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THERMAL RESPONSE PERFORMANCE OF THE HEAT EXCHANGER OF A STANDING COLUMN WELL BASED ON THE LOCATION OF THE RETURN PIPE

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Abstract

In this study, mobile measurement devices and a thermal response test for the application of a standing column well (SCW)-type heat exchanger have been developed for obtaining design parameters from on-site measurements. The main objective of this study is to determine the effect of the in situ thermal conductivity and thermal resistance of the ground, including the flow and effect of natural convection of groundwater in a borehole. Constant heating power is injected into the SCW through the test rig, and the gradient temperature of the SCW is recorded. These temperature data are analyzed using a source model

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that indicates the values of the effective in situ thermal resistance and thermal conductivity of rocks. The thermal resistance and thermal conductivity were, respectively, ~44.91% and ~6.56% higher in the lower return pipe than in the upper return pipe.

Nomenclature

H	:	borehole depth (SCW) [m]
R_b	:	thermal resistance [K/(W/m)]
T	:	temperature of fluid [°C]
R	:	radius of borehole [m]
T	:	time elapsed [h]
K	:	slope of fluid temperature against $\ln(t)$
α	:	heat capacity [W/m^3]
λ	:	thermal conductivity [W/m·K]
γ	:	Euler's constant (= 0.5772)

Subscripts

eff	:	effective
sur	:	surface
b	:	borehole
o	:	outside
f	:	fluid

1. Introduction

Geothermal heat sources are increasingly being extracted through heat pumps in both buildings and in agricultural/industrial production. This approach basically uses the thermal energy in the ground. Compared with other renewable sources of energy, the initial investment is relatively small, and it is possible to use a smaller facility. An underground heat exchanger installed in the ground has a lifetime of 40-50 years. It affords advantages such as continuously available energy to compensate for temperature changes depending on the season.

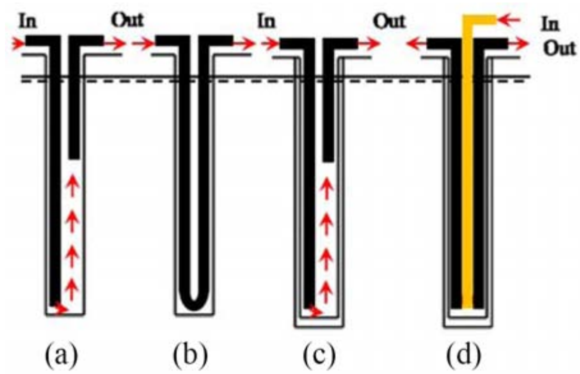
Ground heat exchangers having different configurations are currently available. The most preferred approach is to use a heat pump for extracting heat from underground rocks in a limited area and to establish a continuous underground heat exchanger with high thermal performance. In South Korea, vertical closed loop and standard column geothermal heat exchangers are popular, accounting for ~65.1% and ~29.3% of installed geothermal capacity [1].

A pumping and recharging well (PRW)-type geothermal ground-hole exchanger is [2] widely used in China. In Korea, large-diameter geothermal heat exchangers have been developed, and their thermal performance has been studied [3]. However, it is expected that standardizing the installation process will take time because the development of the underground heat exchanger system has not been completed. With the increasing use of underground heat exchanger systems, efficient dissemination of the optimal design parameters of a geothermal heat exchanger is urgently needed.

This study aims to realize the commercialization of the design and construction of an underground heat exchanger. The thermal performance of the extraction method (effective thermal conductivity and heat resistance) using current standards of testing and measurement was compared to its performance.

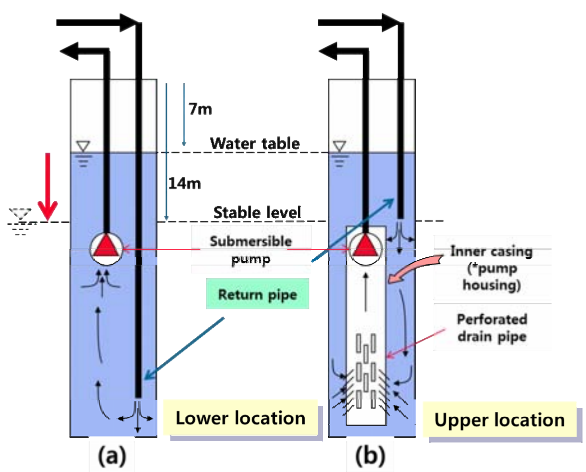
A geothermal well, as shown in Figure 1, uses the flow of groundwater from a borehole. It is an underground heat exchanger that uses direct heat transfer from standing column wells (SCWs) in the groundwater. It uses the GLHEpro program, and the coaxial type uses the EED program. It is possible to design a modified open ground heat exchanger using closure-type concentric tubes.

On the other hand, SCW-type ground heat exchangers have been installed in geothermal wells with 6in, 8in and 10in borehole diameters. The installation of a vertical closed geothermal heat exchanger configuration is different. Although domestic laws regarding groundwater use are relaxed, the installation and configuration still need attention. Nonetheless, an underground heat exchanger that uses geothermal heat generally shows good performance and is therefore advantageous.



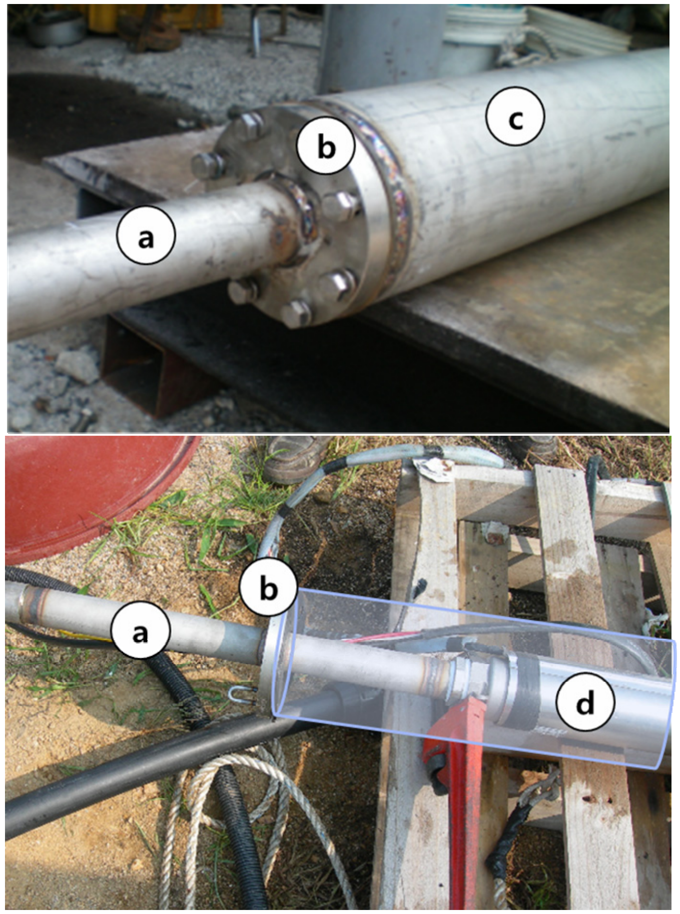
(a) SCW-type, (b) and (c) enclosed types, and (d) circular type

Figure 1. Types of ground heat exchangers.



(a) Lower location and (b) upper location

Figure 2. Location of return pipes in SCW-type ground heat exchanger.



(a) Discharged pipe, (b) connected flange, (c) housing of submersible pump, and (d) submersible pump

Figure 3. Photograph of structure of submersible pump system.

This paper proposes an SCW-type underground heat exchanger based on the current standard of upper installation of the return pipe as shown in Figure 2(b); it was installed at the bottom as shown in Figure 2(a). This experimental apparatus was used to measure the thermal conductivity in a thermal response test. Depending on the position of the return pipe as Figure 3 was showed the configuration of submersible pump system, the thermal response and thermal conductivity were compared.

2. Experimental Methodology

The thermal performance of the underground heat exchanger was evaluated using a thermal response test rig. This was mainly applied to a vertical closed-in ground heat exchanger. In this paper, the experimental apparatus for measuring the effective thermal conductivity and thermal resistance was evaluated.

2.1. Experimental apparatus

The measurement apparatus of the thermal response test used in this paper is shown in Figure 4. The thermal response test rig is composed of various components, as described in Table 1, and the set up on the trailer bed is as shown in Figure 4(a). The schematic diagram of the test rig is also presented in Figure 4 (examples of components include electric and control units, data logger and flowmeters). The inlet and outlet pipes, boiler and filter are equipped with a 4-wire RTD-type temperature sensor. The maximum power used by a boiler in this study that was installed in this system was 84kW (42kW × 2EA), and flowmeters (MACNAUGHT) were used for measuring the specific fuel consumption.

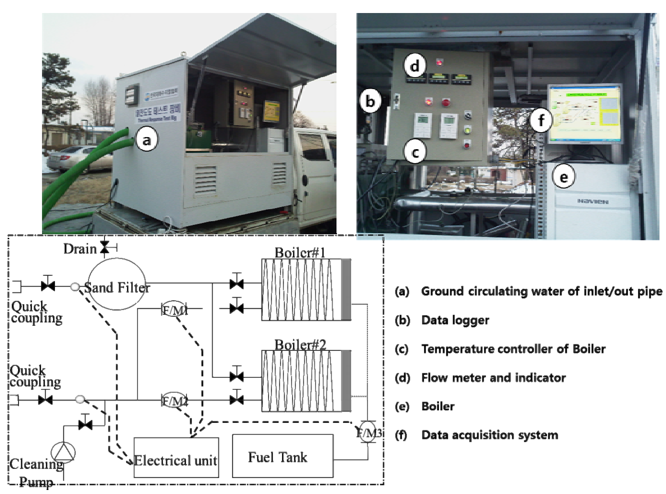


Figure 4. Photograph and schematic diagram of experimental apparatus for measuring thermal conductivity with SCW-type exchanger.

Table 1. Specifications of thermal response test rig

No.	Component	Manufacturer	Specification	Remarks
1	Boiler	Kyungdong	35,300-36,500kcal/h	
2	Sand filter	Weizhen	400LPM	-
3	Pump	WILLO	$8m^3/h$	-
4	Oil tank	-	400L	-
5	Flowmeter (water)	BLUE-WHIT	20-200LPM	±1%
6	Flowmeter (oil)	MACHNAUGHT	35-830cc/min	±1%
7	Temp. sensor		Pt 100Ω, 4-wire	±0.5%
8	Data logger		34790A, 34902MUX	±1%
9	Inverter	LS	SV015iG5A, 380V, 30-60Hz	
10	Measurement program	National instruments	LabView 8.6	-

2.2. Measurement theory

In this study, to develop a thermal response test for the SCW-type geothermal heat exchanger, the line-source theory was employed; this theory is well established and has been applied since 1980 [10-12]. The present study was based on a comparative study of the model for the loss of extreme temperature of the *g*-function in a geothermal heat exchanger using the line-source theory. It was even extended to a comparison study for energy loss in different heat exchanger arrays [14, 15]. The line-source theory is also applied to the thermal response test for an open SCW-type heat exchanger in this study.

The effective thermal conductivity and thermal resistance can be obtained from the thermal response test data by equations (1) and (2), respectively, [12-15]:

$$\lambda_{eff} = \frac{Q}{4\pi kH}, \tag{1}$$

$$R_b = \frac{H}{Q}(T_f - T_{sur}) - \frac{1}{4\pi\lambda}\left(\ln(t) + \ln\left(\frac{4\alpha}{r_o^2}\right) - \gamma\right). \tag{2}$$

The thermal resistance is an important design parameter for the geothermal heat exchanger. Because most existing design programs perform computations by using some approximated parameter values, using properly measured thermal resistance data can provide a useful way to improve its design.

2.3. Uncertainty of heat balance

To verify that the experimental measurements are reasonable, a justifiable means of validation is required. This is achieved using a heat balance. The simplest expression of the heat balance equation is

$$q_{in} = V \cdot C_p \cdot (T_{out} - T_{in}), \tag{3}$$

where q_{in} [W] is the measured heat input to the water heater elements and pumps. V[LPM] is the flow rate; C_p is the specific heat of water; and T_{in} and T_{out} are measured from the thermostat.

After applying all calibration equations to the measurement devices, the heat transfer rate predicted by the right-hand side of equation (3) can be compared with the measured power input (left-hand side of equation (3)). The numbers summarized in Table 2 are the average values over the length of each test, and they are used to compare the instrumentation uncertainties and total heat input error.

The uncertainties in the temperature measurements are $\pm 0.01°C$ for probes and $\pm 0.04°C$ for the signal conditioner of the digital displays with the analog signal. Adding the error in quadrate gives the total uncertainty for the temperature measurements given in equation (4):

$$\Delta T = \sqrt{(\pm 0.01)_{in}^2 + (\pm 0.04)_{in}^2} + \sqrt{(\pm 0.01)_{out}^2 + (\pm 0.04)_{out}^2} \approx \pm 0.2872. \quad (4)$$

Taking into account that ΔT for each test is approximately 5°C, the uncertainty due to the temperature measurement becomes

$$\text{Error} = \frac{\pm 2.872°\text{C}}{5°\text{C}} = \pm 5.74\%. \quad (5)$$

Table 2. Heat balance check

Location	Transducer reading [W]	Average q [W]	Difference [W]	% of average power
A	2506.6	2657.8	151.2	5.68
B	3207.2	3302.5	95.3	2.89

Table 3. Result from flowmeter calibration

Actual flow [LPM]	Calibration flow [LPM]	Error [%]
3.316	3.192	3.73
7.355	7.494	1.85
10.749	10.991	2.20
14.929	17.703	1.51

By using the highest error for the flowmeter of ±3.73%, taken from Table 3, the total uncertainty in the heat balance equation is

$$\text{Total error} = \sqrt{(\pm 0.0574)^2 + (\pm 0.0373)^2} \approx 6.85\%. \quad (6)$$

3. Results and Investigations

The thermal response developed in this study is installed in a glass greenhouse with an SCW-type ground heat exchanger. Granite gneiss is installed as the geological structure in the geothermal heat exchanger. The borehole diameter and drill depth are 8in and 203m (effective depth 195m), respectively. The water withdrawal rate is 190m^3/day, and the stable water level should be –9.0m. Measurements were performed in the geothermal heat exchanger at two locations, namely, the lower and upper locations of the return pipe. The thermal response test for this system based on the conditions shown in Table 4 achieved a period of underground circulating water, which is operated at intervals of 8-10 days. The recovery interval for the temperature of the underground re-circulating water is around 8-10 days. This was measured two times for each condition.

Table 4. Experimental condition for thermal response test of SCW-type heat exchanger

Item	Value
Injected heat (kW)	42.0±0.1
Circulation flow rate (LPM)	160±3
Difference between inlet and outlet temperatures (°C)	Over 3.5
Measuring time (h)	>12
Measuring interval (s)	12

3.1. Analysis of geothermal conductivity

The geothermal response after installation at the upper and lower locations of the return pipe is shown in Figures 5 and 6, respectively. The initial temperature of the geothermal heat exchanger installed at the upper location of the return pipe was measured two times, and the obtained temperatures were 16.75°C and 16.69°C, respectively. For the exchanger installed at the lower location of the return pipe, the initial temperatures were 16.91°C and 17.68°C, respectively.

From Figure 5, the inlet and outlet temperatures first decreased for 20min and then increased for 20min, showing a clear tendency of gradual increase. However, as shown in Figure 6, the position of the lower return pipe did not appear as expected in Figure 5; this is attributed to the temperature gradients of the circulating groundwater inside the underground borehole during heating, as a result of which the return pipe lies between the upper and lower locations.

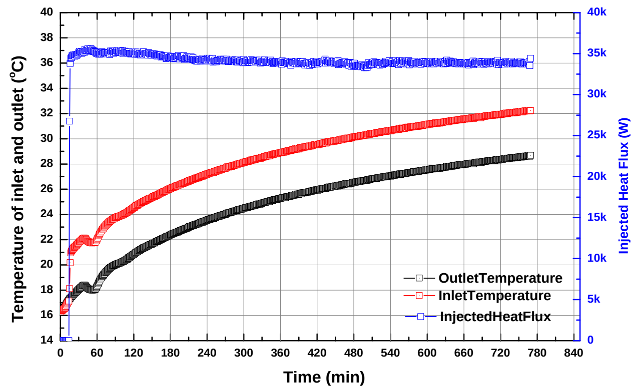


Figure 5. Temperature and injected heat flux characteristics between inlet and outlet of circulation water (for lower return pipe).

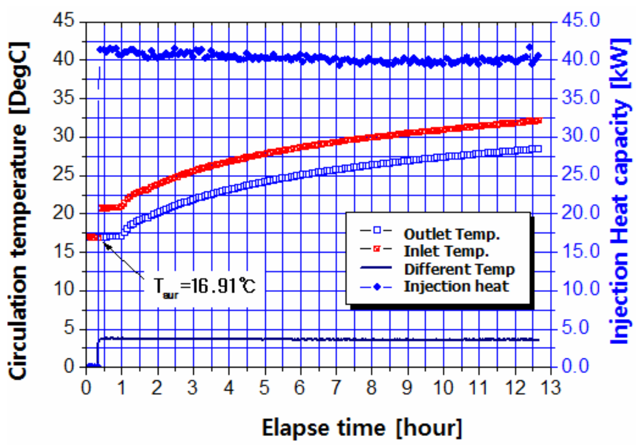


Figure 6. Temperature and injected heat flux characteristics between inlet and outlet of circulation water (for upper return pipe).

Meanwhile, Figures 7 and 8 show linearized fitting graphs of the elapsed time with respect to the average temperature change measured in the recirculation medium of the geothermal heat exchanger. Two conditions are tested in the vertical return pipe to calculate the effective thermal conductivity of the SCW-type ground heat exchanger using equation (1) based on the conditions given in Table 2. For the lower and upper return pipes, the effective thermal conductivity is 3.81W/m·K and 3.56W/m·K, respectively. A comparison of the two conditions indicates that the thermal conductivity in the lower return pipe is 6.56% higher than that in the upper return pipe.

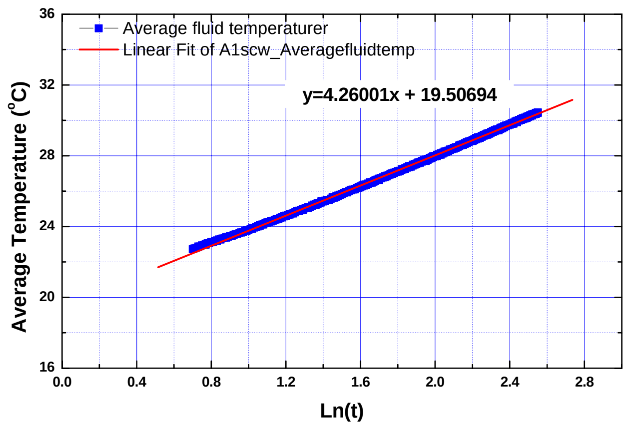


Figure 7. Linearization of average temperature between inlet and outlet (for lower return pipe).

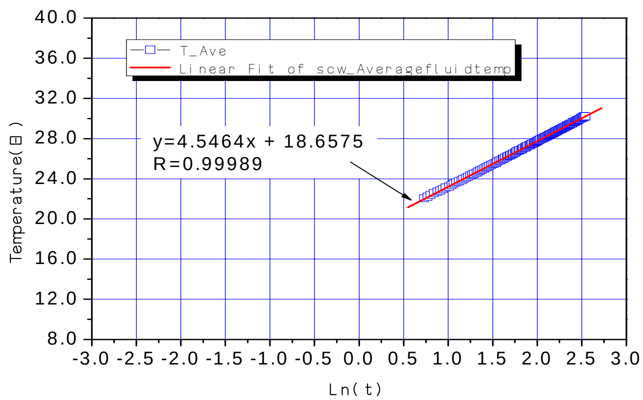


Figure 8. Linearization of average temperature between inlet and outlet (for upper return pipe).

3.2. Analysis of thermal resistance

Figure 9 shows the thermal resistance in the SCW-type geothermal heat exchanger. The effective thermal conductivity of this system was obtained by substituting the values into equation (2). Finally, the thermal resistance value was obtained, as shown in Figure 9. The result of the effective thermal conductivity was summarized in Table 5. During 60min under the initial condition, the thermal resistance value alternately showed sudden decreases and increases, before converging to a constant value. Despite the short measurement time of 12h, the overall thermal resistance value converged to a constant. In the lower return pipe, the thermal resistance value also generally converges to a constant value. The average thermal resistance values in the lower and upper return pipes are ~0.0118K/(W/m) and ~0.0053K/(W/m), respectively. A comparison of the two conditions indicates that the thermal resistance value in the lower return pipe is 44.91% higher than that in the upper return pipe as summarized in Table 5.

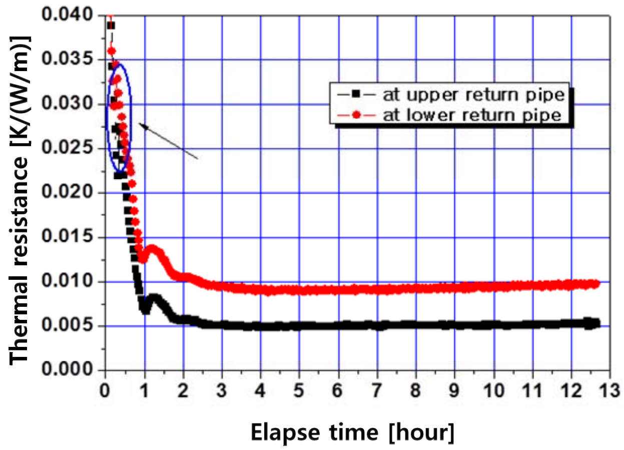


Figure 9. Resistance value in lower and upper return pipes.

Table 5. Effective conductivity calculation results

Type	Lower return pipe		Upper return pipe	
Items	1st	2nd	1st	2nd
Injection heat rate [kWh]	503.0	489.8	495.82	486.21
Measuring time [h]	12.82	12.48	12.47	12.33
Injection heat flux per meter [W/m]	201.26	201.21	203.96	202.17
Slop (k)	4.259	4.146	4.455	4.545
Effective conductivity	3.76	3.86	3.57	3.54
λ_{eff} [W/(m·K)]	3.81		3.56	

4. Conclusions

The thermal performance of an open SCW-type geothermal heat exchanger is measured using a thermal response test rig. The test rig is built on a trailer bed, and the measured data are analyzed using line-source theory. By using the measured data, the effective thermal conductivity and thermal resistance are evaluated. The effective thermal conductivity yields rather high values, indicating high heat transfer ability.

In this paper, the measured values of the thermal effective conductivity and thermal resistance are, respectively, 6.56% and 44.91% higher in the lower return pipe than in the upper return pipe of the SCW geothermal heat exchanger. This result indicates that the thermal resistance and conductivity values change with the installed location of the return pipe. Finally, as predicted by Lee and Woo [13] and these results, the thermal resistance is an important design parameter. Therefore, we conclude that it is necessary to properly select the location of the return pipe in this SCW geothermal heat exchanger system.

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