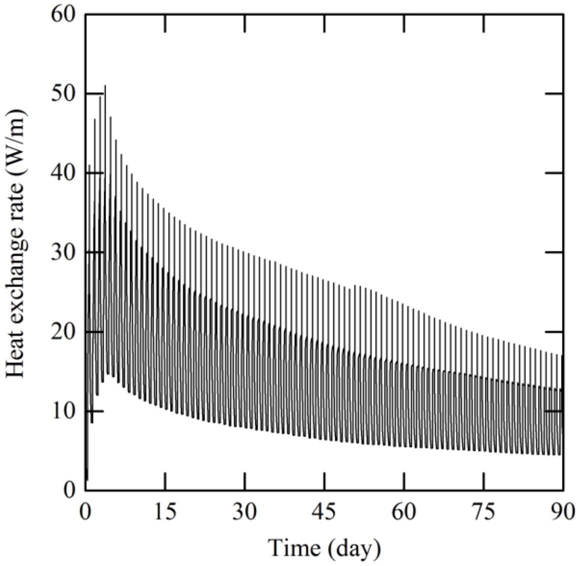
(c) Copper as pipe material (Case 5)

Figure 7: Heat exchange rate for 9 h operation a day in heating mode



(a) Reclined orientation (Case 1)

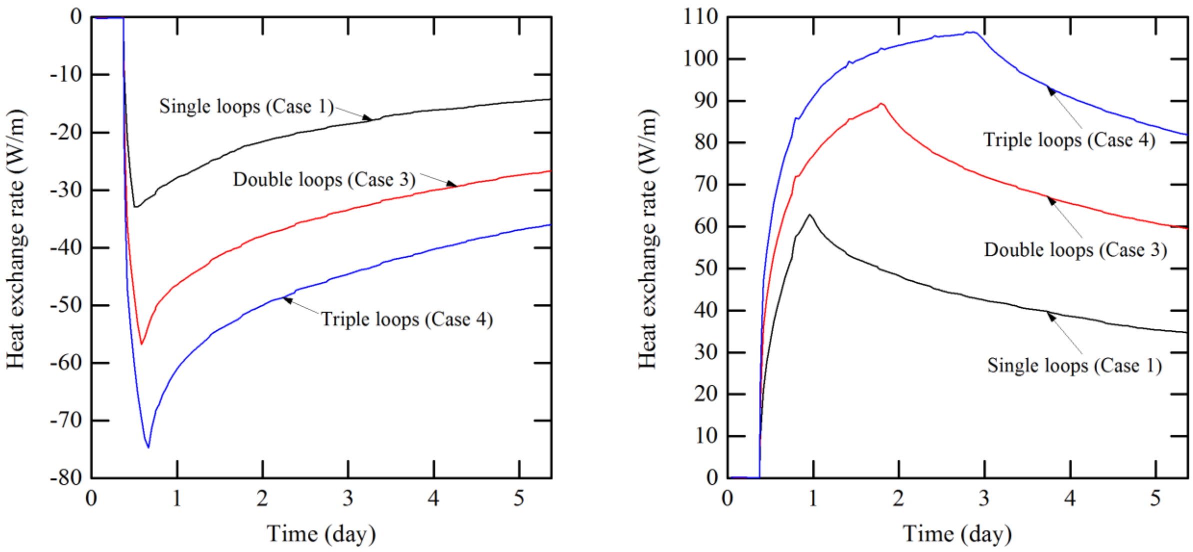
(b) Standing orientation (Case 2)



(c) Copper as pipe material (Case 5)

Figure 8: Heat exchange rate for 9 h operation a day in cooling mode

The results of heat exchange rate are presented in Figure 7(a)–(c) for discontinuous operation in heating mode and Figure 8(a)–(c) in cooling mode. Among all cases in discontinuous operation, Case 1 performed the best with the mean heat exchange rate of 7.7 W/m and 17.2 W/m in heating and cooling mode respectively. The mean heat exchange rate in Case 2 was 7.6 W/m and 15.6 W/m in heating and cooling mode respectively. Case 5 showed the lowest thermal performance with the mean heat exchange rate of 6.5 W/m and 15.1 W/m in heating and cooling mode respectively. Among these three cases, heat flow was observed to occur at the highest rate during off period in Case 5. Off period lessen heat buildup or reduction in the ground thus improves heat exchange rate. Water inside GHE during off period still rejects or absorbs heat thus increases the heat exchange rate in the next flow period. The high thermal performance in discontinuous operation could reduce the land area and pipe material required as well as pumping work in the system.



(a) Heating operation

(b) Cooling operation

Figure 9: The effect of multiple parallel operation of GHE on heat exchange rate

Table 3: Summary of mean heat exchange rate in different cases

Mean heat exchange rate (W/m)				
Operating mode	*Continuous operation*		*Discontinuous operation*	
	Heating	*Cooling*	*Heating*	*Cooling*
Case 1	19.0	41.0	7.7	17.2
Case 2	17.1	39.2	7.6	15.6
Case 5	17.8	37.8	6.5	15.1
Case 3				
0 m spacing	33.6	66.9		
0.5 m spacing	34.8	71.1		
1.0 m spacing	34.8	69.6		
2.0 m spacing	35.0	69.7		
4.0 m spacing	35.1	71.4		
Case 4				
0 m spacing	44.6	87.6		
0.5 m spacing	47.5	80.7		
1.0 m spacing	47.7	80.0		
2.0 m spacing	47.8	84.6		
4.0 m spacing	47.8	91.9		

3.3 Multiple Parallel Operations

The effect of multiple parallel operations was compared as presented in Figure 9(a) and (b). Case 3 and Case 4 were modelled for double and triple parallel operation respectively in both heating and cooling mode for 5-day continuous operation. In multiple parallel operations, identical GHE were positioned side by side with initial spacing of 0 m being given. The mean heat exchange rate in Case 3 was 33.6 W/m and 66.9 W/m in heating and cooling mode respectively. This is an increase of 76.8% and 63.2% in heating and cooling mode respectively compared to that in Case 1. Meanwhile, the mean heat exchange rate in Case 4 was 44.6 W/m and 87.6 W/m in heating and cooling mode respectively. The heat exchange rate increased compared to that in Case 1 by 134.7% and 113.7% in heating and cooling mode respectively. Multiple parallel GHE installations cost more initially in the form of surplus amount of pipe material and trench works as well as land area. However, operating costs for example pumping work is required less to obtain the heat exchange rate comparable to that in single operation.

Heat flow from adjacent GHE in multiple parallel operations interferes with one another penalizing the overall thermal performance. Hence, interference from adjacent GHE on the thermal performance of multiple parallel operations was also investigated. Table 3 presents the effect of spacing between adjacent GHE on heat exchange rate for both Case 3 and Case 4. It was observed that the mean values were almost with a minimum spacing of 0.5 m except for in Case 4 in cooling mode. The minimum increase in mean values compared to that in 0 m spacing were 3.6% and 4.2% in heating and cooling mode respectively in Case 3 while 6.5% in heating mode in Case 4. In cooling mode in Case 4, the mean value decreased in the first three spacing distances by 8.7% maximum before increased by 4.9% at 4.0 m spacing.

4. CONCLUSIONS

In this work, numerical modelling was performed using FLUENT to predict the thermal performance of horizontal slinky-loop GHE. Time- and position-varying parameters were used in order to achieve realistic simulation. The heat exchange rate in 5-day continuous and 90-day discontinuous operation in different GHE configurations was investigated in heating and cooling mode. The heat exchange rate in reclined orientation was slightly higher compared to that in standing orientation suggesting that heat flow in GHE operation to be more dominant along vertical axis. This analysis supports the common claim that heat exchange rate is predominantly limited by the thermal conductivity of the ground. In discontinuous operation, water inside GHE during off period continues to reject or absorb heat thus increases the heat exchange rate in the next flow period. In parallel GHE operation, adjacent loops spaced with 0.5 m distance from each other were able to minimize the interference of heat flow that would penalize the overall thermal performance.

NOMENCLATURE

ΔT	temperature difference	(°C)
$\bar{q}$	total surface heat flux	(W/m^2)
$\bar{Q}$	heat exchange rate	(W/m)
A	surface area of slinky pipe	(m^2)
L	length of slinky pipe	(m)

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ACKNOWLEDGEMENT

The data used in this effort were acquired as part of the activities of NASA's Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).