Field Tests of Horizontal Ground Heat Exchangers

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ABSTRACT

Field tests were carried out in Fukuoka City, Japan, to evaluate the applicability of horizontal Ground Heat Exchangers (GHEs) on Geothermal Heat Pump (GHP) systems for the use in greenhouse farming. As the type of horizontal GHEs, slinky coils were employed considering the limited land space in Japanese greenhouse farming. Two types of installations of slinky coils were examined, namely, horizontal and vertical setting in trenches excavated in the shallow ground. The depth and length of each trench were 1.5 m deep and 70 m, respectively. The GHEs were connected to a heat pump and circulation pump to be completed as a GHP system. Using the GHEs, thermal response tests and air-conditioning tests were carried out from summer 2008 to spring 2009 for collecting detailed operation record of the system and ground temperature data during the operation. The obtained field data were examined to evaluate the heat exchange capacity of the horizontal GHEs and to compare the heat exchange performances with those of vertical GHEs. The field tests showed that horizontal installation of slinky coils results in superior performance to vertical installation in terms of energy efficiency, due to the less influence of atmospheric temperature changes. The heat medium temperatures in the air-conditioning test showed that horizontally-installed slinky coils have comparable heat exchange capacity with vertical U-tube GHEs drilled in a formation with favorable thermal conductivity, though installation costs of horizontal GHE are significantly lower than those of vertical GHEs.

1. INTRODUCTION

Greenhouses are widely used for raising flowers, vegetables, etc. in many countries. Due to the recent high crude oil prices, however, fuel costs for heating greenhouses are becoming a serious problem. The application of energy-efficient Geothermal Heat Pump (GHP) systems will be one of the most promising replacements of conventional fossil-fuel based heaters, if the installation costs are not excessive. The effectiveness of GHP system for agricultural use has been more recognized in the past few years, but the number of actual application is still limited due to the lack of intensive evaluations of energy efficiency of the system for practical uses. Fujii et al. (2008) carried out long-term field tests in a greenhouse for orchids in Maebaru City, Japan. In their field tests, high COPs between 4.2 and 5.0 were observed in heating operations, resulting in the reduction of both energy cost and CO_2 emission by over 50% in comparison with the case of using fossil fuels. Due to the high initial cost for the drilling of Ground Heat Exchangers (GHEs), however, more reduction of initial cost was considered important to enhance the distribution of GHP systems in greenhouse farming.

Horizontal GHEs are commonly used in GHP systems in northern America as a heat source/sink of GHP systems. Since the installation cost of horizontal GHEs is significantly lower than that of vertical GHEs, the feasibility of GHP systems will be remarkably improved if available land space for installing the horizontal GHEs is large enough. Among the horizontal GHEs, slinky coils uses coil-like polyethylene tubes instead of straight tubes to improve the heat exchange rates in a limited land space as shown in Figure 1. The procedures of installation of slinky coils have been well established as presented in Jones (1995). Meanwhile, the heat exchange capacity and long-term performance of the slinky coils have not been well studied in the past researches by performing intensive field tests.

In this research, field tests are carried out in Fukuoka City, Japan, to evaluate the applicability of horizontal GHEs to GHP systems for greenhouse farming. Since the land space is generally limited in the greenhouse farming of Japan, slinky coils are used as the heat source/sink of GHP systems. Two types of installations of slinky coils are examined, namely, horizontal and vertical setting in horizontal trenches. The GHEs are connected to a heat pump and circulation pump to be completed as a GHP system. Thermal Response Tests (TRTs) and air-conditioning (A/C) tests are carried out for collecting detailed operation data of the system and temperature data in the ground. The obtained field data are examined to determine the most cost-effective type of GHEs and interpret the long-term performance of the GHP system. The field test results are also compared with those of vertical GHEs in terms of heat exchange rate and installation cost.

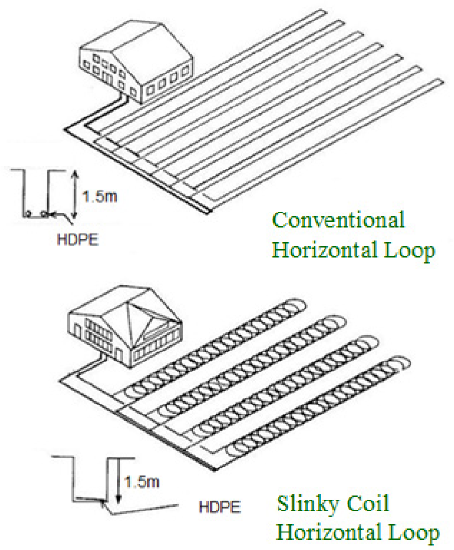

Figure 1: Type of horizontal GHE (modified from Kavanaugh and Rafferty, 1997).

2. INFORMATION ON FIELD TEST

We conducted field tests in a test field in the Ito Campus of Kyushu University, Fukuoka City, Japan (Figure 2). The test field is located on a hill of 50 m in elevation where thick granite underlies the surface soil of 10 m thick. The groundwater level was measured as approximately -17 m below ground surface throughout the year.

Figure 2: Location of field test site.

In the field test site, slinky coils of polyethylene were installed in trenches of 1.5 m deep as shown in Figure 3. Slinky coils were laid horizontally in Loop 1 and vertically in Loop 2. The diameter of coil, ID and OD of pipe are 0.8 m, 0.034 m and 0.024 m, respectively. The average depth of coil in Loops 1 and 2 are -1.5 m and -1.1 m, respectively. Thermal conductivities of polyethylene pipe and soil were measured as 0.35 W/m/K and 1.09 W/m/K, respectively, using a probe-type thermal conductivity meter. After laying the coils and covering them with soil, water was sprayed on the soil for reducing the void space and hence thermal resistance around the coil. The trenches were then back-filled and compressed with power shovels. Photos taken during the construction of GHEs are shown in Figure 4.

Figure 5 shows a schematic drawing of the experiment facility. The lengths of each trench are 72.0 m and 71.7 m, respectively, while the length of polyethylene pipes is 500 m in each trench. Circulation rate of each loop can be controlled with a valve with flow meter. Temperatures of heat medium were measured at the inlet and outlet of each loop with Pt100. Ground temperatures were also measured using Pt100 at Points A, B and C as shown in the Figure 5.

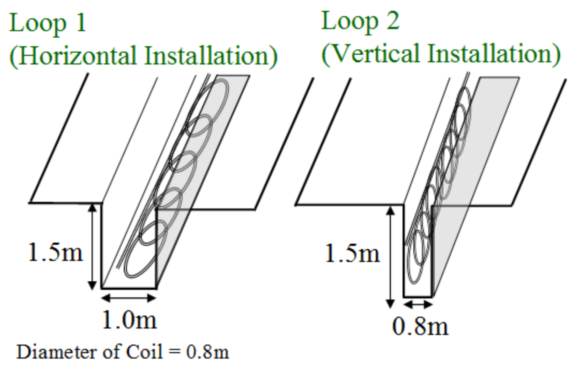

Figure 3: Cross-sectional view of horizontal loops.

Figure 4: Excavation of trench (left) and laying of slinky coils (right).

In the mini house, the water lines from the GHE were connected to a water-source (water-air) heat pump and a circulation pump. The water-source heat pump, Florida Heat Pump GT-010, has a heating/cooling capacity of 3-4 kW, which is oversized for the installation in a mini house of 6.5m^2. To maintain constant temperature in the mini house, an air-source heat pump was installed to provide pseudo heating/cooling loads. Climate data, i.e., temperature, precipitation, wind velocity, solar radiation, etc. were measured every 1minute at the field test site.

3. RESULTS AND DISCUSSION

For the interpretation of heat exchange performance of the GHP system using horizontal GHEs, TRTs and A/C tests were carried out using Loops 1 and 2. In this chapter, the conditions and results of these tests are presented.

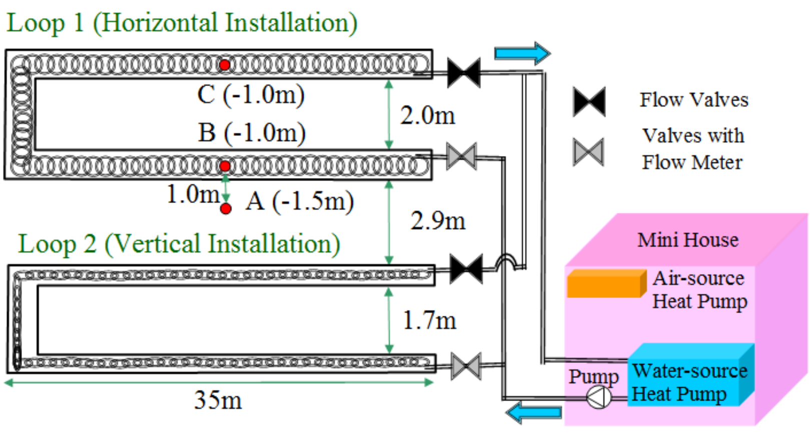

Figure 5: Schematic of experiment facilities.

3.1 Thermal Response Tests (TRTs)

TRTs were conducted from August to September 2008 as a simultaneous test and individual tests. In these tests, heat medium with constant heat load was circulated through the GHEs while measuring the temperatures and circulation rates of heat medium. Water was used as a heat medium in the TRTs.

3.1.1 Simultaneous Test

In the simultaneous test, the heat medium was circulated through Loops 1 and 2 simultaneously with same circulation rates and inlet temperatures for 48 hours. Circulation rates of each loop were adjusted using the valves with flow meters. Figure 6 shows the inlet and outlet temperatures of heat medium and heat exchange rates of Loops 1 and 2. With a heat load of 3.2 kW on the two loops, the inlet water temperatures increased with continuous circulation, reaching 32°C after 48 hours. The heat exchange rate of Loops 1 was larger than that of Loop 2 by 45% at the end of circulation. Since the thermophysical properties of soils and pipes are considered quite close in both loops, the difference would be due the difference in the temperature of ground. At the beginning of the test, the ground temperature at -1.0 m and -1.5 m depth were 28.2°C and 26.5°C, respectively. Since heat exchange rates are functions of the temperature difference between heat medium and the ground, the larger pipe installation depth of Loop 1 resulted in the larger heat exchange rates than those of Loop 2. The results of the simultaneous test show that horizontal installation of slinky coils is more preferable to increase heat exchange rates due to the larger difference in temperatures between the ground and heat medium.

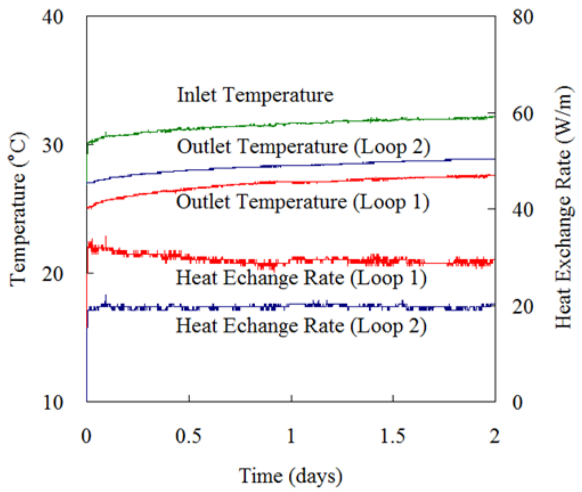

Figure 6: Temperatures and heat exchange rates in simultaneous test.

3.1.2 Individual Tests

In August and September, 2008, TRTs were conducted on Loops 1 and 2 independently under similar heat loads and circulation rates. The average heat loads on Loops 1 and 2 during TRTs were 61.1 W/m and 58.6 W/m, respectively. The average values of inlet and outlet temperatures of heat medium during the circulation of 120 hours are shown versus logarithmic time in Figure 7.

For the interpretation of the TRTs, the conventional semi-log graphical method was applied as shown in Figure 7. The estimated thermal conductivities of soil were above 2.0 W/m/K, which is much larger than those of soil samples measured by a thermal conductivity meter (1.09 W/m/K). Since the conventional interpretation method is based on the line source theory and constant heat exchange rate along the heat source, the interpretation method is considered to overestimate the thermal conductivity of soil in the case of horizontal GHEs. At approximately 3 days in the circulation period, the slope of temperature changed in Loop 2 as shown in Figure 7, which resulted in the different thermal conductivity estimation between the two loops. This occurred as the heat exchange became affected by the soils of high temperatures near ground surface as the circulation of heat medium was continued. Since the pipes are closer to ground surface in Loop 2 than in Loop 1, the effect of surface appeared earlier in Loop 2.

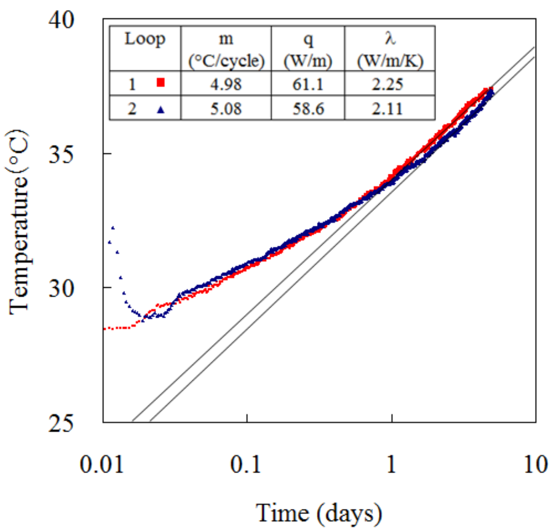

Figure 7: Average fluid temperatures vs. time in individual tests.

3.2 Air-conditioning (A/C) Tests

From November 2008 to March 2009, A/C tests were carried out in Loops 1 and 2. Since heat exchange performance of horizontal loops should be affected by the seasonal temperature changes of shallow ground, A/C tests on Loop 1 was conducted twice, first test (A/C Test 1-1) from November to December 2008 for 17 days and second test (A/C Test 1-2) from January to March 2009 for 52 days.

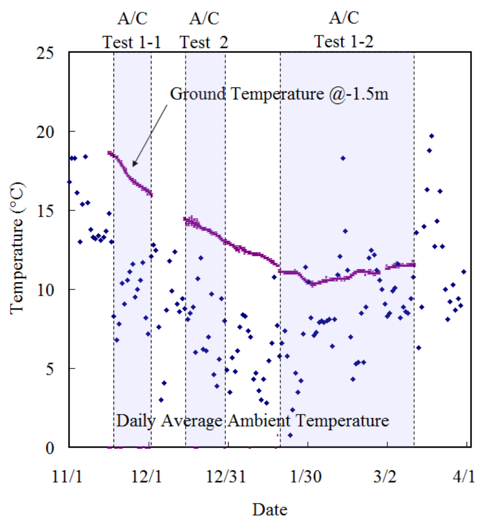

Figure 8: Ground temperatures and ambient temperatures during A/C tests.

In each A/C test, the GHP system was operated in a heating mode for 20 hours/day continuously, from 4:00 PM to 12:00 Noon on the basis of the normal heating schedule used in local greenhouses of orchids. The room temperature in the mini house was fixed at the common temperature in the greenhouse of orchids, 20°C, by operating the air-source heat pump in cooling mode. As heat medium, water was used in A/C tests as well as in TRTs since the operation data showed that the heat medium temperatures were well above 0°C.

Figure 8 shows the farfield ground temperatures at -1.5 m and the daily average ambient temperatures at the field test site. The period of A/C tests are also shown in the same figure. With the decrease of ambient temperatures, ground temperatures showed a continuous decrease until the end of January. Ground temperatures showed slight recovery in February with the increase of ambient temperatures.

3.2.1 Short-term A/C Tests on Loop 1

The short-term A/C test on Loop 1 was carried out from November 15 to December 2, 2008 for 17 days. Chronological changes of inlet/outlet temperatures of heat medium and heat exchange rates are shown in Figure 9. In the daily operation, the heat medium temperatures showed a recovery during the four hours between 12:00 noon and 4:00 PM, in which the GHP system is switched off. The temperature of heat medium showed a rapid decline with the heat extraction by the heat pump. The average temperature of heat medium, however, was maintained above 10°C even at the end of test since the ground temperature at -1.5 m was still high in December. Due to the high temperature of heat medium, the average heat exchange rates were maintained high, 41.8 W/m, though they showed decrease toward the end of the test.

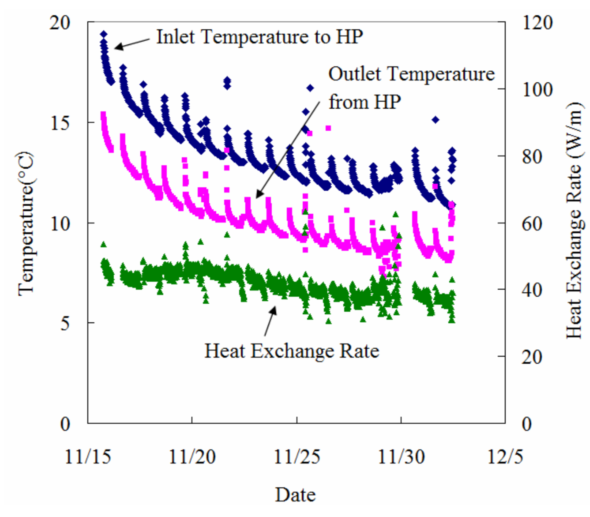

Figure 9: Temperatures of heat medium and heat exchange rates in short-term A/C test on Loop 1.

3.2.2 Short-term A/C Tests on Loop 2

The short-term A/C test on Loop 2 was carried out from December 14 to 29, 2008 for 15 days. Chronological changes of inlet/outlet temperatures of heat medium and heat exchange rates are shown in Figure 10. Similarly to the short-term test on Loop 1, the temperature of heat medium showed a rapid decline with the heat extraction. Due to the low temperature of heat medium, the average heat exchange rates was 27.3 W/m, which was 34.7% lower than those in the short-term test on Loop 1. The average temperature of heat medium dropped to 6°C at the end of test, since farfield ground temperature at -1.5m decreased to 13°C (3°C lower than the A/C test on Loop 1) as approaching the mid-winter.

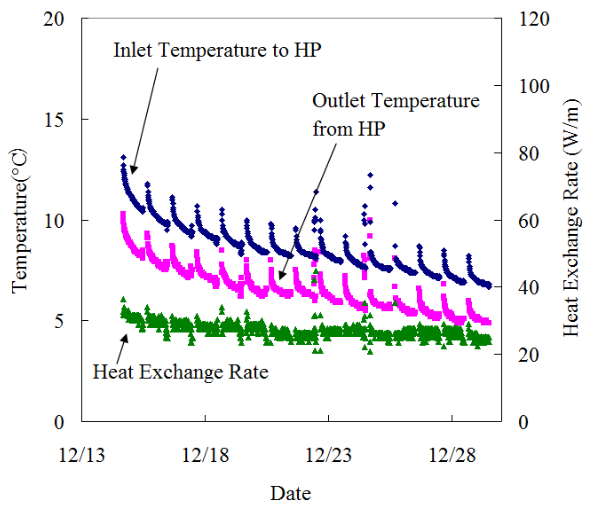

Figure 10: Temperatures of heat medium and heat exchange rates in short-term A/C test on Loop 2.

3.2.3 Long-term A/C Test on Loop 1

After sufficient temperature recovery period of 50 days, a log-term A/C test was carried out on Loop 1 for 52 days from January 19 to March 12, 2009. Same operating conditions were applied as was used in the short-term A/C tests. Figure 11 shows the chronological changes of inlet/outlet temperatures of heat medium and heat exchange rates. Heat medium temperatures and heat exchange rates became stabilized around 6°C and 24 W/m, respectively, at the end of January when ground temperatures started to increase gradually as shown in Figure 8. The average heat exchange rate in the entire test period was 25.5 W/m, which is 39% smaller than the short-term test on the same loop. This indicates that the heating capacity of horizontal GHEs can drastically change with the change of ground temperatures. For the design of horizontal GHEs, therefore, it is crucially important to consider the effect of seasonal change of ground temperatures to avoid the shortage of heat exchange rates in mid-winter or mid-summer.

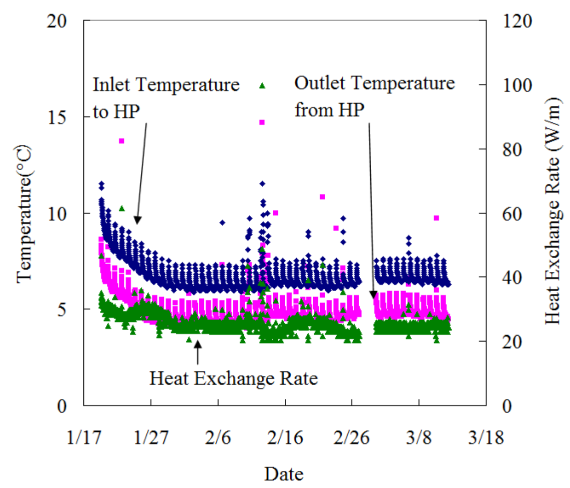

Figure 11: Temperatures of heat medium and heat exchange rates in long-term A/C test on Loop 1.

Figure 12 shows the temperatures in the ground at Points A through C as indicated in Figure 5 and the farfield temperatures at -1.0 m and -1.5 m measured during the long-term A/C test on Loop 1. The farfield temperatures at -1.0 m were only available from the beginning of February due to a problem in the data acquisition system. At point A, 1.0 m horizontally apart from the pipe, the temperature started to deviate from the farfield temperature after 10 days from the beginning of the test. The separation of temperature from the farfield temperature at -1.5 m, however, was as small as 0.7°C even at the end of the A/C test of 54 days, which indicates that the temperature change was not so large in the horizontal direction. At Points B and C, on the other hand, the separation of temperature from the farfield temperature at -1.0 m was much larger. At Point B, located close to the inlet of coils and 0.5 m above the coil, the temperature separation was approximately 3°C, indicating the primary direction of heat flow from the coil was perpendicular to the plane of the slinky coils. These results suggests the possibility of reducing the spacing between the trenches from the current ones (1.7-2.0 m) without major reduction of heat exchange capacities.

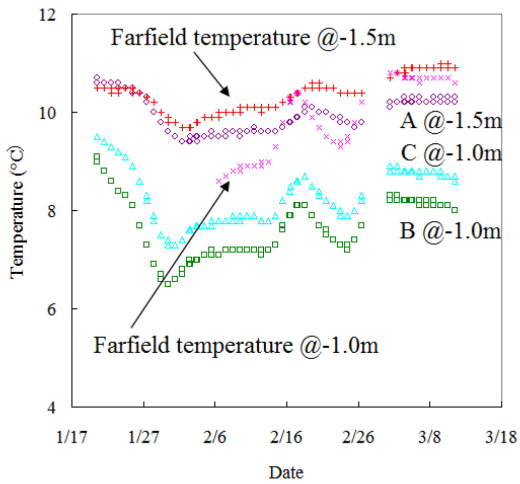

Figure 12: Ground Temperatures at observation points A-C in long-term A/C test on Loop 1.

3.2.4 Prediction of long-term performance

As was observed in the above A/C tests, the temperature change in the ground depends on the farfield temperatures and heat exchange rates. For eliminating these effects to accurately evaluate the heat exchange capacity of each loop, we introduced a parameter $dT/\dot{q}$ as below:

$$dT/\dot{q} = \left|T_{avg} - T_{ff}\right|/(q/L) \qquad (1)$$

where $\dot{q}$, T_{ave}, T_{ff}, q, L are heat exchange rate per unit trench length, average temperature of heat medium, farfield temperature, heat exchange rate and length of trench, respectively. As seen in Figure 13, similar trend of $dT/\dot{q}$ was obtained in Tests 1-1 and 1-2, though these tests were carried out under quite different temperature conditions of ground. This indicates that parameter $dT/\dot{q}$ could be used for characterizing the heat exchange performance of slinky coils. The temperature changes in Test 2 is larger than those in Tests 1-1 and 1-2 since Loop 2 is more likely affected by the change in ambient temperatures. In terms of heat exchange capacities, therefore, the horizontal coil installation used in Loop 1 is considered to be more preferable than the vertical installation used in Loop 2. Parameter $dT/\dot{q}$ in Loop 1 showed a nearly straight line versus logarithmic time as shown in Figure 13. The slope m of the $dT/\dot{q}$ in Loop 1 was calculated as 0.0533mK/W/cycle, which could be applied for the prediction of long-term heat exchange performance of the loop.

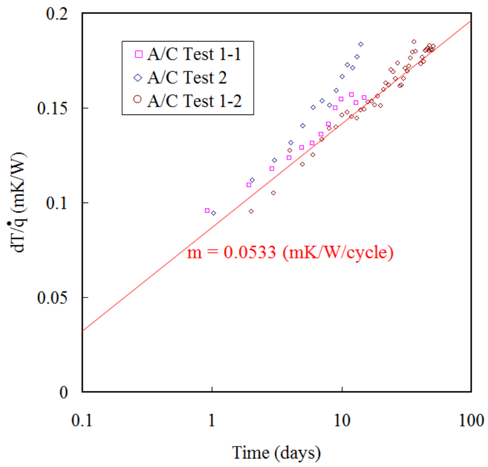

Figure 13: Chronological change of temperature drop divided by heat exchange rates in all A/C tests.

For the evaluation of the long-term performance of the horizontal GHE, the average temperatures of heat medium was compared with those obtained from actual operation data from a vertical U-tube GHE. The GHE was drilled in a granite formation in Maebaru City, Japan, 20 km apart from the field test site of the horizontal GHE. The vertical GHE was completed with double U-tube and silica sand and has been used in a GHP system for a greenhouse. The thermal conductivity of the formation was estimated as 2.76 W/m/K in a TRT (Fujii et al., 2008), which is considered a favorable value for the installation of GHP systems. The GHP system was operated for approximately 20 hours/day with an average heat exchange rate of 31.7 W/m in a heating mode from December 2007 to March 2008.

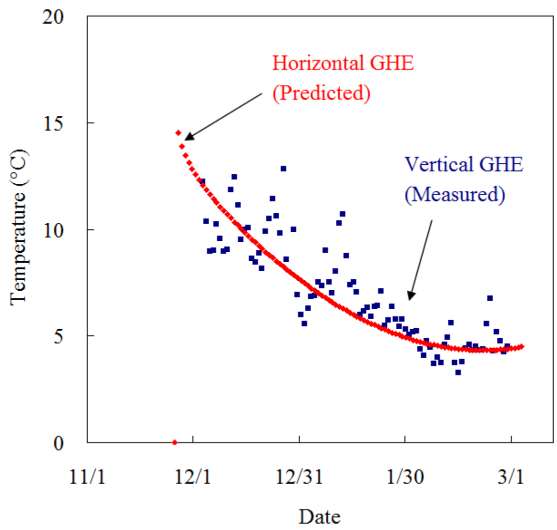

Figure 14: Predicted long-term performance of heat medium temperatures in horizontal GHEs in comparison with measured temperatures in a vertical GHE.

The blue solid squares in Figure 14 shows the measured average temperatures of heat medium (water) in the heating operation. With the long daily operations of the GHP system, heat medium temperature decreased to 3°C in February 2008. The same heat load, 31.7 W/m, was then applied in Equation

(1) to estimate the temperature change in a horizontal GHE. The farfield temperature, T_{ff}, in Equation (1) was estimated using a thermal conduction model on the basis of normal ambient temperatures obtained from the local observatory and the soil thermal conductivity at the field test site (1.09 W/m/K). The figure shows that the heat medium temperatures in horizontal and vertical GHE are quite close, indicating that the heat exchange capacity of the horizontal slinky coil GHE is similar to that of a vertical double U-tube GHE drilled in a formation with favorable thermal conductivity.

3.2.5 Economics and Land Space Requirements

In Japan, the drilling, completion and material costs of a double U-tube GHE is above $100/m due to the heterogeneous nature of shallow ground and high personnel cost. On the other hand, horizontal GHE can be completed below $50/m including the cost of slinky coils since the excavation does not require expensive drilling machines. Since horizontal GHEs are considered to have similar heat exchange capacities as vertical GHEs based on the results of our field tests, the application of horizontal GHE could remarkably improve the feasibility of GHP systems if sufficient land space is available for the installation of slinky coils.

Table 1: Calculation conditions of land space requirement.

Heat exchange rate	30	W/m
Width of trench	0.8	m
Spacing between trenches	0.2	m
Area for heating	1000	m^2
Heating load	150	W/m^2
COP for heating	4.0	-

Assuming the conditions in Table 1, the required land space in the installation of horizontal GHEs for the heating of greenhouses is estimated as follows:

Total heating load = 150 W/m^2 x 1000 m^2 = 150 kW
Heat exchange rate = 150 kW x 3/4 = 112.5 kW
Trench length = 112.5 kW / 30 W/m = 3750 m
Land space for GHE = 3750 m x 1.0 m = 37500 m^2

The above shows that assuming a heat exchange rate of 30 W/m, which is applicable in a heavy use of the greenhouse (long daily operation hours), horizontal GHEs require 3.75 times as much as the space to be heated, which may not be easily found. In case of assuming a larger heat exchange rate of 50 W/m, which will be applied in a lighter use of the greenhouse with shorter operating hours, the required land space becomes much smaller 22500 m^2, 2.25 times as much as the space to be heated. For the optimum design of GHP systems with horizontal GHEs, therefore, detailed design of the minimum necessary length of GHEs should be made on the basis of careful estimation of heat load and available heat exchange rates.

4. SUMMARY

Field tests were carried out to evaluate the applicability of slinky coil horizontal Ground Heat Exchangers (GHEs) on greenhouse farming. Two types of installations of slinky coils were examined, namely, horizontal and vertical settings in trenches excavated in the shallow ground. Using the GHEs, thermal response tests and air-conditioning tests were carried out for collecting detailed operation record of the system and temperature data in the ground. The obtained field data were examined to determine a cost-effective type of GHEs and to compare the heat exchange performances with those of vertical GHEs. The results of field tests showed that horizontal installation of slinky coils is superior to vertical installation in terms of energy efficiency, due to more stabilized ground temperatures. The comparison of heat medium temperatures in the air-conditioning test showed that horizontally-installed slinky coils have a comparable heat exchange capacity with vertical U-tube GHEs drilled in a formation with favorable thermal conductivity. Necessary land space for GHEs was estimated 3.75 times as much as the space to be heated assuming a heat exchange rate per unit trench length of 30 W/m, though the ratio can be reduced depending on the operation conditions of the greenhouse.

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