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Development of a spiral type heat exchanger for ground source heat pump system

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Abstract

In Japan, net Zero Energy Buildings are crucial for reducing energy use and environmental load to realize a sustainable society. Ground-source heat pump systems are a key technology for reducing energy consumption by air conditioning systems. There are two types of ground-source heat pump systems: “closed loop type” and “open loop type”. In general, open loop type ground-source heat pump systems have better relative performance than closed loop type systems. However, pumping up underground water is prohibited in urban areas of Japan to prevent the ground surface level from sinking. Therefore, closed loop type systems are used more extensively in Japan. The typical and conventional heat exchangers used for closed loop type heat pump systems are of the “U tube” or “double U tube” types. However, neither type has a high heat exchange capacity per unit length. Thus, in this study, a spiral-type heat exchanger for a ground-source heat pump system is developed. The aim of the heat exchanger is to perform intensive heat-exchange in the aquifer layer near the ground surface (ten to twenty meters in depth). To use the underground water flow in order to facilitate intensive heat exchange, the length of the heat exchanger is planned to be inserted between ten and twenty meters below the surface into the upper part of the aquifer. The diameter of the spiral-type heat exchanger is determined such that a borehole machine for piles can be used for settlement of heat exchangers to reduce the construction cost. The performance of the heat exchanger is simulated under various flow rates and soil conditions using the numerical simulator “TOUGH2/EOS1.” Based on the simulation and construction cost study, the cost-effectiveness of the spiral-type exchanger is made clear.

Keywords: ground source heat pump system; ground heat exchanger; spiral type

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1. Introduction

In Japan, nZEB (net Zero Energy Building) is crucial for reduction of energy use and environmental load in order to realize a sustainable society.

Ground source heat pump system (GSHP) is one of the key technologies to reduce energy consumption for air conditioning system. There are two types of ground source heat pump system, one of those is closed loop type heat pump system and another type is open loop type heat pump system.

Generally, open loop type ground source heat pump system has relatively higher performance compared to that of closed loop type. However, it is prohibited to pump up the underground water in urban area in Japan to avoid ground surface level sinking.

Therefore, closed loop type system is spread in Japan. The typical and conventional heat exchanger used for closed loop type heat pump system is “U tube” type or “double U tube” type. However, both “U tube” and “double U tube” type do not have high heat exchange capacity per its length.

In Japan, there are many place where aquifer layer is near the ground surface. It is often observed that the areas in which rich underground water exist, the flow rate of groundwater is relatively high in shallow underground (ten to twenty meters depth).

Purpose of this study is to develop a high performing and low cost heat exchanger for GSHP in order to accelerate the introduction of GSHP in Japan.

The aim of newly developed spiral type heat exchanger is to intensive heat exchange in the aquifer layer near the ground surface (ten to twenty meters in depth). In order to use the underground water flow to intensive heat exchange, length of the heat exchanger is planned between ten to twenty meters to insert the top aquifer from the surface. Diameter of the spiral type heat exchanger is determined so that borehole machine for piles can be used for settlement of heat exchangers to reduce the construction cost. Performance of heat exchanger is simulated in various flow rate and soil conditions used numerical simulator “TOUGH2/EOS1” (see Note1). Based on the simulation and construction cost study, cost effectiveness of the spiral type is made clear.

2. Overview of Spiral Type Heat Exchanger

High performance polyethylene PE100, the material having high, long term durability mainly used for U-tube, is used for the exchanger, and bending of small diameters which used to be impossible to be conducted is applied to the exchanger (see Figure 1). As the foundation construction and installation of the new ground heat exchangers may be conducted during the same period, it can be expected that using an excavator which is normally used for piling works for installing the ground heat exchangers into the ground will reduce the cost of installation. Therefore, we assumed that the spiral pipes made of high performance polyethylene were installed in the small-diameter boreholes drilled by a piling machine. As shown in Figure 1, the spiral type heat exchangers with 10 - 20 m in depth, 100 - 200 mm in pitch and slightly less than 400 - slightly less than 600 mm in diameter are commercialized.

3. Results of Measurement and Comparison of Simulated Values

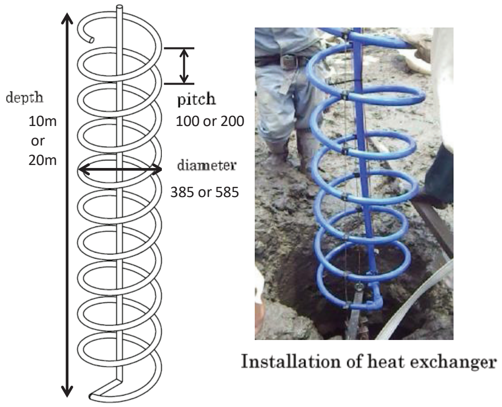
3.1. Overview of Installation of Ground Heat Exchangers

The ground heat exchangers were installed as the heat source of the research institute building which was newly built in Tokyo. High performance polyethylene PE100 with high, long term durability was used for all the heat exchangers. The spiral type heat exchanger has 21 mm in inside diameter of the pipe, and single-U-tube and double-U-tube heat exchangers have 27 mm in inside diameter of the pipe. A diameter of a spiral is 385mm.

Figure 2 shows the illustration of the arrangement of the heat exchangers and temperature measurement points. Two spiral type heat exchangers (20m in length) and three single-U-tube and three double-U-tube heat exchangers

(70m in length) were installed in the ground. After inserted into the ground, each exchanger was backfilled with coarse sand. As the field was not large enough, the distance between the exchangers caused slight heat interference in each exchanger.

Moreover, the construction site was a clay soil and it was assumed that the flow rate of the groundwater was very small. The “clay soil” section of Table 1 shows the properties of the soil estimated based on the thermal response test conducted in the field. These properties of the soil are also used as the properties of the clay soil in numerical simulation for the cost study, which is shown later. Furthermore, the hydraulic conductivity of the sand used for backfilling was 5.0 x 10 $^{-5}$ m/sec, which was the measured value by the permeability test in the laboratory. The hydraulic conductivity of the sand soil shown in Table 1 provides a typical in-situ value for simulation. The initial value of the temperature with respect to increasing depth of soil is the temperature profile shown as 2013/6/5 in Figure 3. A ground source heat pump has a thermal energy storage tank and stores heat at night. In most cases, it does not work during the daytime except midsummer when heat load is very high. As shown in Figure 7, the temperature of coolant is low at the beginning of the operation, but it increases to slightly more than 30 degree C in a few hours. Figure 7 shows the values measured 2 months after the air conditioning operation starts. It is observed in Figure 3, the temperature increases to approximately 1.5 - 2.0 degree C five months after the air conditioning operation starts, and it causes the rise in the temperature of supplying pipe.



Installation of heat exchanger

Fig. 1. Spiral type heat exchanger

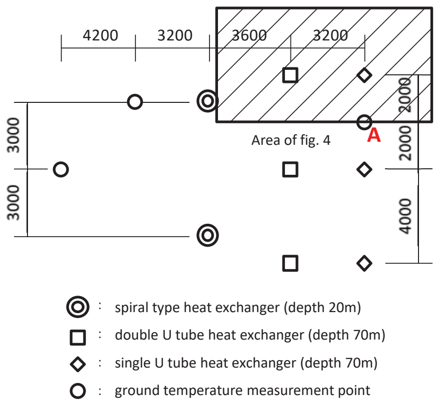


Fig. 2. Location of heat exchangers and temperature measuring points

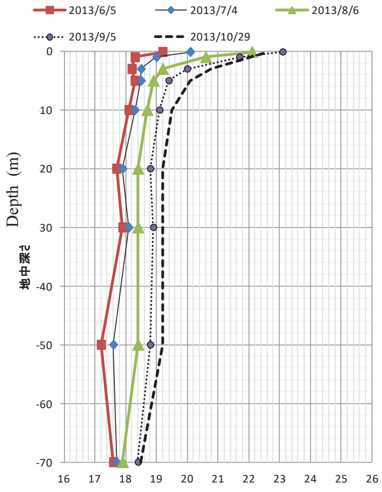


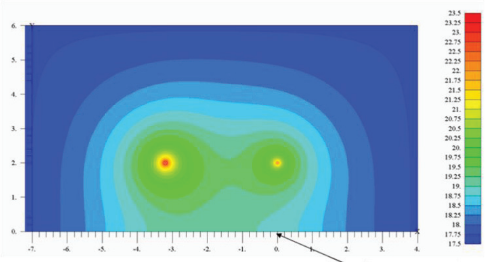
Fig. 3. Temperature profile

Table 1. Physical property

	cray soil	sand soil coarse sand	polyethylene pipe
Thermal conductivity(saturated)	1.85W/mC	1.53W/mC	0.4W/mC
Heat capacity(saturated)	1.61kJ/kgC	1.52kJ/kgC	1.9kJ/kgC
Density	1990kg/m^3	1990kg/m^3	950kg/m^3
Hydraulic conductivity	5x10^{-6}m/sec	1x10^{-3}m/sec	-
Porosity	0.4	0.4	-

3.2. Evaluation for Accuracy of Analysis of U- tube Ambient Temperature

Figure 3 shows the changes in the temperature regarding the temperature measured point A indicated in Figure 2 due to the air conditioning operation. There are the temperature measured points of 0.1, 1.0, 3.0, 5.0, 10, 20, 30, 50 and 70 m in depth. Dates of displaying temperatures are 5 June (operation start day), 4 July, 6 August and 5 September. The estimated quantity of heat injection from 6/5 to 9/5 was generated from three double-U-tube (19.8 GJ) and three single-U-tube (14.9 GJ). Figure 4 shows the distribution of the temperature near the temperature measured point A for 93 days (from 5 June to 5 September) with the calculation result by TOUGH2 / EOS1 (see Note 1) which is the numerical simulator to calculate non-isothermal groundwater flow. The values of the actual operations were considered as heat input, and the average temperature of 10, 20 and 50 m in depth on 5 June was used as the initial temperature. The scope of measurement is the area enclosed in a square shown in Figure 2. While the field up to 20 m in depth was actually affected by the spiral type heat exchanger, such influence was ignored and two-dimensional simulation was conducted. In the actually measured data (average data at 20, 30 and 50 m in depth), increase in temperature (17.6 degree C (6/5) → 18.87 degrees C (9/5)) was observed. In the simulation, there was also an increase in temperature (17.6 degrees C (6/5) → 18.81 degrees C (9/5)). Thus, the difference between the measured and the calculated values was only 0.06 degree C. As the values in both cases were almost equivalent to each other, it seems accuracy of calculation has been verified.



temperature measurement point A

Fig. 4. Temperature profile around point A

3.3. Spiral-pipe Ambient Temperature and Evaluation for Accuracy of Analysis with Exchanged Amount of Energy

Figure 5 shows the simulation model. TOUGH2/EOS1 was used as the numerical simulator. The actual diameter was determined in consideration of the extra size necessary for the diameter of the pile used in the building. The measured quantity of heat injected into the ground was given as the heat flow on the surface of a pipe, and ground temperature distribution was calculated for 93 days, starting with the initial temperature. The quantity of heat was determined as three different values (17.67 W / m (depth), 21.53 W / m and 20.92 W / m) for different three period (0 - 30 days, 30 - 63 days and 63 - 93 days) by averaging the measured data of each period. Figure 6 shows the calculated ground temperature distribution. Note that the influence of the ground heat exchanger in other areas outside the analyzed area was ignored in this calculation. Therefore, there could be calculation errors in the ground temperature distribution near the boundaries of the analyzed area. In this study, the temperature of the coolant flown into the heat exchanger due to heat exchange on the 63rd day was given to the temperature field generated by the simulation for 63 days. We then verified the accuracy of the simulation by comparing the measured and the calculated values of heat flow. Figure 7 shows the measured returning and supplying temperatures in the pipe and the average of them. The average temperature indicated in Figure 7 was given as the temperature of the inside wall of the pipe in simulation, and the quantity of heat exchanged obtained in the 4-hour simulation was compared with that obtained in the actual operation in the ground on the 63rd day. As a result, it was observed that the estimated quantity of heat exchanged during the simulated operation (1.55 MJ / m (depth)) was equivalent with the actually measured quantity of heat exchanged (1.55 MJ / m). The heat and flow analysis method using TOUGH2 / EOS1 to measure heat transfer and groundwater flow at the same time allowed us to confirm the accuracy of the formation of the temperature field in the spiral type heat exchanger and analysis of the amount of heat exchanged by the exchanger for a short period of time.

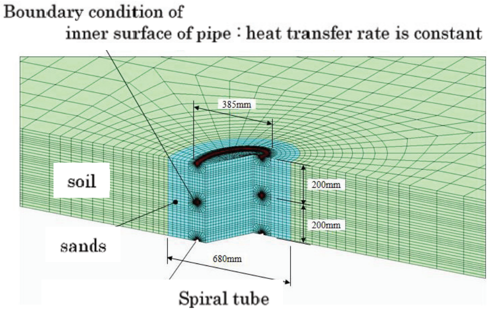


Fig. 5. Simulation model

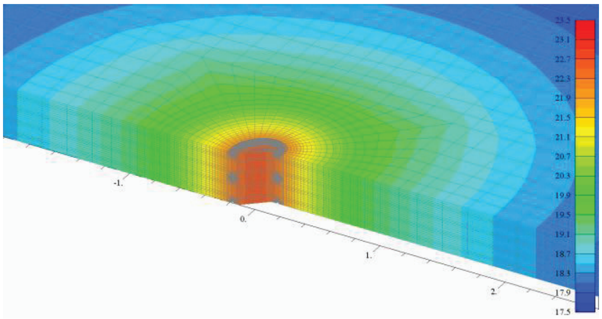


Fig. 6. Calculated temperature profile after 63 days

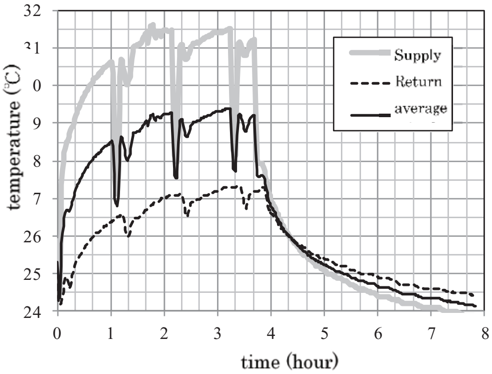


Fig. 7. Measured temperature of coolant after 63 days

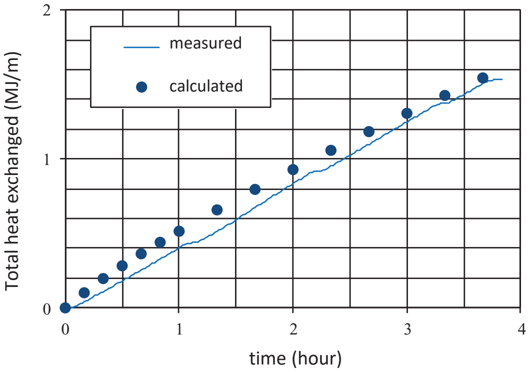


Fig. 8. Comparison of measured and calculated values of exchanged heat

4. Estimations of Heat Flow Using the Velocity of the Groundwater Flow as a Parameter

Figure 9 shows one example of the simulation model. Regarding the geometry of the model, two spirals were extracted and divided at the center of the spirals in consideration of symmetry to generate a cross-section view which was modeled as the three-dimensional structure. Assuming that a polyethylene pipe that the diameter of its spiral was 600 mm was installed in the hole whose diameter was 800 mm and extra space was filled with sand, the property values of the ground, filling sand and polyethylene were determined as shown in Table 1.

Figure 9 also shows the boundary conditions of the model. The initial temperature of the ground was set at 15 degree C and the initial velocity of the groundwater flow was set within the range of 0 - 0.2 cm / min as an analytical parameter.

Moreover, the difference ΔT between the temperature inside the pipe (brine temperature) and the initial temperature of the ground was set within the range of 2 – 10 degrees C. In addition to the spiral with 100 mm in pitch as shown in Figure 2, another spiral with 200 mm in pitch was also set for simulation. Moreover, a polyethylene double-U-tube whose inside diameter is 27 mm was also simulated for comparison. The simulation was done in two cases. One of them is under the condition of adiabatic boundary and another case was for isothermal boundary condition. As it was observed that the difference in temperatures in both cases was up to less than 0.01 degree C, we determined that the influence of temperatures in boundaries on the results of the analysis could be ignored. In Figures 10 and 11, relation between heat exchange capacity per depth and temperature difference ΔT around 120 hours after exchanging heat were plotted. The almost linear correlation among the velocity was indicated.

Moreover, Figure 5 illustrates the temperature distribution around the spiral pipe, indicating that the increase in temperature around the pipe was reduced and the heat flow on the surface of the pipe was increased due to the convection effect in the case of larger velocity of flow.

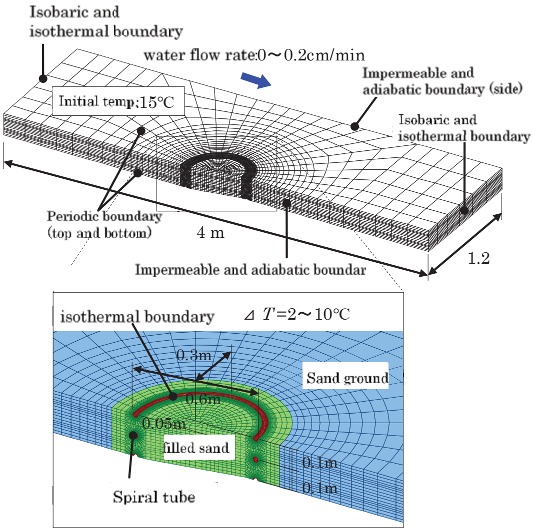


Fig. 9. Simulation model (pitch: 100mm)

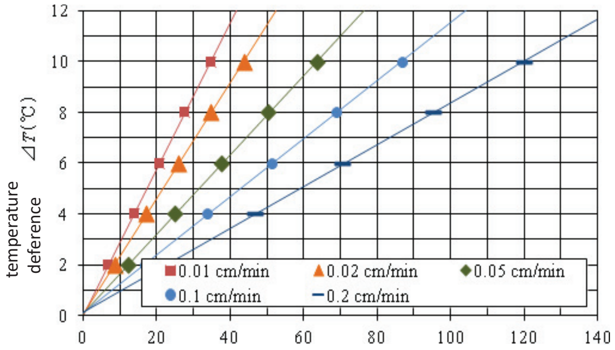


Fig. 10. Heat exchanging capacity of double Utube heat exchanger

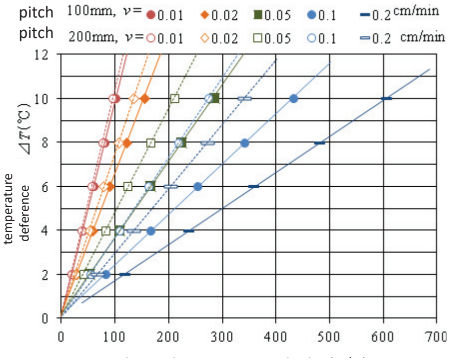


Fig. 11. Heat exchanging capacity of spiral type heat exchanger

5. Cost Consideration

In order to examine the advantages of the spiral type heat exchanger, we compared the initial costs of heat exchange capacity of the spiral type heat exchanger and the double-U-tube heat exchanger, and initial cost per heat exchange capacity based on the estimated initial costs of materials and installation of both types of heat exchangers.

In cost consideration, material prices and fees of drilling and installation conducted by specialized contractors were estimated based on the following parameters: 10 m and 20 m in depth, 600 mm in diameter of the spiral and 100 mm and 200 mm in spiral pitch. Gravel and clay layers were assumed for the ground, and the velocity of the groundwater flow for these layers were assumed as 0.1 cm / min and 0.005 cm / min respectively. Moreover, the difference between the average temperature of the fluid in the pipe and the initial temperature of the ground was assumed at Δt= 10 degree C in both cases.

When estimating the costs, it was assumed that steel casing was used and the pipe was taken out when backfilling after inserting the heat exchanger in the case of a gravel layer. In the case of a clay layer, it was assumed that the excavation was made in the fluid-replacing method and backfilling was conducted after inserting the heat exchanger without casing. The scale of construction with the spiral type heat exchanger was assumed to be 34 units at 10 m in depth, 600 mm in diameter and 100 mm in pitch. In other cases, the number of units was estimated to ensure the same quantity of heat exchanged was obtained in each case.

The heat exchange capacity in a gravel layer are indicated in Figures 10 and 11. The same simulation was performed with only Δt= 10 degree C in the case of a clay layer. The property values of a clay layer were assumed at 1.85 W / mC in thermal conductivity, 1.61 kJ / kgC in specific heat capacity and 5×10^{-6} m / sec in hydraulic conductivity.

Figure 12 shows the comparison between the result of cost calculation for the spiral type heat exchanger at 10 m, 100 mm in pitch and 600 mm in spiral-diameter, which was the most advantageous among the assumed cases and that for the double-U-tube heat exchanger. The case using the double-U-tube in a clay layer was set as the standard value (100) in Figure 12.

The results indicate that the initial cost per collected quantity of heat in the case of the spiral type heat exchanger was less than that in the case of the double-U-tube heat exchanger by 30 % at both gravel and clay layers.

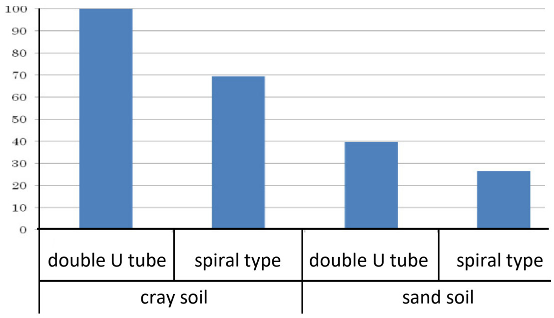


Fig. 12. Comparison of initial cost per unit heat exchanging capacity

6. Conclusion

With the simulation using TOUGH2 / EOS1 which is the numerical simulator to calculate non-isothermal groundwater flow, we partially verified the accuracy of the formation of the temperature field and heat flow of the spiral type and double-U-tube heat exchangers in comparison with the actually measured results.

Based on such results, we calculated the initial cost per unit heat exchange capacity in the spiral type and double-U-tube heat exchangers, using estimated the construction fees and material costs.

As a result, the costs in case of the spiral type were less than those in case of the double-U-tube by approximately 30 % at both gravel and clay layers, leading to confirmation of the advantages of the spiral type.

However, the result can be changed in case that the mutual heat interference is occurred as this result is based on the assumption that there is no mutual heat interference among several ground heat exchangers. In order to avoid such situation, it seems to be necessary to implement some measures such as understanding the direction of the groundwater flow and arranging the heat exchangers vertically.

Moreover, regarding the verification of accuracy of the simulation, further consideration would be necessary in the future as the simulation in this study was performed only under the limited conditions.

Note that Re-editing, deletion, addition and summarizing were implemented for the reference 1) to create this paper.

Notes

Note 1] TOUGH2 is a versatile multiphase-flow and heat flow numerical simulator developed by Lawrence Berkeley National Laboratory, analyzing unsteady flow behaviors of various fluids (e.g. water and air) and heat (thermal conductivity and convection) in porous media such as the soil. It uses the integrated finite difference method (IFDM) as its numerical solution, and time is implicitly discretized as the first-order finite difference. This study uses EOS1, the equation of state (EOS) module for water and steam, to predict the flows of groundwater and heat in the ground near heat exchangers.

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