Performance of Shallow Borehole of spiral-Tube Ground Heat Exchanger

Jalaluddin, Rustan Tarakka
Department of Mechanical Engineering, Hasanuddin University, Tamalanrea, Makassar 90245, Indonesia
Email: jalaluddin_had@yahoo.com

Akio Miyara
Department of Mechanical Engineering, Saga University, 1 Honjomachi, Saga-shi 840-8502, Japan

ABSTRACT

The use of geothermal energy has been recognized as a possible solution for reducing emissions. This energy source is a renewable and green energy sources with wide applications such as for space air conditioning and hot water supply. A ground heat exchanger (GHE) can be applied in the space air conditioning system for exchanging heat with the ground. This study present an investigation of thermal performance of shallow spiral-tube GHE buried in the 5 m depth. The performance of this GHE is investigated by numerical method using CFD code. The performance of the spiral-tube GHE is 46.9 Watt per meter borehole depth in laminar flow and 64.6 Watt per meter borehole depth in turbulent flow. Comparison between the spiral-tube and the conventional U-tube GHEs shows the possibility to reduce borehole depth and installation cost. Using the spiral-tube GHE can reduce the borehole about a half compared with using the conventional U-tube GHE. Shallow spiral-tube GHEs can be arranged in series and parallel configurations to meet the needs in the application.

Keywords: *ground heat exchanger, shallow spiral-tube GHE, performance.*

Introduction

The ground source heat pump (GSHP) system is a promising technology for space air conditioning system in the building. The system can be applied with wide applications such as for space air conditioning, water heating and

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agricultural applications. Space air conditioning using the GSHP system in residential and commercial buildings is the well-known application. The performance of ground heat exchanger (GHE) is a significant parameter in design of the GSHP system. The heat exchange performance of the ground heat exchanger (GHE) is an important subject of GSHP system design. Operation modes for various models and conditions of the GHEs explains the different characteristic of their heat exchange rates. Experimental study of various types of GHEs such as U-tube, double-tube, and multi-tube types was carried-out to investigate their performances. The result shows that the heat exchange rate of the double-tube has the highest [1]. The performances of various types of GHEs have been investigated for different operation modes including short-time period, discontinuous and continuous operations. The operation modes affected the different characteristics of their heat exchange rates [2,3]. Furthermore, the performance of a multiple-tube GHEs arranged with a number of pipes placed inside the borehole have been studied. The performance of the GHEs was affected by the thermal interferences between the pipes [4]. Also, the performance of the GHEs was affected by temperature of inlet water and borehole depth [5]. In the hot weather like Indonesia, the GSHP system is used for space cooling as an air conditioning system as known as ground-source cooling system. The hybrid GSHP system was applied for air conditioning system in hot weather condition such Hongkong [6]. Naili et al. [7,8] conducted a study of ground-source cooling system using horizontal GHE in Tunisia. The performance of the system was analyzed experimentally and analitically. The utilization of the GSHP system is appropriated for cooling building in he hot climate such Tunisia.

In the GSHP system, a GHE is used for exchanging heat with the ground. The spiral-tube GHE is gaining interest in recent years. Some studies developed analytical solutions for spiral coil type of GHE including Man et al. [9], Cui et al. [10], Man et al, [11] and Li and Lai [12]. The line and “hollow” cylindrical heat source models as the classical approaches are no longer valid for thermal investigation and design of the spiral coil GHE in foundation pile. Man et al. [9] developed a model of “solid” cylindrical source taking in to account the heat capacity and the radial dimension of the borehole or foundation pile. Considering the effect of coil pitches and the discontinuity of the heat source, Cui et al. [10] developed the ring-coil source model. However, the heat transfer of water circulating inside the spiral coil can not be simulated by using this model. Furthermore, Man et al. [11] improved the model by developing a spiral heat source model for better thermal investigation. Zarella et al. presented a comparison study of helical GHE and double U-tube [13] and triple U-tube [14]. The result shows that the thermal performance of the helical GHE is better than others.

The spiral-tube GHEs have been proven by a number of studies that providing a better performance. Different types of spiral-tubes GHEs placed in a borehole and concrete pile were investigated [15,16]. Also, the performance of the spiral-tube GHEs and its pressure drop along the pipes are discussed as a significant parameter in GSHP design [17]. For deep vertical spiral-tube GHE, large investment cost is needed. Pumping power due to pressure drop and ineffective of outlet pipe due to thermal interference should be considered. A shallow spiral-tube GHE is taking interest because of providing the possibility to reduce a borehole depth. Performance and distance between shallow spiral-tube GHEs have been studied [18]. Determining the distance between GHEs (spacing) and its effect on the heat transfer rate becomes an important issue. However, there is a limited number of works on shallow spiral-tube GHEs. In addition, an optimum design of horizontal ground heat pump systems is also investigated for spiral-coil-loop heat exchangers [19]. Horizontal GHE is usually need a large of land area. If a large of land area is not available, using a number of shallow spiral-tube GHEs can be used as alternative solution.

In order to study the possibility to use shallow spiral-tube GHEs, this work present an investigation of thermal peformance of shallow spiral-tube GHE. Performance comparison of this GHE with the conventional U-tube GHE is also presented. Reducing the depth of borehole become an attractive economically in the GSHP application due to reducing the cost of installation. The GHE models namely U-tube and spiral-tube were built and simulated. Furthermore, investigation of its heat exchange rates was carried-out.

Ground Heat Exchanger System

The two types of GHEs namely the conventional U-tube and the spiral-tube are presented in Figure 1. The GHE tubes consist of Polyethylene pipes. In the conventional U-tube GHE, a U pipes is installed in the borehole of 20 m depth. A spiral pipe as the inlet tube and a straight pipe as the outlet tube is used in the spiral-tube GHE. Then, the spiral-tube GHE is installed in the borehole of 5 m depth. Silica sand is used as backfilled material in the borehole. In addition, the spiral-tube GHE is also installed in the concrete pile as presented in Figure 1(b).

Simulation Set-Up

<u>Three-dimensional model of GHE</u>

The GHE models were created in three-dimensional unsteady-state model. Numerical simulation was carried-out by using CFD code, FLUENT in order to analyze the heat exchange between the GHEs and ground in the borehole. A finite volume method is applied in the software to convert the governing equations to numerically solvable algebraic equations. The spiral-tube GHE model is presented in Figure 2.

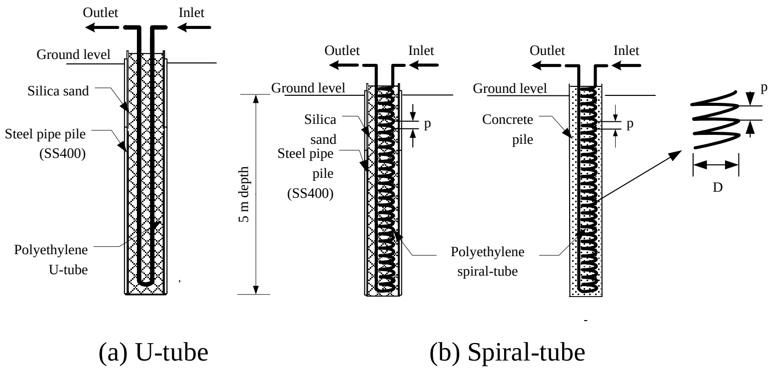


Figure 1: The two types of GHEs namely (a) the conventional U-tube and (b) the spiral-tube.

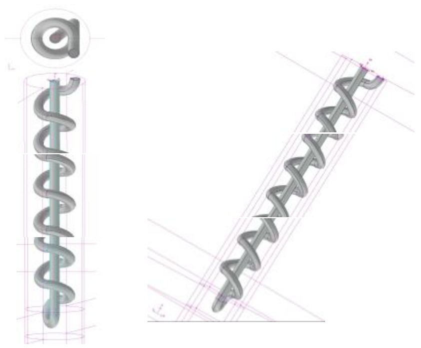


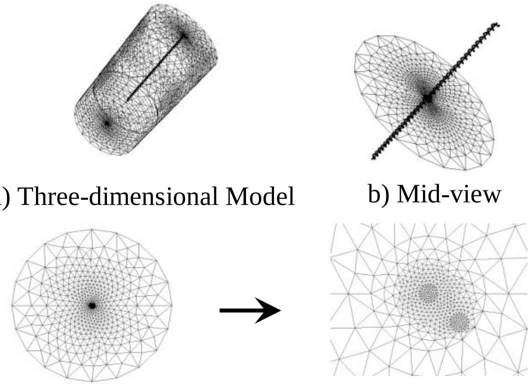
Figure 2: The spiral-tube GHE

Table 1 presented the GHE parameters and thermal properties of materials. In addition, the profile of the ground that consist of Clay in the borehole and its properties are also presented in Table 1.

The surface temperatures of the top and bottom of the model was assumed to be constant and uniform. Ground temperature was initially constant at 17.7 °C (290.85 K). The effect of ambient climate to the ground temperature near the surface is negligible. The circulated water flowed with flow rate of 2 l/min in the laminar flow and 8 l/min for turbulent flow. Constant temperature of inlet water was set of 27 °C (300.15 K). In the simulation set-up for turbulence model, k-epsilon two equation models were applied and scaled residuals were also observed. Turbulence intensity, $I=0.16(Re_{DH})^{-1/8}$ is used for turbulence specification method.

Table 1: The GHE parameters and thermal properties of materials

Parameters	Value	Unit
U-pipe and Spiral-pipe including inlet and outlet pipes of the GHEs (All pipes are Polyethylene)		
Inner diameter, d_i	0.026	m
Outer diameter, d_o	0.033	m
Density, ρ	920	kg/m^3
Specific heat, c_P	2300	J/kg K
Thermal conductivity, k_{PE}	0.35	W/(m K)
Leg spacing for U-Tube GHE, x	0.02	m
Pitch for Spiral-tube GHEs, p	0.1	m
Backfilled material (Silica sand)		
Density, ρ	2210	kg/m^3
Specific heat, c_P	750	J/kg K
Thermal conductivity, k_{grout}	1.4	W/(m K)
Foundation pile (Concrete)		
Density, ρ	2200	kg/m^3
Specific heat, c_P	1000	J/kg K
Thermal conductivity, $k_{Concrete\text{-}pile}$	1.65	W/m K
Ground (Clay)		
Density, ρ	1700	kg/m^3
Specific heat, c_P	1800	J/kg K
Thermal conductivity, k_{Clay}	1.2	W/m K



a) Three-dimensional Model b) Mid-view

c) Top-view d) Mesh near the borehole

Figure 3: Numerical mesh of the spiral-tube GHE

Grid and meshing

The three-dimensional GHE model was built with hybrid mesh generation. Figure 3 shows the numerical mesh of the spiral-tube GHE including the borehole and ground. The mid-view of the GHE in the cross-section of 2.5 m depth and numerical mesh near the the borehole is presented in the Figure 3(b) and 3(d) respectively.

Grid independence test was carried-out to validate the GHE model. The grid of U-tube GHE was generated using gambit and its cell number is presented in Table 2. Then, heat exchange rate of the GHE was investigated after simulating in 24 h continuous operation. The heat exchange rate of the GHE with total cell number of 197581 (grid 2) has the same results with the finest grid (grid 3 and 4) as presented in Figure 4. Consequently, the grid 2 was applied in the simulation model.

In comparison with the experimental result [1], the heat exchange rate of the GHE model from simulation result confirms the reasonable agreement. Small different with the both results were affected by discrepancies of some uncertain factors including thermal properties of local ground, initial and boundary conditions, ets. The both results show the heat exchange rate deviation of 2-18%.

Table 2 Total cell number of grid

Total cell number of the U-tube GHE			
Grid 1	Grid 2	Grid 3	Grid 4
46446	197581	438346	388681

Furthermore, a similar hybrid mesh mentioned previously is applied in the spiral-tube GHE model.

Heat exchange rate

The heat exchange rate of the spiral-tube GHE was calculated through the water flow to investigate its thermal performance. The following equation is used to calculate the heat exchange rate.

$$Q = \dot{m} c_p \Delta T \qquad (1)$$

where $\dot{m}$ is flow rate, c_p is specific heat, and ΔT is the different between inlet and outlet temperatures of the water flow.

The thermal performance of each GHEs are expressed by the heat exchange rate per unit length of borehole depth as the following equation.

$$\overline{Q} = Q / L \qquad (2)$$

where L is the borehole depth of each GHE.

Results and Discussions

Temperature distributions

Borehole temperature distribution

The thermal performance of GHE is affected by the heat buildup in the ground around the borehole. The distributions of borehole temperatures at x=0.1 and 0.25 m (distance from borehole axis) and z= 2.5 m depth of spiral-tube GHE with silica sand backfill operated in the laminar and turbulent flows are pesented in Figure 5. The borehole temperatures increase with operation time. This fact indicated that the large of heat rejected to the ground and increasing the ground temperature.

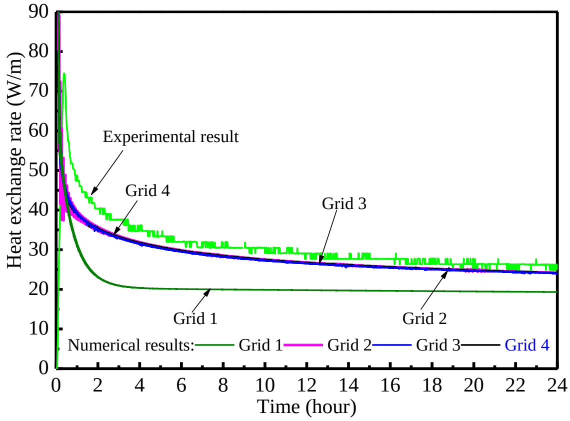


Figure 4: Experimental and numerical results of the GHE.

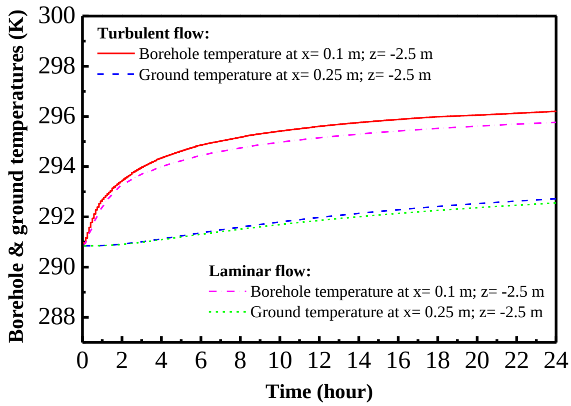


Figure 5: The temperature distributions of borehole and ground

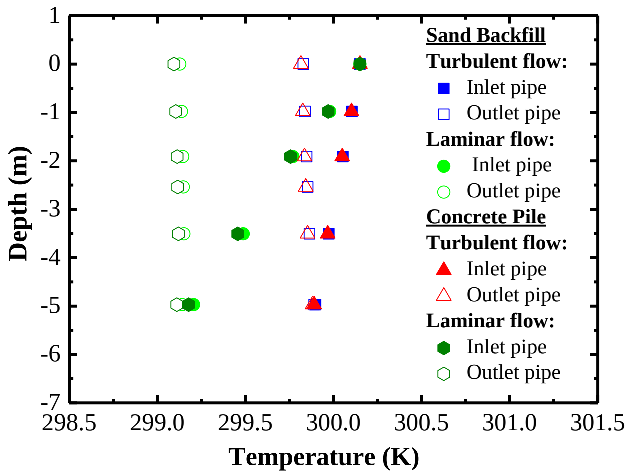


Figure 6: The temperature distributions of water after 24 h operation

Water temperature distribution

Figure 6 presents the water temperatures of the spiral-tube GHEs through the depth with silica sand backfill and concrete pile in the laminar and turbulent flows. Constant temperature of inlet water was set of 27 ^{o}C (300.15 K). Water flows through the pipes of inlet and outlet. The water temperature decreases because of heat in the flow direction. The low flowrate of the water in the laminar flow contibutes to the high reduction in temperature of water in the spiral tube. The relatively small change in the outlet pipe temperature is due to the thermal interference from the inlet pipe. In addition, the water temperature distribution is slight different between the GHE with silica sand backfill and the GHE installed in concrete pile due to their thermal conductivities.

Heat exchange characteristics of spiral-tube GHEs

The heat exchange rates of the GHE with silica sand backfill and concrete pile in the laminar and turbulent flows are presented in Figure 7. Average heat exchange rate of the spiral-tube GHE with silica sand backfill is 46.9 W per meter borehole depth in laminar flow. In turbulent flow, its performance in average is of 64.6 W per meter borehole depth. In addition, average heat exchange rate of the spiral-tube GHE with concrete pile in laminar and turbulent flows are 49.6 and 68.5 W per meter borehole depths respectively. Installing the GHE in the concrete pile increases slightly its performance compared with that of silica sand backfill. The high thermal conductivity of concrete pile compared with that of silica sand contributes to its performance.

Thermal conductivities of silica sand and concrete pile are 1.4 W/m K and 1.65 W/m K respectively.

The cross-sectional temperature contours of the GHE backfilled with silica sand at 2.5 m depth for laminar and turbulent flows are presented in Figures 8 and 9. The contours of the GHE installed in concrete pile at 2.5 m depth for laminar and turbulent flows are presented in the Figures 10 and 11. Heat rejected from the GHE to the ground is not uniform through the depth and cross-sectional. Water circulates through the spiral pipe and heat rejected to the ground. It causes non-uniform of temperature contours around the borehole.

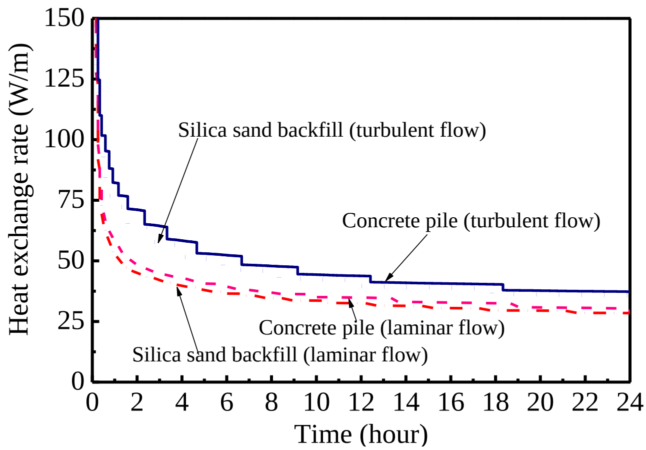
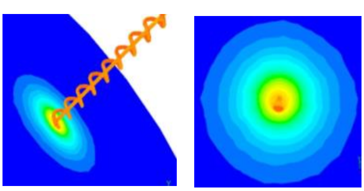
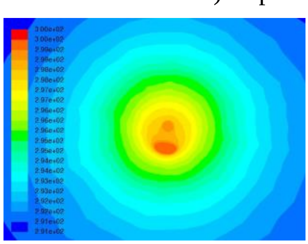


Figure 7: Heat exchange rates of GHEs.

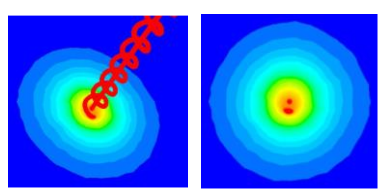


a) Isometric view b) Top-view

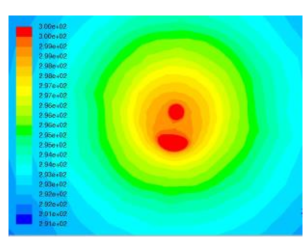


c) Magnified around the borehole

Figure 8: The cross-sectional temperature contours at 2.5 m depth for laminar flow.

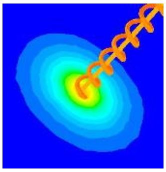


a) Isometric view b) Top-view

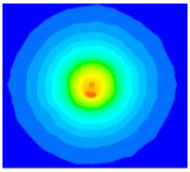


c) Magnified around the borehole

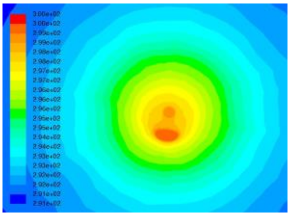
Figure 9: The cross-sectional temperature contours at 2.5 m depth for turbulent flow.



a) Isometric view

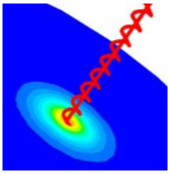


b) Top-view

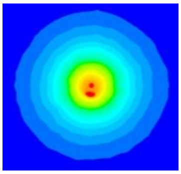


c) Magnified around the borehole

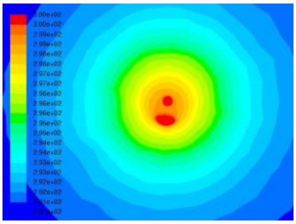
Figure 10: The cross-sectional temperature contours at 2.5 m depth for laminar flow.



a) Isometric view



b) Top-view



c) Magnified around the borehole

Figure 11: The cross-sectional temperature contours at 2.5 m depth for turbulent flow.

Comparative performance with the conventional U-tube GHE

Comparative performance of the shallow spiral-tube GHE with the conventional U-tube GHE is discussed. Heat exchange rate of shallow spiral-tube GHE with silica sand backfill is 46.9 W per meter borehole depth in laminar flow and 64.6 W per meter borehole depth in turbulent flow. This GHE is installed in the ground of 5 m depth. It means that rejected heat to the ground is 234.5 W in the laminar flow and 323 W in the turbulent flow. For performance comparison, the heat exchange rates of the conventional U-tube GHEs installed in the ground of 20 m depth are presented. Its heat exchange rate from experimental data [1] is 24.9 W per meter borehole in laminar flow and 31.5 W per meter borehole in turbulent flow. In addition, its heat exchange rate from simulation result is 20.1 W per meter borehole in laminar flow and 32.5 W per meter borehole in turbulent flow [16]. These results from simulation data show that rejected heat to the ground is 402 W in the the laminar flow and 650 W in the turbulent flow. Based on its amount of rejected heat to the ground, the rejected heat of 2 (two) shallow spiral-tube GHEs with 5 m depth is approximately same with that of 1 (one) conventional U-tube GHE. It will reduce the borehole depth about 10 m. This fact indicates that the borehole can be reduced about a half by using shallow spiral-tube GHE. Shallow spiral-tube GHEs can be arranged in series and parallel configurations to meet the needs in the application.

Conclusions

Performance investigation of the shallow spiral-tube GHE has been carried-out by numerical method using CFD code. From the results of this study, the following conclusions are drawn:

1. The performances of spiral-tube GHE are 46.9 and 64.6 W per meter borehole depth in laminar and turbulent flows, respectively.
2. Installing the GHE in the concrete pile increases slightly its performance compared with that of silica sand backfill.
3. Based on the performance comparison, using the shallow spiral-tube GHE can reduce the borehole about a half compared with using the conventional U-tube GHE.

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