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Effect of Water Injection into a Ground Heat Exchanger Drilled in a Low-λ Formation

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ABSTRACT

In ground source heat pump (GSHP) systems, the heat exchange rate per unit length of a ground heat exchanger (GHE) needs to be improved to reduce the initial cost of the system. When the formation has high thermal conductivity (λ) or fast groundwater flow because of high hydraulic conductivity (k), high heat exchange rates usually are expected at the GHE, which facilitate the introduction of the GSHP systems. Alternatively, when the λ is low or the groundwater velocity is slow, the excessive requirement of the GHE length hampers the application of the system. This research hence focuses on the enhancement of heat exchange rate by water injection into the GHEs, which could cause an artificial groundwater flow in the GHEs.

A series of thermal response tests (TRTs) were carried out in an ungrouted GHE of 100 m deep drilled in an alluvial deposit in Akita City, northern Japan. The GHE was drilled in formation of low-λ and low-k, mainly consisted of clay, silt and sand. In the TRTs, water injection rates were varied as 0, 1, 3 and 5 L/min, while keeping the heat load and the circulation rate as constant. The TRTs showed that the water injection could suppress the rise of heat medium temperatures effectively even when applying small amount of water injection rates, which could improve the COP (Coefficient of Performance) of heat pumps. The improvement was more evident when the heat exchange pipes are located in the upper part of the deposit, which show higher water injectivity than the deeper zone. The field tests suggested the possibility of shortening the length of GHE in low-λ formation with minimal additional operation costs.

1. INTRODUCTION

In Japan, the number of installation of GSHP systems are still small, about 1,000 systems at the end of 2011, due to the high drilling cost of GHEs (commonly US$100-150/m). The high drilling cost mainly comes from the geological complexity of the shallow deposits of Japanese residential areas, which are mostly located on alluvial plains. Hence, the improvement of heat exchange rate per unit length of a GHE is considered as one of the most important measures for the wider application of GSHP systems. In case the GSHP systems have GHEs in formations with fast groundwater flow due to high hydraulic conductivity (k), the GHEs generally show high heat exchange rates and the good feasibility of the GSHP systems are expected. Several research efforts have been carried out to evaluate the capacity enhancement of GHE by groundwater flow based on field tests (e.g., Okubo, et al., 2006, Fujii et al., 2009) or numerical simulations (e.g., Gehlin and Hellström, 2003, Fujii et al., 2005). The advantages of positioning the GHE in a formation with groundwater flow have been confirmed through these studies.

When the groundwater velocity is slow or the λ is low, on the other hand, the GSHP systems require longer GHE length than the cases with fast groundwater flow or high λ, which lowers the competitiveness of the GSHP systems. Hence, we try to enhance the heat exchange rates of a GHE by forming an artificial in-hole groundwater flow by water injection from surface into the GHE in this research. The authors carried out a research to enhance the heat exchange rate by water injection into a GHE of 70 m deep drilled in a granite formation of high λ (~3.00 W/m/K) (Fujii, et al., 2013). In the research, field tests and numerical simulation were carried out to investigate the effects of water injection. The authors found in the field tests that the water injection could keep the rise of heat medium temperatures in a low level, but the rate of increase in heat medium temperatures strongly depend on the water injection rates and temperatures. They also concluded that the enhancement in heat exchange rate by water injection became less evident when the water injection rate exceeded 5 L/min. The effects of water injection were confirmed in a high-λ formation as above, but the effects were not investigated in a low-λ formation, where the enhancement of heat exchange rate is considered more important than in a formation of good heat exchange capability. Hence, we carry out field tests using an ungrouted GHE of 102 m deep drilled in a low-λ (~1.44 W/m/K) and low-k formation in Akita City, northern Japan. First, we carry out thermal tracer tests with hot water injection into the GHE while measuring the in-hole temperature to clarify the permeable intervals in the GHE. We then conduct series of TRTs in the GHE applying four different water injection rates of 0, 1, 3 and 5 L/min, while keeping the heat load and the circulation rate constant. The objective of the TRTs is to investigate the relationship between the water injection rates and temperature increase of the heat medium, which is proportional to the heat exchange capacity of the GHE. Next, we change the length of heat exchange pipes of find the optimum length of pipes at the test location. Through these field tests, the contribution of water injection in low-λ and low-k formation will be investigated for the wide application of GSHP systems.

2. CONDITIONS OF THERMAL RESPONSE TESTS

We carried out series of TRTs at a GHE installed in Akita City, Japan, from September 2013 to January 2014. The borehole is 102.0 m deep with a diameter of 179 mm. The schematic drawing of the GHE, the geological column at the well site and the undisturbed ground temperature measured using a thermo-resistance thermometers (Pt100Ω) are shown in Figure 1. The upper part (surface to 60 m) of the formation is an alluvial deposit of the Quaternary System mainly consisted of silt, sand and gravel. The lower part (60 m to 102 m) consists of siltstone of the Tertiary System. Water injection tests were carried out twice at the GHE, which yielded hydraulic conductivities of 2.1 - 4.4 × 10^{-7} m/s. These values indicate that the formation consists of fine sand or silt of low hydraulic conductivity. Below 15 m, a clear geothermal gradient of 4.0 °C / 100m was observed.

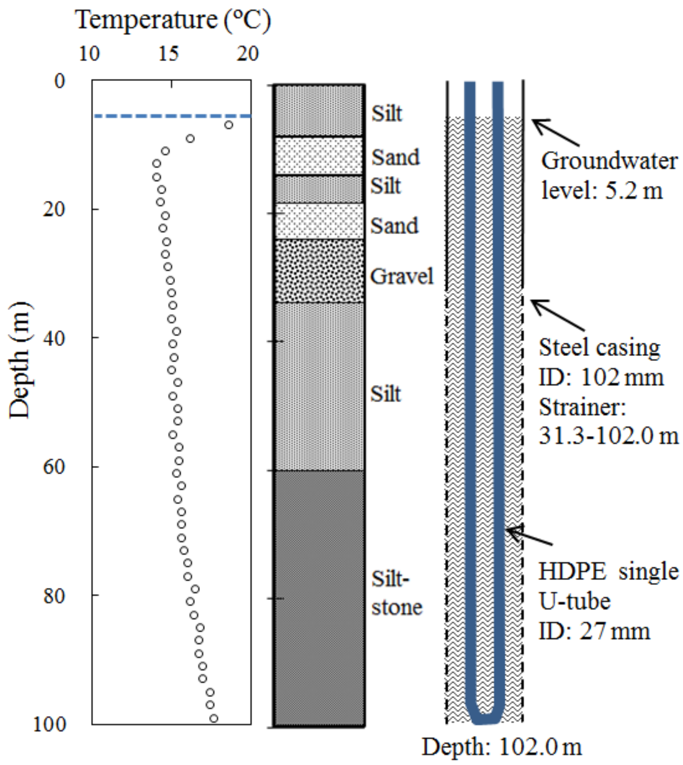

Figure 1: Ground temperatures, geological column and well completion design of the ground heat exchanger.

A steel casing was inserted in the GHE from the land surface to the bottom of the GHE to prevent the collapse of the formation. The ID and OD of the casing were 100 mm and 114 mm, respectively. The annular space between the well wall and the casing was filled with 20–65 mesh/in. silica sand to stabilize the casing. From 31.3 m to the bottom, slotted casings were used to allow the groundwater flow through the GHE. The GHE was completed with single U-tube of high-density polyethylene without grouting. The ID/OD and the thermal conductivity of the U-tube are 27 mm / 34 mm and 0.46 W/m/K, respectively. Two U-tubes length were examined in the TRTs, namely, 102.0 m and 60.0 m due to the reason discussed in Section 4. The groundwater level locating at 5.0 m, the effective length of the U-tube is calculated as 97.0 m and 55.0 m in the two cases. The U-tubes between the land surface and the groundwater level were thermally-insulated to avoid the heat loss to the air.

Table 1: Conditions of TRTs.

TRT No.	Strat	U-tube depth	Circulation rate	Heat exch. rate	Water inj. rate	Inj. water temp.
		m	L/min	W/m	L/min	°C
TRT-0A	2013/09/09	102	15.2	69.3	0.0	-
TRT-1A	2013/11/19	102	15.2	67.1	1.0	17.0
TRT-3A	2013/11/12	102	15.3	65.8	3.0	17.0
TRT-5A	2013/10/22	102	15.5	66.8	5.0	17.0
TRT-0B	2013/12/24	60	15.6	55.3	0.0	-
TRT-1B	2014/01/06	60	15.6	55.6	1.0	17.0
TRT-3B	2014/01/14	60	15.7	57.2	3.0	17.0
TRT-5B	2014/01/27	60	15.5	57.4	5.0	17.0

A total of eight TRTs were conducted using the GHE under different water injection rates and U-tube depth. The names of the TRTs and their conditions are summarized in Table 1. The numbers in the names of each TRT indicate the approximate water injection rates and the symbols (A or B) indicate the length of U-tube (102.0 m or 60.0 m). In all TRTs except TRT-0A and TRT-0B, tap water was injected from the wellhead of the GHE using a water hose. TRT-0A and TRT-0B were carried out without water injection as a reference case. The maximum water injection rate was set as 5 L/min based on the results of sensitivity studies in Fujii et al. (2013) and considering that excessive water injection rates lead to high operation cost for water supply. The circulation rates of heat medium though the U-tubes were maintained nearly same though all TRTs, 15.2 - 15.7 L/min. An electric heater of 6 kW and 3 kW output were used in TRT-*A and TRT-*B, respectively (* indicates a wildcard). Since the effective GHE lengths are 97 m and 55 m for TRT-*A and TRT-*B, respectively, the heat exchange rates per unit GHE length are calculated as 65.8 – 69.3 W/m and 55.3 – 57.4 W/m in TRT-*A and TRT-*B, respectively. The circulation of heat medium was continued for 2 days and the recovery of in-hole temperature was monitored in the up-flow U-tube using an optical fiber thermometer (NK OPTIS N7A DTS, NK Systems Ltd.) for the following 4 days. The time and depth intervals of the optical fiber thermometer measurement were 0.5 m and every 1 minute, respectively. The temperatures of injected water were maintained as 17.0 °C, which is slightly higher than the average ground temperature (15.6 °C between 10 m and 100 m), using an electric heater. In each TRT, inlet and outlet temperatures of heat medium and the temperatures of injected water were measured using Pt100Ω every one minute. The circulation rates of heat medium and the water injection rates were measured using an electromagnetic flow meter every one minute.

3. RESULTS OF WATER INJECTION TEST

Before the TRTs, we carried out thermal tracer tests to clarify the intervals through which the injected water flows into the formation. We first injected a heated water of 30 °C for 4 hours at 5 m (groundwater level) and measured the vertical temperature profiles using the optical fiber thermometer. Figure 2 (a) shows the temperature survey results of every one hour. A clear temperature increase was observed in the upper part of the GHE due to the downward flow of the injected hot water. The lower part of the formation below 50 m, however, did not show any change in temperature during the injection of 4 hours. The reason of this trend could indicate that the upper part of the formation has reasonable hydraulic conductivity (k), while the lower part has very low k, which agrees with the geological condition at the GHE as shown in Figure 1. Another possibility of this trend could be the thermal saturation of the injected water that will occur when the thermal energy was all transmitted to the upper part even in case the lower zone has some k. To clarify this, we changed the water injection depth to 50 m and repeated the same water injection test. The results of the test are shown in Figure 2(b). Similar to the results of the case of injecting at 5 m, the temperature changes mostly occurred in the upper part of the formation, indicating that most of the injected water invaded to the formation to the upper zone (the Quaternary formation) due to the high k. In the upper zone, the temperature trend is opposite in Figures 2(a) and 2(b), because the water temperature was highest at the injection depth and showed a gradual decrease as flowing upwards through the GHE. Since the outflow of the water mostly occurred in the upper zone of the formation, the TRT-*B were carried out using a shorter U-tube of 60.0 m long in addition to the TRT-*A using the 102.0 m tube.

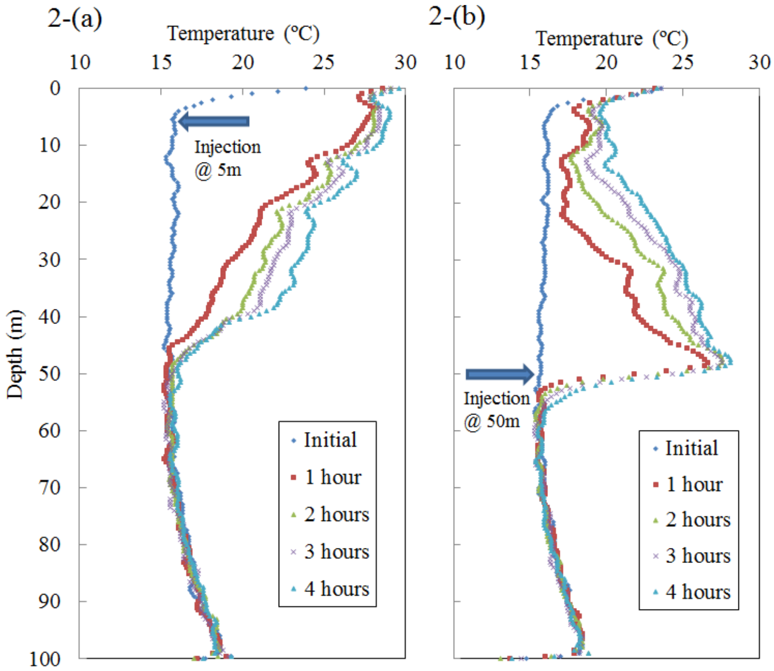

Figure 2: Temperature profiles in the ground heat exchanger during thermal tracer tests, (a) with water injection at 5 m, (b) with water injection at 50 m.

4. RESULTS OF THERMAL RESPONSE TEST

Figure 3 shows the inlet/outlet temperatures and circulation rates of heat medium and the heat exchange rates calculated based on the measured values in TRT-0A. The circulation and heat exchange rates were reasonably stable indicating that the TRTs were carried out in good conditions. Similar stable performances were observed in other TRTs. The average temperature of heat medium (average of inlet and outlet temperatures) reached 36.0 °C at the end of the circulation period. Figures 4(a) and 4(b) are the semi-log plots of time vs. the average temperature of heat medium in TRT-0A and TRT-0B, respectively, which are not affected by water injection. Clear straight lines were observed in both plots after 0.5 days from the start of circulation. As given in the figures, the λ values were evaluated as 1.44 W/m/K and 1.77 W/m/K in TRT-0A and TRT-0B, respectively. This suggests that the average λ from 5.0 m and 102.0 m is 1.44 W/m/K, while the average λ from 5.0 m and 60.0 m (in the Quaternary formation) is 1.77 W/m/K. Considering that the heat flow direction in a TRT is radial, a weighted average can be applied to calculate the average λ of multi-zones. Using the length of 55.0 m and 42.0 m as the thickness of the Quaternary and Tertiary systems in the GHE, the weighted average method gives a λ of 1.01 W/m/K for the Tertiary formation. Comparing the λ of the both systems, it is clarified that the Quaternary formation has much higher λ than the Tertiary formation has at the well location.

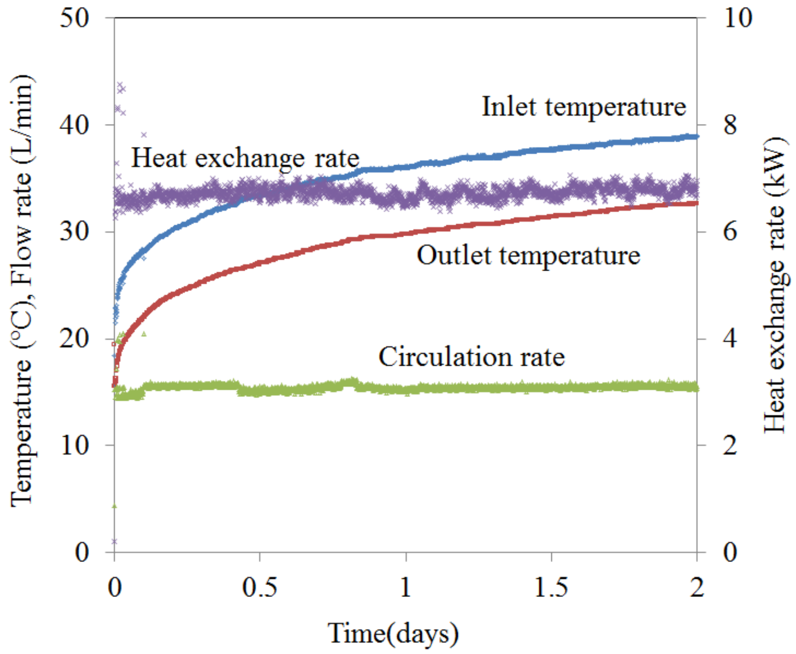

Figure 3: Inlet/outlet temperatures and circulation rates of heat medium and heat exchange rates in TRT-0A.

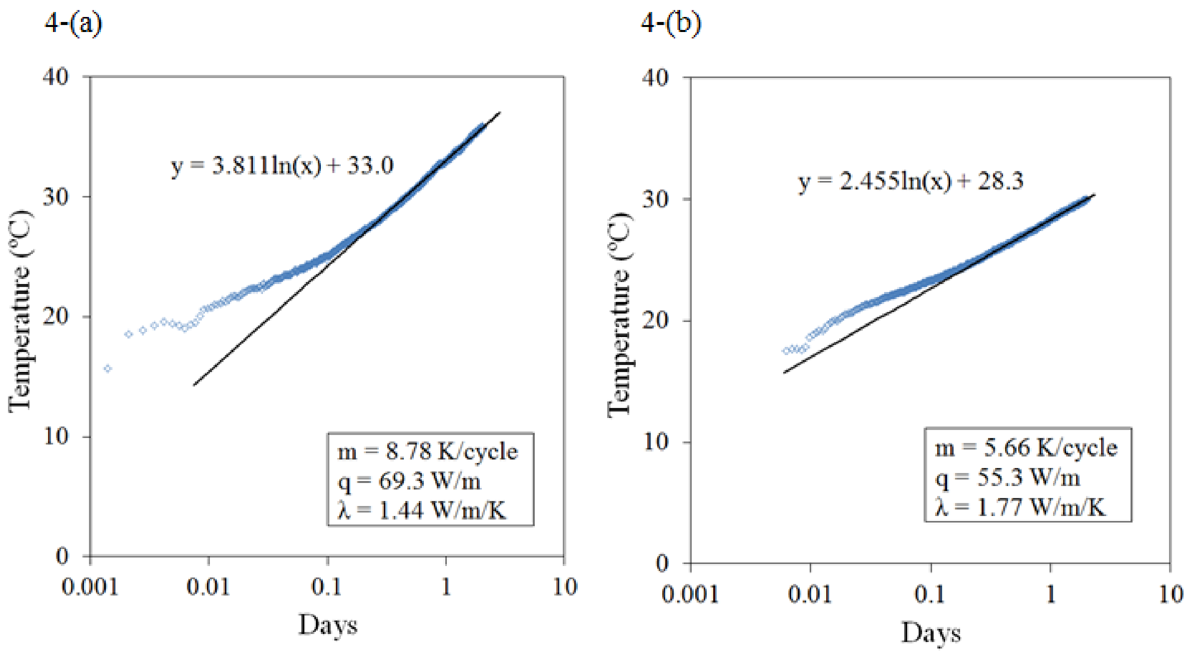

Figure 4: Semi-log plot of time vs. average temperature of heat medium and estimated thermal conductivity, (a) in TRT-0A and (b) TRT-0B.

Figure 5 shown the distribution of λ valuated using the temperature recovery trend in TRT-0A based on the TRT interpretation approach by Fujii et al. (2009). The inlet/outlet temperatures and circulation rate of heat medium and the temperature distribution in the GHE after 1 and 2 days after the end of circulation of heat medium were used for interpretation. Though the average λ was not exactly same as the ones in the semi-log interpretation, the trend well agrees with the interpretation results using the conventional semi-log plots.

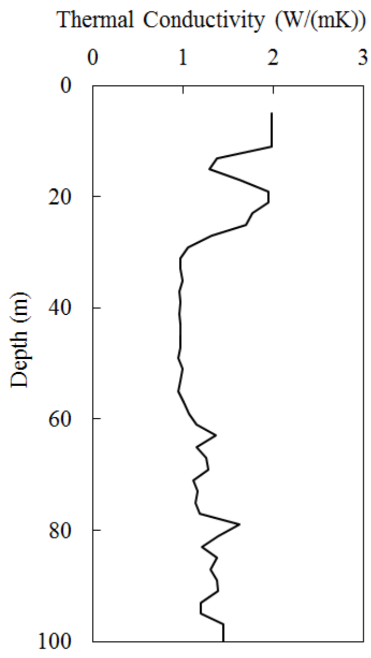

Figure 5: Estimated thermal conductivity profile in TRT-0A using temperature profiles during TRT-0A.

Figure 6 shows the inlet/outlet temperatures and circulation rates of heat medium and the heat exchange rates in TRT-5A. In comparison with the results of TRT-0A in Figure 3, the increase of heat medium temperature was slower and the average heat medium temperature at the end of the circulation period was significantly lower than the case without water injection, 30.6 °C. The slow temperature increase is due to the advection effect of the water flow from surface to the upper part of the GHE, which effectively carried the heat to the formation and kept the in-hole temperature in a low level.

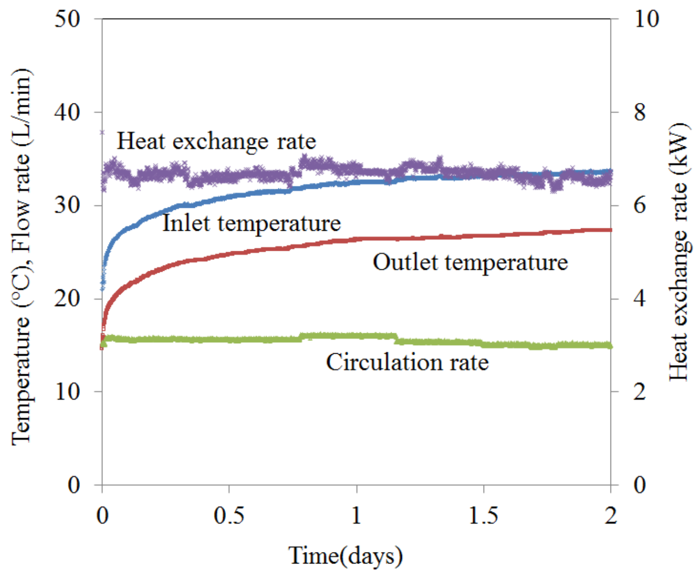

Figure 6: Inlet / outlet temperatures and circulation rates of heat medium and heat exchange rates in TRT-5A.

To investigate the effect of water injection on the temperature distribution in the GHE, the vertical temperature profiles at the end of circulation measured by the optical fiber thermometer in TRT-0A through TRT-3A are compared in Figure 7. The data in TRT-5A is not available due to the malfunction of the equipment. The initial temperature is also shown for reference. Since the temperature sensor is placed in the upflow U-tube, slight temperature drop was observed from the bottom to the top of the GHE in each data. The highest temperature was observed in TRT-0A since the artificial groundwater flow did not exist in this case and the heat conduction was dominant in the heat transfer in the GHE. The difference between TRT-0A and TRT-1A are negligible since the small injection rate minimally sustained the increase of well temperature. With the increase of water injection rate, the temperature decreased because the rejected heat was effectively injected to the formation with the artificial flow of water.

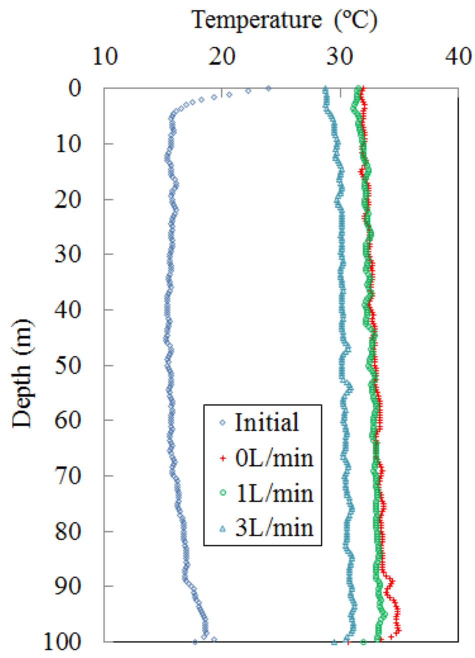

Figure 7: Measured vertical temperature profiles in TRT-0A, 1A and 3A at the end of circulation period.

Figure 8(a) and 8(b) compares the average temperature of heat medium in TRTs-*A and TRTs-*B, respectively. In both cases, the increase of heat medium temperatures were more effectively suppressed with the increase of water injection rates. In Figure 8(a), the temperature behavior in TRT-0A and TRT-1A showed similar performance and the effect of water injection was not clearly seen, which agrees with the observation in Figure 7. The temperature performance in TRT-1B showed some erroneous behavior due to a trouble of the electric heater during the circulation period. The comparison between Figure 8(a) and 8(b), on the other hand, is not reasonable considering that the heat exchange rates per unit well length is not same between the TRT-*A and TRT-*B. To clarify this, the results of all TRTs are compared as shown in Figure 9. In this figure, the horizontal axis shows the water injection rates, varying from 0 L/min to 5 L/min. The vertical axis shows the temperature increase from the original temperature divided by the unit heat exchange rates ($\Delta T/q$). The smaller $\Delta T/q$ indicates the superior capacity of GHE since smaller temperature change is preferable to maintain higher COP in heat pumps. As seen in Figure 9, $\Delta T/q$ showed a smaller value when using a shorter U-tube in zero injection cases. This is because the average λ in the upper formation is higher than the λ value averaged in the entire GHE length, which resulted in the smaller increase of formation temperature due to the faster diffusion of heat to the formation. As the water injection rate increased, the effect of water injection was more clearly observed in the case of using the U-tube of 60 m long. This is mainly due to the fact that the nearly all length of the U-tube was washed by the injected water when using the U-tube of 60 m long, which retarded the increase of heat medium temperatures. These results implied that the enhancement of GHE performance by the water injection is more evident when the injected water reach the deeper part of the heat exchange pipes.

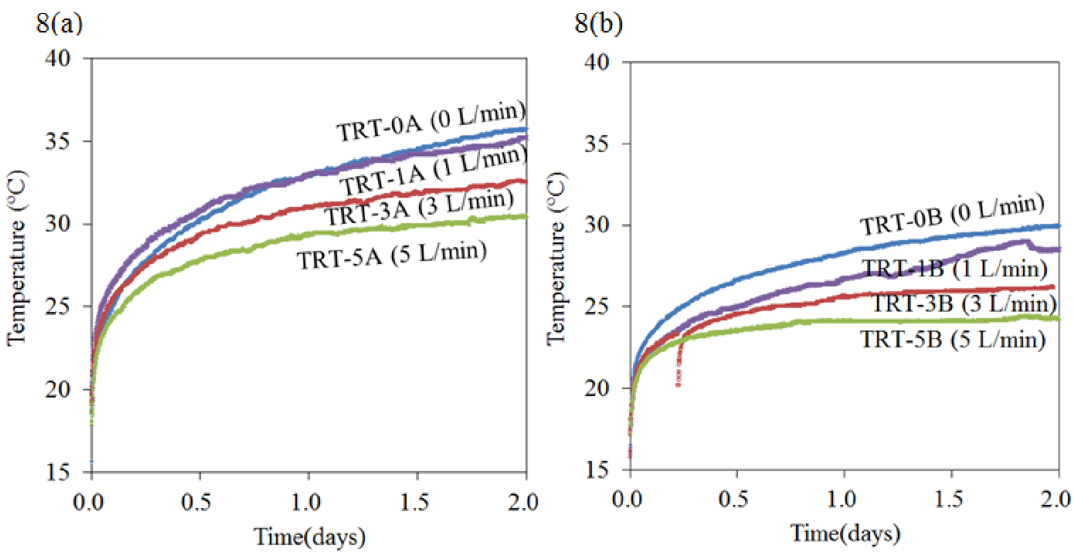

Figure 8: Performance of average temperature of heat medium in all TRTs (8(a): TRT-*A, 8(b): TRT-*B)

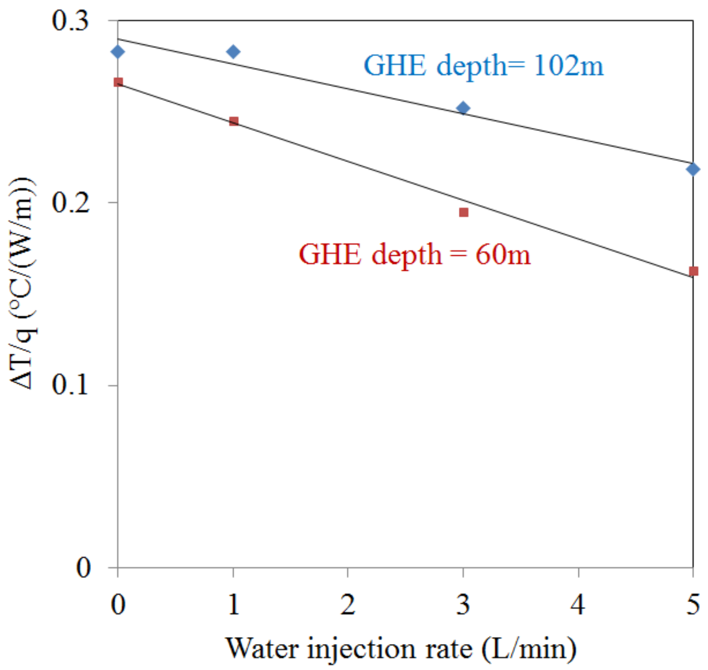

Figure 9: Water injection rate vs. (temperature increase/unit heat exchange rate) in all TRTs.

4. ECONOMIC ANALYSIS

In the above field tests, the positive effects of the water injection to GHEs were confirmed. Hence, the procedure is judged as attractive in case cheap water sources, i.e., spring water, groundwater, river water of stable temperature, etc., are available. If such water sources are not available and tap water is used, economic analysis needs to be performed to check the feasibility of the water injection. Here, a simple economic analysis is performed using the above results of field experiments and the performance curves of heat pumps. As the performance curve of heat pumps, the catalog of small size water-water heat pump, GSHP-1001, a widely used product by Sunpot Co., Ltd. (Japan), was referred. The heat pump has a heating and cooling capacity of approximately 10 kW and the heating and cooling COP curves are represented as below using a hot water and cold water supply temperature of 7 °C and 45 °C, respectively and the compressor frequency of 30 Hz:

Heating $COP = 0.104T_{in} + 3.14$

Cooling $COP = -0.22T_{in} + 11.56$

T_{in} is the inlet temperature of heat pump, which is treated same as the outlet temperatures of the GHE. For the evaluation, the outlet temperatures after 2 days' circulation in TRT-*B was used to calculate the COP for each case. The outlet temperatures and the COPs calculated using the cooling curve as above is summarized in Table 2. Based on the COP, the total of the electricity charge of heat pump and the charge of injected water was also calculated in the same table. The electricity and water rates come from the ones applied in Akita City in April, 2014. Cooling load and operation hours are set as 10 kW and 24 hours/day, respectively.

Table 2: Results of cost evaluation.

TRT No.	Water inj. Rate	Outlet temp. at 2 days	Cooling COP	Power consumption	Cost for electricity	Cost for water	Total cost
	L/min	°C	-	kW	Yen/day	Yen/day	Yen/day
TRT-0B	0.0	30.0	5.0	2.016	760	0	760
TRT-1B	1.0	28.5	5.3	1.890	712	194	907
TRT-3B	3.0	26.2	5.8	1.725	650	583	1,233
TRT-5B	5.0	24.3	6.2	1.609	606	972	1,578

Cooling load: 10kW
Operation hours: 24 hours/day
Electricity rate: 15.7 Yen/kWh
Water rate: 135 Yen/m^3

The total cost in the table shows that the water injection scheme is not feasible in any water injection rates due to the high cost of the tap water. Hence, it is concluded that the enhancement of heat exchange rate by a water injection is difficult to apply economically when using a tap water. On the other hand, when a free water source is available, the water injection would remarkably improve the COP of heat pumps, from 5.0 to 6.2, which will drastically improve the competitiveness of the GSHP systems. When natural water source is not available, one alternative to introduce in this system is the combination with the water pumping from a GHE, which also improves the performance of GHEs as demonstrated in past studies (i.e., Fujii et al., 2008). The schematic drawing of the system is shown in Figure 10. Further field tests, numerical simulation and cost analysis will be crucial to investigate the feasibility of the system.

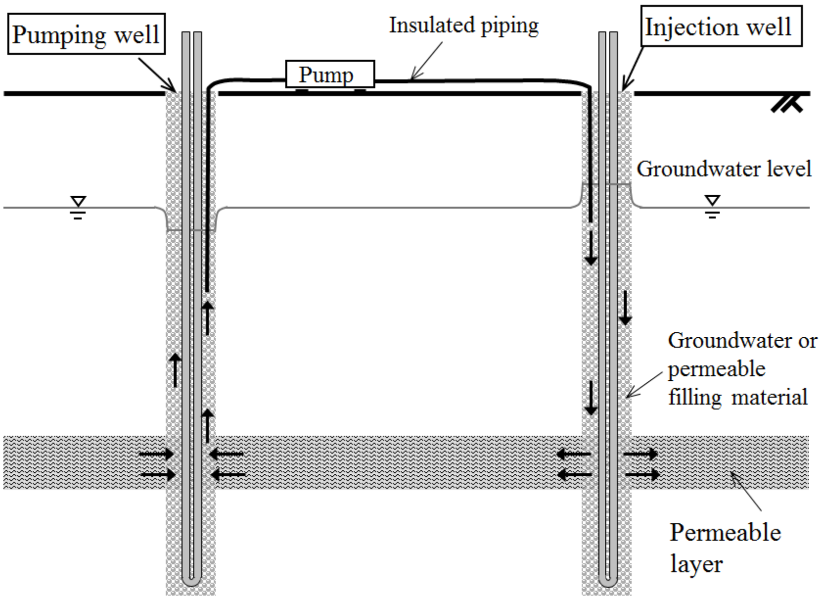

Figure 10: Schematic of the combined GSHP system using water-pumping GHE and water-injection GHE.

5. CONCLUSIONS

Field tests and their interpretations were carried out in an ungrouted GHE drilled in Akita City, Japan to investigate the possibility of enhancing the heat exchange rate by water injection in a formation of low thermal and hydraulic conductivities. Before the TRTs, thermal tracer tests were carried out to detect the interval of good water injectivity to find that the Quaternary deposit above 60 m deep showed a good injectivity. Then, a series of TRTs were carried out using various water injection rates as 0, 1, 3, 5 L/min. and a U-tube length of 102.0 m and 60.0 m. The results of TRTs showed that the water injection could suppress the rise of heat medium temperatures, which could improve the COP of heat pumps. The rate of increase in heat medium temperatures strongly depended on the water injection rates; a larger injection rate resulted in slow increase of heat medium temperatures.

An economic analysis was then conducted to evaluate the feasibility of the water injection scheme to the GHE. The analysis based on the COP of heat pumps indicated that the water injection is not feasible when using a tap water under any water injection rates. This implies that the water injection will be applicable to a GSHP system where a natural water source is available.

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