Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Field Test and Numerical Simulation for Evaluating the Effect of Ground Surface Coverage on Slinky-Coil Type Horizontal Ground Heat Exchanger

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Keywords: Horizontal ground heat exchanger, thermal response test, ground surface coverage, numerical simulation, Slinky-coil

ABSTRACT

In ground source heat pump (GSHP) system, the use of horizontal ground heat exchanger (HGHE) is a promising choice for reducing the initial cost of the system. However, it is hard to secure the land for installation in Japan where the use of land is limited. Therefore, the heat exchange rate per unit installation area of HGHE needs to be improved to reduce the required land area. In HGHEs which is installed at shallow depth from the land surface to a depth of 2 m, the heat medium temperature of HGHE is considered to be varied positively or negatively by kinds of ground surface coverage above the installed HGHE. This research hence focuses on the effect of ground surface coverage on the HGHE, which could enhance the heat exchange rate.

A long-term monitoring of ground temperature at -1m depth under three kinds of ground surface coverage, which are the asphalt, soil, and lawn, was conducted to observe the effect of ground surface coverage on the ground temperature behavior. The monitoring showed that the ground temperature of the lawn was lowest in summer, while the temperature of the asphalt was highest. These differences were considered to be caused by the different characteristic of solar reflectance. In addition, the thermal response tests (TRT) were carried out using the HGHE installed at a -1m depth to evaluate the effect on the heat exchange efficiency. In the TRTs, the heat load and circulation rate were set as 30 W/m and 15 ℓ /min, respectively. The TRTs showed that the heat exchange efficiency of the HGHE under the lawn was excellent comparing to the other surfaces because the lawn helps to have the ground with high water content which can improve the heat exchange rate of the HGHE. Finally, the cooling and heating simulations considering the ground surface coverage were carried out to estimate the effect of various coverages on the coefficient of performance (COP) of heat pumps. The simulations showed that the lawn improves the COP by 1.1 times as large as the asphalt in cooling operation in case of the HGHE installed at a -1m depth. These results confirmed the possibility of decreasing the land area for installation of HGHE.

1. INTRODUCTION

In Japan, the number of installed GSHP system is small due to the high installation cost of vertical ground heat exchangers. The high cost comes from the drilling into the ground (US$100-150/m). In contrast to vertical ground heat exchangers, the HGHE installed at the shallow depth can reduce the installation cost because of the use of power shovels instead of the drilling machine. However, the use of HGHE is difficult in Japan since the HGHE requires the wide land space for the installation and the land use is limited. Hence, the improvement of heat exchange rate per unit area of a HGHE is considered as one of the most important measures for wider application of GSHP systems. The numerical simulations in past study showed that ground surface coverages affect the heat medium temperature, indicating the improvement of heat exchange rate (Fujii et al., 2012). Moreover, the field tests using the four systems of the HGHE which are installed under the asphalt or lawn with different conditions showed that heat medium temperatures were varied depended on the ground surface coverages (Philippe, 2015). Thus, the importance of ground surface coverage on the heat medium temperature has been proven. However, its effect on the heat exchange rate still has not been quantitatively clarified. Therefore, if we confirm the positive effect on the HGHE, the installed area could turn down by considering the ground surface coverage into the design of GSHP system.

Field tests and simulations are carried out to investigate the effect of ground surface coverage in this research. The field test site is located in Akita city in northern Japan. In field test site, three Slinky-coil type HGHEs are installed under the ground covered by the asphalt, soil and lawn. First, a long-term monitoring of the ground temperature at a depth of -1m was conducted to observe the effect of ground surface coverage on the ground temperature behavior. TRTs then are carried out while the heat load and the circulation rate were kept constant. The objective of the TRTs is to investigate the relationship between the ground surface coverage and the heat exchange efficiency, which is given by the increase in the heat medium temperature per unit heat exchange rate. Next, heating and cooling simulations are carried out with numerical models considering the characteristic of ground surface coverage on the HGHE developed using FEFLOW ver.7.1 to estimate the effect of ground surface coverage on the COP of heat pumps. Finally, using the numerical models, sensitivity studies are performed by changing the solar reflectance and evaporation efficiency as representative parameters of ground surface coverage to estimate the correlation between the effect and heat exchange rate.

2. FIELD TEST SITE IN AKITA CITY, JAPAN

The local average annual temperature in 2018 in the field test site was 12.3℃ . The field test site is located on the courtyard surrounded by the university buildings, which means the environment is not airy and sunny. The type of soil is sandy clay, which is widespread in the shallow ground. The ground water level was measured as being approximately 5 m below the ground surface throughout the year in a 60 m deep observation well, indicating that the shallow ground soil was unsaturated (Fujii et al., 2015). For the determination of soil properties, the measurements were conducted at the bottom of a trench of 1.0 m located adjacent to the HGHEs during the excavation of the trench. The thermal conductivity and heat volumetric capacity were measured as 1.16 W/(mK) and 2.15 MJ/(m^3K) using a single probe type thermal conductivity meter (Meter, Inc., KDPro2). The schematic of the Slinky-coil type HGHEs, the TRT equipment connected to these HGHEs in parallel and the thermo-resistance thermometers (Pt100Ω) to measure the ground temperatures are shown in Figure 1. Each loop is a single layer HGHE with a land space of nearly 10 m^2; a total coil length of 10 m and a trench depth of 1.0 m. In this paper, the coil length is defined as the length of coil-shaped heat exchangers, and does not mean the total length of polyethylene pipes when laid straight. In all loops, the anti-freezing solution (Ethylene glycol 40wt%) is used as heat medium considering the cold local climate. The diameter of the loop and the ID and OD of the polyethylene are 0.8 m, 0.034 mm and 0.027 mm, respectively. The thermal conductivity of the polyethylene is given as 0.32 W/(mK) in the catalog. Each HGHE is connected to the TRT equipment having 3 kW heat load capacity. All surface piping between the HGHEs and the TRT equipment are insulated using polystyrene covers. Figure 2 shows a photograph taken during the construction of HGHEs and after the completion. After laying the HGHEs and covering them with soil, water was sprayed on the soil to reduce the void space around the HGHEs. The trenches were then back-filled, and the soil was compressed with power shovels. The two land surfaces were paved by the asphalt and lawn. On the other hand, the last surface was not paved and left as a soil surface. The condition of each ground surface coverage was maintained by removing obstacles such as weeds or gravel on the surface and mowing the lawn on a regular basis. During the long-term monitoring and the TRTs, the meteorological data (i.e., ambient temperature, precipitation, wind velocity, and solar radiation) were recorded every hour at the field test site using a weather data measurement (Davis instrument, Co., Inc., VantagePro2).

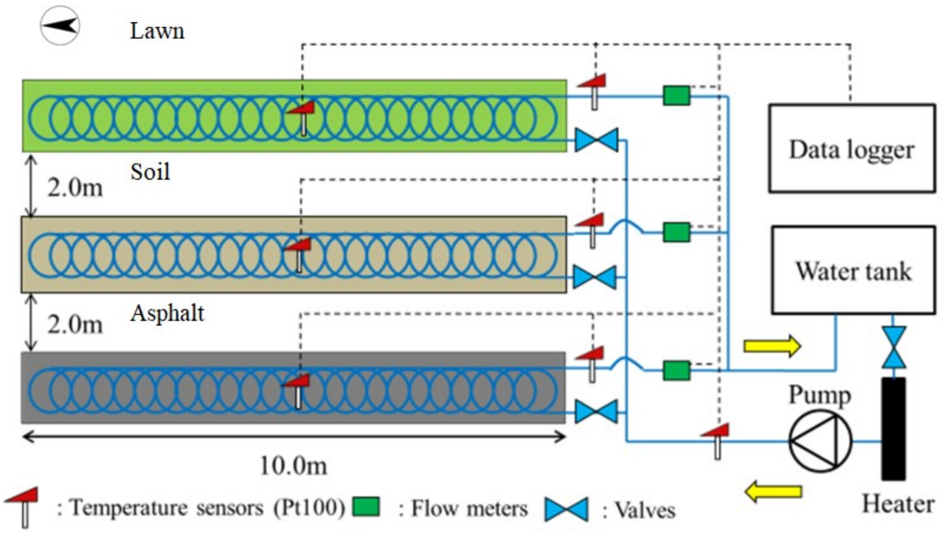

Figure 1: Schematic of field test site installed three Slinky-coil type horizontal ground heat exchanger under different ground surface coverage.

Figure 2: Photograph of field test site under construction and after completion.

3. RESULTS OF LONG-TERM MONITORING OF GROUND TEMPERATURE

The changes of ground temperature under each cover and ambient temperature are shown in Figure 3. In this figure, the calculated value with 10 days-average represents on the y axis to easily check the amplitude and phase of ground temperature behavior. The approximate curve of the ambient temperature measured in field test site is expressed by the following equation (1).

$$T_a = 11.2 + 14.0 \sin 2\pi \left(\frac{t + 242.9}{365.25} \right) \quad (1)$$

Where, T_a, t are ambient temperature [°C], elapsed days from 1st January, respectively.

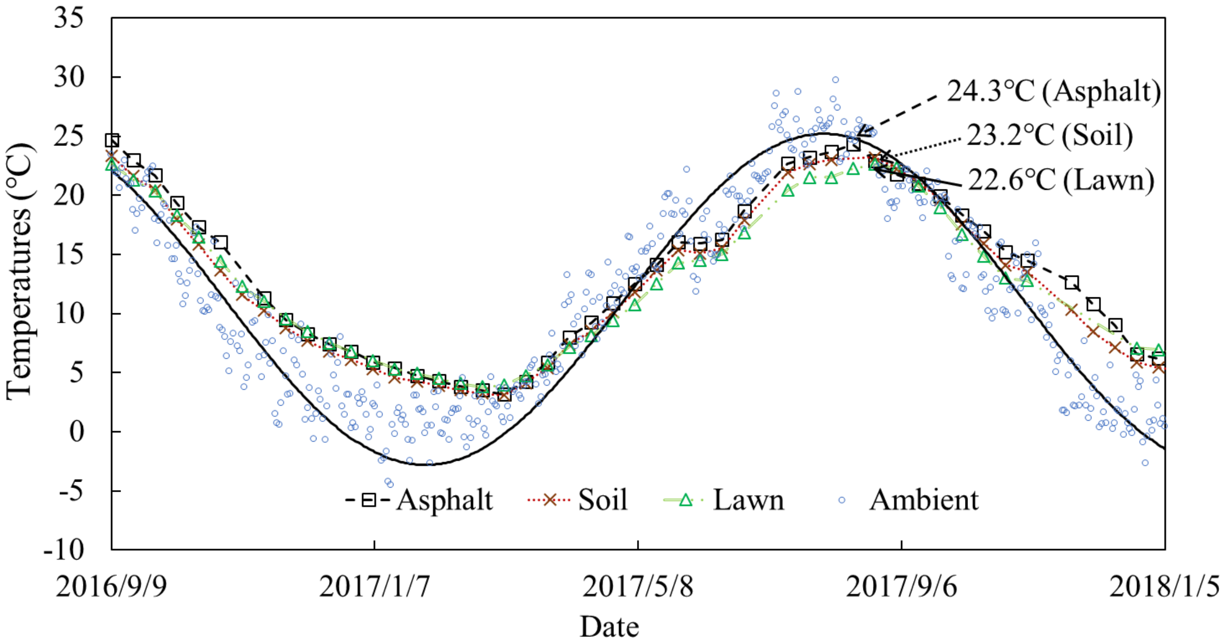

Figure 3: Changes of ambient temperature and ground temperature at 1 m depth under each ground surface coverage.

During the winter of 2017, the difference between the covers were scarcely seen because the snow accumulation from December to February could mitigate the effect of ground surface coverage. During the summer of 2017, the asphalt showed the highest ground temperature of 24.3 ℃ because the solar radiation was absorbed easily and therefore the heat flux to the ground was increased significantly. In addition, the asphalt used in this research is not a water retainable pavement, leading the increase of ground temperature due to the low latent heat to the atmosphere. Meanwhile, the lawn showed that lowest ground temperature of 22.6°C . This can be explained by the transpiration of a plant. The transpiration increases the latent heat to the atmosphere with the consequence that temperature increase is mitigated. The ground temperature behavior under the asphalt delays 7 days compared with the change of the ambient temperature. The length of delay is considered to be inversely proportional to the strength of solar absorption, thus the ground temperature under the asphalt is strongly influenced by the effect of weather conditions. Therefore, the asphalt is not preferred as ground surface coverage for the cooling operation of GSHP systems considering the temperature difference between ambient and ground temperature. Conversely, the lawn is considered to be the best cover on surfaces since the change of ground temperature showed that the amplitude is lower compared with the other covers.

4. RESULTS OF THERMAL RESPONSE TEST

A total of six TRTs were conducted using the HGHE under different ground surface coverages and duration times for estimating the heat exchange efficiency. The TRT names and conditions are summarized in Table 1. The numbers in the names of each TRT indicate the duration time in days and the symbols (A, S and L) indicate the kind of ground surface coverage (the Lawn, Soil and Asphalt). An electric heater of 0.6 kW and 0.3 kW output were used in TRT-*1 and TRT-*15, respectively. Since the length of each HGHE is 10 m, the heat exchange rates per unit HGHE length are calculated as 60W/m, 30W/m for TRT-*1 and TRT-*15, respectively. The circulation rates of heat medium through the HGHEs were maintained nearly constant through all TRTs, 15.0 L/min. In case of the circulation rate of 15 L/min with heat medium temperature of 25°C , the Reynolds number is calculated as above 10,000, indicating the turbulence flow in the heat medium of the HGHE. Therefore, these conditions of TRTs are consider to be similar to the operational condition of actual GSHP system.

Table 1: Conditions of TRTs.

TRT No.	Start	Duration time	Circulation rate	Heat load
		day	L/min	W/m
TRT-A1	2017/11/21	1	15.0	46.5
TRT-S1	2017/11/20		14.8	51.2
TRT-L1	2017/11/22		14.5	50.7
TRT-A15	2018/5/28	15	14.8	31.8
TRT-S15	2018/5/7		15.0	20.7
TRT-L15	2018/6/18		14.9	32.4

In the TRT-A1, TRT-S1 and TRT-L1, the heat exchange rates were lower approximately 100 W compared with the set value (600 W), due to the insufficient heat insulator around the water tank in the TRT equipment, however the heat exchange rates were stable at approximately 500 W. Accordingly, the temperature increase per unit heat exchange rate $\Delta T/\dot{q}$ were calculated using the following equation (2).

$$\Delta T/\dot{q} = |T - T_i| / (q/L) \quad (2)$$

where, T , T_i , q , L are average heat medium temperature, initial ground temperature at a depth of 1 m, heat exchange rate, length of trench, respectively. Figure 4 shows the temperature increase per unit heat exchange rate $\Delta T/\dot{q}$ in each ground surface coverage in the TRT-*1. In all calculation results, the $\Delta T/\dot{q}$ of the asphalt was highest value 0.083 °C /(W/m). This means that the increase rate of heat medium temperature to the heat exchange rate is fast, indicating the poor heat exchange efficiency in cooling. On the other hands, the $\Delta T/\dot{q}$ of the lawn was lowest value 0.073 °C /(W/m), and changed while keeping the lower value of 0.01 °C /(W/m) compared with the other coverages. Moreover, the difference appeared already at 6 hours after the beginning of the TRT-L1. The difference is estimated to be caused by the difference in thermal properties of the ground which is dependent on the water content of the ground.

Figure 5 shows the results of TRT-*15, including the inlet temperature, outlet temperature, ground temperature at a depth of -1 m, heat exchange rate and ambient temperature. The heat exchange rate of the TRT-S15 was lower approximately 100 W than the set value (300 W) because the heat loss to the atmosphere occurred due to the insufficient insulation around the piping. Also, the heat exchange rates of the all TRT-*15 were slightly varied depending on the change of the ambient temperature. However, the variation of the range was about 30W and this value is considered to be low on the evaluating the heat exchange efficiency. As the case of the long test duration with low heat load, the change of temperature increase per unit heat exchange rate $\Delta T/\dot{q}$ for each ground surface coverage in the TRT-*15 are shown in Figure 6. All coverages showed that the changes of the $\Delta T/\dot{q}$ were depended on the weather conditions such as the ambient temperature. While being affected by the effect of weather condition, the $\Delta T/\dot{q}$ for the lawn was lowest around 0.248 °C /(W/m) among all coverages and changed while keeping the lower value except the period from 11 to 13 days.

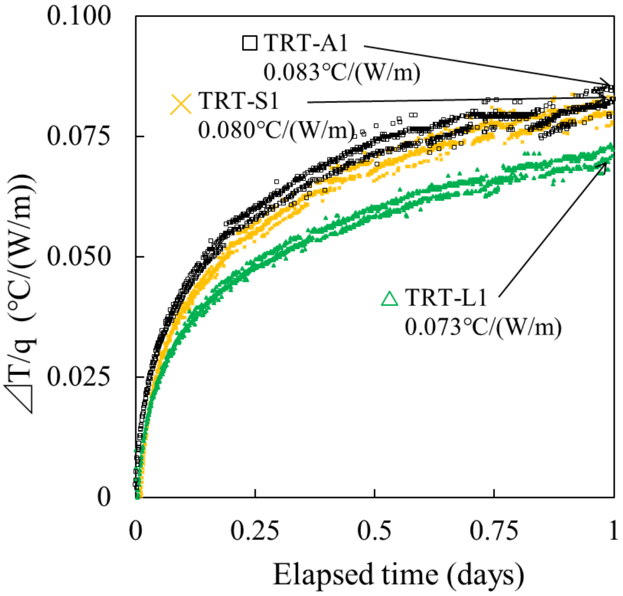

Figure 4: Change of temperature increment per unit heat exchange rate in each ground surface coverage in TRT -*1 results.

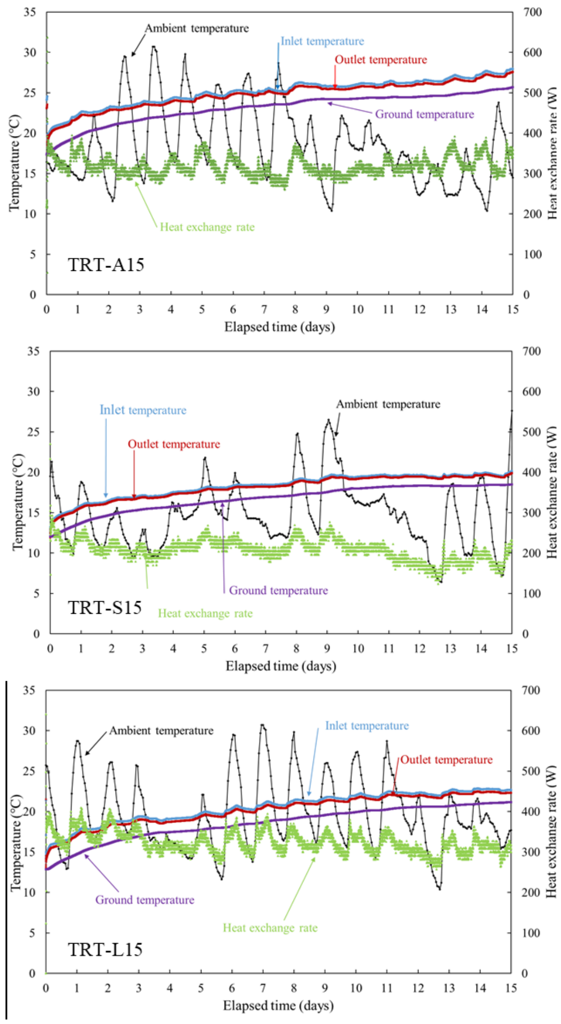

Figure 5: Results of TRT-*15 in each ground surface coverage.

During this time, the asphalt of the $\Delta T/\dot{q}$ was lower comparing to the lawn because the heat flux to the ground was decreased owing to the drop in ambient temperature. As a whole, the lawn is considered to be best coverage in cooling since the lawn could reduce the heat flux due to the transpiration and form the ground with high water content, which improve the heat conductivity of the ground. In addition, the water contents below 5cm deep from the top surface at the central point of installation area were measured during TRT-L15 using the probe type water content meter (Meter, Inc., ProCheck) and this result is shown in Figure 7. The change of the water content under the lawn exceeded the soil and the variation range is low. According to the other research (Kagawa et al., 1998), a lawn plays a role to keep the water content by mitigating the vapor released from the ground. In conclusion, the best ground surface coverage in cooling of GSHP systems is considered to be a lawn because of the itself characteristic.

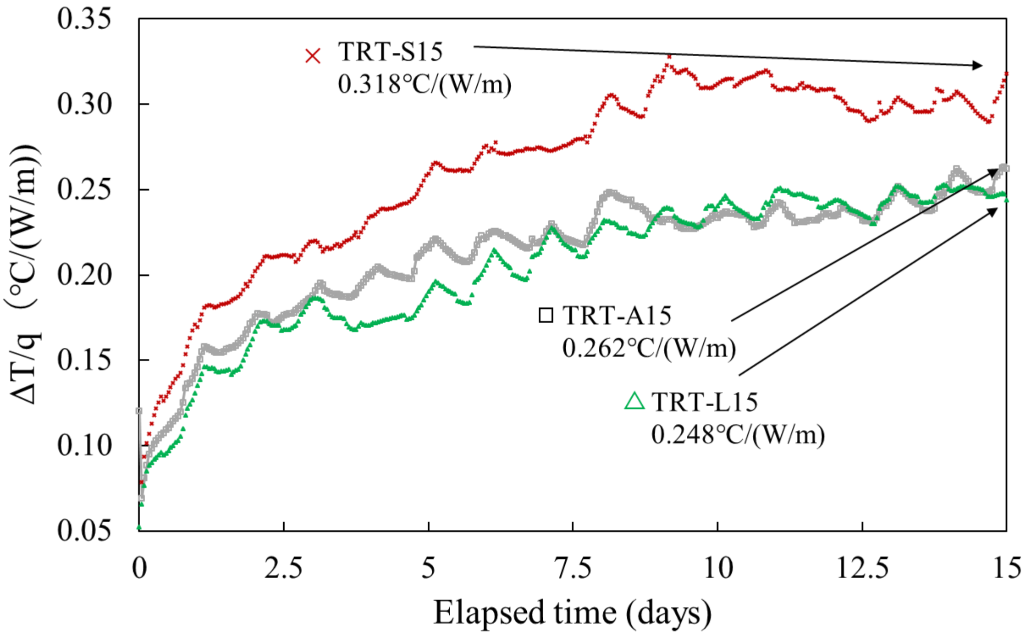

Figure 6: Changes of temperature increment per unit heat exchange rate in each ground surface coverage in TRT-*15 results.

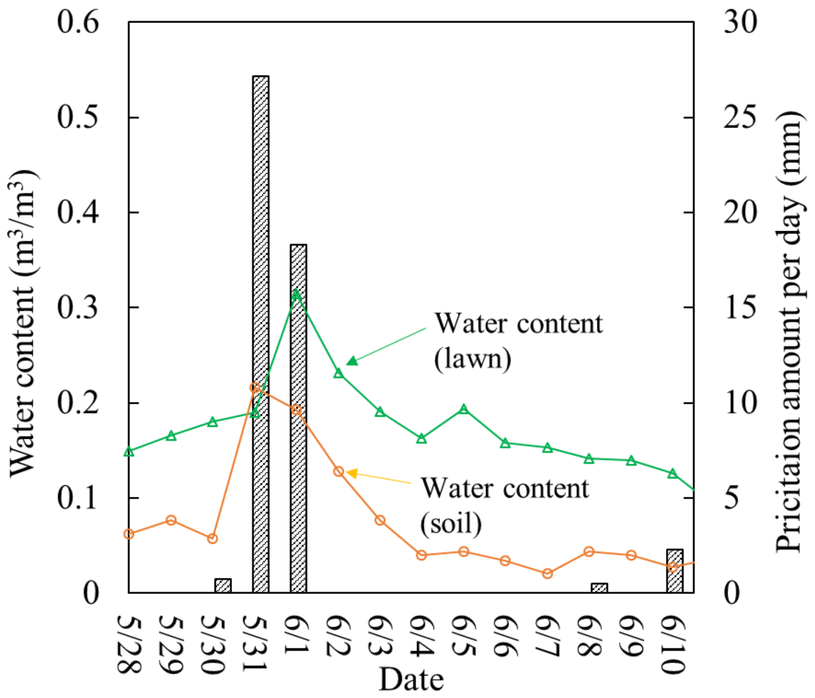

Figure 7: Changes of daily water content under soil and lawn and daily precipitation in period of TRT-S15.

5. COOLING AND HEATING SIMULATIONS

A cooling and heating simulations were carried out with numerical models including the Slinky-coil HGHEs, the surrounding ground and the ground surface coverage for evaluating the COP of heat pumps. The numerical models were developed based on the modeling procedure that the Slinky-coil HGHE were simplified as a thin flat plate whose width was set equal to the diameter of the loops (Fujii et al., 2012) using a finite-element numerical simulator, FEFLOW ver.7.1 (Diersch, 2005). A 3D view and top surface of the numerical model are shown in Figure 8.

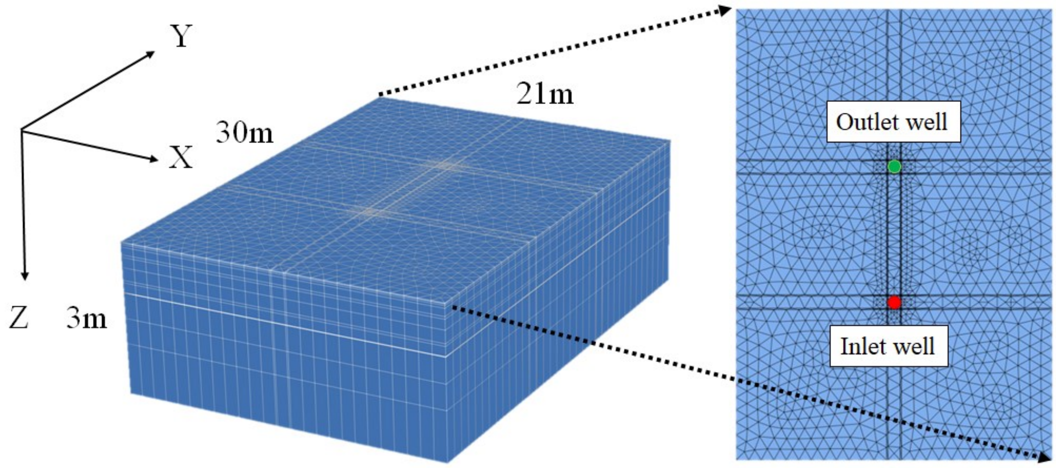

Figure 8: Developed numerical model of horizontal ground heat exchanger in FEFLOW.

The size of the model is 21 m, 30 m and 3 m in X, Y, Z directions, respectively. The peripheral grids of 10 m are defined to leave enough distance between the HGHE and the outer model boundaries to eliminate the influence of the outer boundaries. The number of elements and layers in the model are 31654 pieces, 19 layers, respectively. The finite-element grids are refined near the HGHE and are coarsened as they approach the outer boundaries. As the boundary condition of the numerical model, the peripheral and bottom boundaries were defined as adiabatic and having a constant temperature of with 14℃ reference to the annual temperature of the Akita city, respectively. On the other hand, the surface boundary was set by the following equation considering the energy balance at the land surface, which was programmed and coupled with FEFLOW as an outer module to consider the ground surface coverage in the models.

$$Q = R_{sol} + R_{sky} - R_{surf} - H_{surf} - L_{surf} \tag{3}$$

Where, Q, R_{sol}, R_{sky}, R_{surf}, H_{surf}, L_{surf} are heat flux at the land surface, the total solar radiation, the downward longwave radiation, the upward longwave radiation from the ground, the sensible heat flux and the latent heat flux, respectively. This equation includes parameters related to the ground surface coverage which are Albedo and evaporation efficiency. The evaporation efficiency is defined as the ratio of the evaporation amount to the difference temperature between surfaces and ambient, thus the latent heat flux would be increased if this ratio is high. In this research, the Albedo and evaporation efficiency of the asphalt, soil and lawn were set as 0.01, 0.30, 0.23 and 0.01, 0.10, 0.30, respectively. Figure 9 shows the measured value and simulated outlet temperatures of heat medium and ground temperature at a depth of 1 m in TRT-A15, TRT-S15 and TRT-L15, respectively. Reasonable agreement of heat medium and ground temperature were obtained through the history matching. These results indicate that the HGHE models coupled with the heat balance equation can reproduce the effect of the ground surface coverage on the temperature behaviors.

As the cooling and heating simulation conditions, the weather condition of Tokyo was set as a region with a large amount of solar radiation and no snow accumulation. In addition, the operating conditions were set as interval operation of 9 hours (9 a.m. to 6 p.m.) per a day with the thermal load of 30 W/m, the circulation rate of 15 L/ min. The cooling and heating periods were set from June 1, 2017 to September 30, 2017 and from December 1, 2017 to April 1, 2018, respectively. Under the same conditions, the cooling and heating simulations were conducted even in the case where the HGHE was installed at a 2m depth. The meteorological data of Tokyo was obtained from Japan Meteorological Agency. The average COPs in cooling and heating were calculated based on the simulation results using the performance curve of heat pumps. As the performance curve, the catalog of small size water-water heat pump (Sunpot Co., Ltd, GSHP-1001) was referred. This heat pump has a heating and cooling capacity of 10 kW and the heating and cooling COP curves are represented as below using hot water and cold water supply temperature of 28 ℃ and 12 ℃, respectively and the compressor frequency of 30 Hz:

$$COP_{cooling} = -0.23 \times T_{out} + 14.0 \tag{4}$$

$$COP_{heating} = 0.14 \times T_{out} + 4.60 \tag{5}$$

Where, T_{out} is the outlet temperature of the HGHE. Figure 10 show the comparison of COPs for each ground surface coverage in case of HGHE installed at a depth of 1 m and 2 m in cooling and heating, respectively. As the case of 1m deep, the cooling COP of the lawn was highest among all coverages and became about 1.1 times as large as the asphalt. Also, the heating COPs between ground surface coverages were different and the COP of the asphalt was higher by 0.2 comparing to the lawn. In contrast, the cooling and heating COPs in case of 2 m deep were slightly different. This means the effect of ground surface coverage is decreased as the HGHE become deep and therefore the ground surface coverage is considered the one of elements which needs to be taken into account for the optimum design of GSHP systems using the HGHE installed at a depth of -1 m.

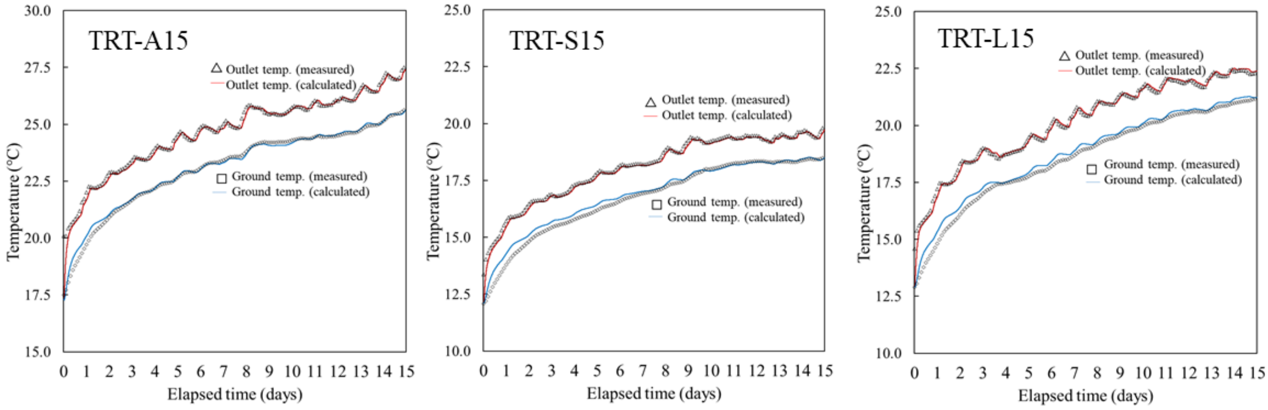

Figure 9: Results of history matching by TRT-*15 results for asphalt, soil and lawn.

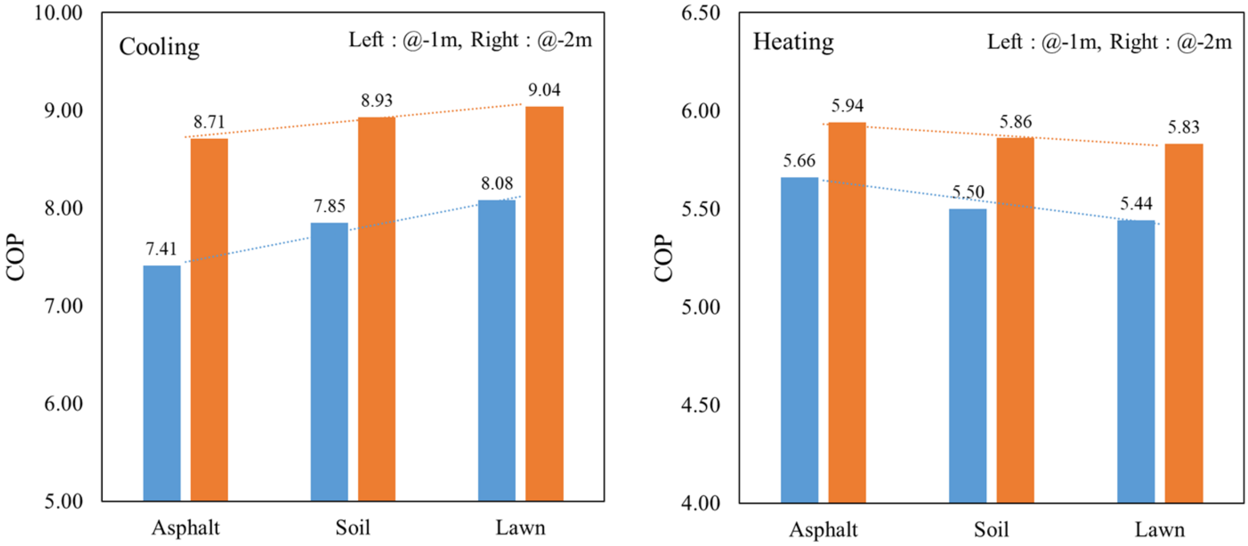

Figure 10: Comparison of COP for different ground surface coverage. cooling (left) heating (right).

6. SENSITIVITY STUDY

Sensitivity studies were performed using the history-matched model used to quantitatively estimate the correlation between the parameter related to the ground surface coverage and heat exchange rate. The model properties and the parameter of ground surface coverage are same as the soil, thus this model conditions are set as base case (Albedo: 0.3, Evaporation efficiency :0.1). In sensitivity studies, the cooling and heating simulations were conducted since the surface coverages differently affect the heating and cooling operations. As the condition of the cooling and heating simulations, the simulation time and the period of cooling and heating are set as 10 days, from 1st August 2017 and from 1st December 2017, respectively. The weather conditions of Tokyo was used due to the same reason as explained in Section 5. The inlet and outlet temperature were fixed as 35°C and 0°C , respectively and the circulation rate was set as 15L/min. The cooling and heating simulations of sensitivity study were performed by changing the albedo and evaporation efficiency as representative parameter characteristic of ground surface coverage. Both parameters were changed as 0, 0.5 and 1.0 in each case. The initial ground temperature was determined through the pre calculation of 2 years after the sensitivity parameter was input into the module. Figure 11 show the correlation between the parameters, which are albedo and evaporation, and heat exchange rate per unit length of HGHE. As the albedo, the heat disposal rate was increased up to 23.8 W/m as the albedo became high in cooling. On the other hands, the heat extraction rate was decreased up to 15.0 W/m in heating because the solar radiation to the ground is considered to be used as a heat source. Thus, the solar energy is preferred to be effectively absorbed for high heat exchange efficiency of HGHE. As the evaporation efficiency, the heat disposal rate was significantly increased up to 28.0 W/m as the evaporation efficiency became high in cooling. Conversely, the heat extraction rate was decreased in heating. However, the evaporation efficiency is considered to be low throughout the winter season because the atmosphere is generally dry and the plant activity is reduced. In conclusion, the potential of heat exchange is estimated to vary due to kinds of ground surface coverage, and therefore the GSHP system considering the kind of ground surface coverage is effective for reducing the initial installation cost.

7. CONCLUSIONS

In this study, we carried out the long-term monitoring of ground temperature and thermal response tests to investigate the effect of ground surface coverage on the ground temperature and heat exchange efficiency. The monitoring of ground temperature showed that the ground temperature under the lawn was lower than other coverages in cooling operations, while the asphalt showed the highest temperature at the same time. The TRTs showed that the heat exchange efficiency of the HGHE installed under the lawn was the best among the other covers. Numerical simulation models were then developed for the HGHE considering the ground surface coverage based on the heat balance equation.

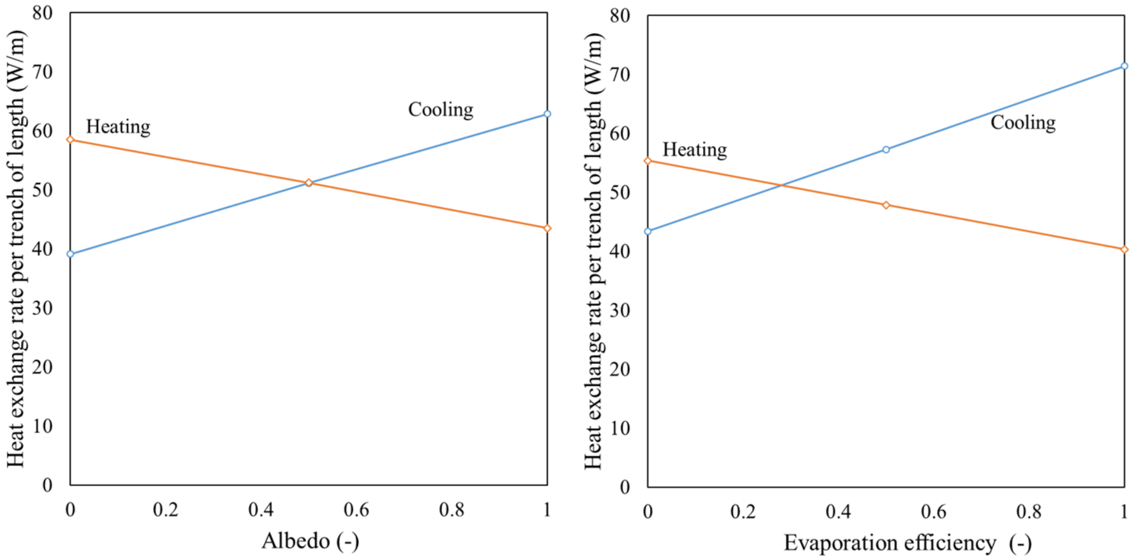

Figure 11: Variation of heat exchange rate with albedo (left) and evaporation efficiency (right).

The models well reproduced the behavior of the heat medium and ground temperatures in the TRTs, which validated the reliability of the numerical models. Next, the cooling and heating simulations were performed to estimate the variation of the COP of heat pumps. As a result, the cooling COP in case the HGHE installed at -1m under the lawn was highest of all covers. Moreover, the effect of ground surface coverage is considered to be decreased as the HGHE becomes deep. Finally, the sensitivity studies were carried out to examine the influence of the albedo and the evaporation efficiency on heat exchange rates using values of 0, 0.5 and 1.0 for both parameters. The numerical simulation showed that a lower albedo was preferable in heating, while a higher albedo was favorable in cooling. On the other hand, a higher evaporation efficiency was best in cooling. The both parameters were influential for the increase of heat exchange rate.

ACKNOWLEDMENTS

This work was partly supported by Grants-in-Aid for Scientific Research (B) (JP19H02655) from the Japan Society for the Promotion of Science (JSPS).

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