Validation of Single Well Geothermal Heat Pump System by Scaled Model Experiments

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ABSTRACT

For shallow geothermal applications, the U-tube ground source heat pump (GSHP) system, the standing column well(SCW) geothermal heat pump system, and the forced external circulation single well(FECSW) geothermal heat pump system are recognized as the most advanced methods of geothermal cooling and heating systems, either by using no groundwater or by recycling groundwater. In order to improve the heat extraction efficiency of these single-well modes, it is vital to experimentally analyze the heat extraction efficiency in different experimental environments that can be encountered under realistic conditions. Based on the 1:20scaled model we design 10 experimental scenarios considering different experimental conditions, such as soil moisture, groundwater convection, heat conduction, abstraction and injection interval selection, and compared the heat extraction efficiency according to the scheme. The experimental results shows that the order of increasing heat extraction capacity is U-tube, SCW, FECSW. Also, in three methods, the heat extraction capability is changed by the water flow into the ground, ground moisture, operating approaches, etc. The results of the scaled model experiments are used as a comparative validation data for numerical simulation of a single well geothermal heat pump system and contribute to the development of modeling method of geothermal single well in real conditions.

Keywords: U-tube ground source heat pump, standing column well, forced external circulation single well, scaled model, heat extraction

INTRODUCTION

Nowadays, due to the worldwide depletion of energy and environmental pollution problems, the development of renewable energy for mankind to live in a clean environment is widely studied.

With the rapid development of science and technology, a large production of high efficiency heat pumps has made active use of shallow geothermal energy with less development cost compared to deep geothermal heat in many countries.

The U-tube GSHE is a shallow geothermal energy development method that embeds the heat exchanger into the ground and extracts the geothermal energy through heat exchange between the ground and the water flowing through the pipe. The U-tube GSHE used in practice includes single U-tube tube, multi-U tube and coaxial tube heat exchangers [1, 2, 3].

There are two major heat transfer models for mathematically modeling U-tube GSHE: linear heat source model and cylindrical heat source model. The linear heat source model includes the Kelvin model, Ingersoll model, and IGSHPA model [4,5], which suppose several hypotheses to avoid and simplify the complexity of the actual heat transfer process and ignore several factors affecting the heat transfer process, such as interference between tubes and heterogeneity of temperature distribution. The cylindrical heat source model was proposed by Carslaw and Jaeger to develop a linear heat source theory model in some cases. Kavanaugh [6] developed a heat transfer model of a vertical U-tube GSHE with some modifications to the original cylindrical heat source model in 1991. In this model, the heat transfer process was considered only due to heat conduction, and the thermal interference between wells and seepage of groundwater in the soil was neglected. The cylindrical heat source model can be reasonably applied to the case operating for short periods of time with U-tube GSHE installed in large diameter wells.

Several experimental and numerical simulation methods have also been proposed to study U-tube GSHE. Egidi et al. [7] proposed a mathematical model of U-tube GSHEs based on unsteady Navier-Stokes problems. They divided the heat exchanger into two computational domains: a straight tube in which the temperature field is calculated analytically, and a U-

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curve tube in which the flow and heat exchange are calculated numerically based on Galerkin finite element method, and evaluated the generated effective energy. These results were analyzed for experimental measurements and validation obtained from the actual geothermal heat exchanger. Al-Khoury et al. [8] calculated the temperature distributions in all well heat exchanger elements and surrounding soil mass using fast Fourier transform in an axisymmetric shallow layer geothermal system consisting of a double U-tube GSHE embedded in the soil. Using 16,384 FFT samples and 100 Fourier-Bessell series samples in the time domain, the temperature distributions in the tube inlet, filler and soil were calculated. Eslammejad et al. [4] proposed an analytical model for predicting steady state heat transfer in a double U-tube GSHE with two independent circuits operating with different mass fluxes and inlet temperatures. The model can be used to describe the tube thermal resistance and thermal interaction of fluid in U-tube circuits and to investigate the new dual U-tube well structure with one circuit connected to a ground source heat pump and a solar thermal collector operating in heating mode. Gharibi et al. [5] carried out a three-dimensional numerical model with U-tube GSHEs in abandoned oil wells to analyze the effects of mass flux, fluid inlet temperature, length of insulation and tube diameter. Cimminino [9] proposed a numerical model and analytical model to calculate fluid and well wall temperatures in geothermal wells with multiple U-tubes. Tilley et al. [10] considered a simple Cartesian model consisting of two finite length parallel channels carrying heat transfer fluid embedded in the soil. One channel carries fluid from the surface to the bottom of the well, and the other carries fluid from the bottom of the well to the surface. Jalili et al. [11] studied the convective conductive heat transfer process between all components such as tube interior, tube exterior, and grout of a geothermal borehole heat exchanger (BHE) using an Modified Homotopy Perturbation Method(MHPM). Lyu et al. [12] established a three dimensional steady state numerical model including U-tubes, wells and geothermal layers based on geological data and studied the effect of important geological parameters such as bed depth, porosity, permeability and heterogeneity on heat exchanger performance. Maestre et al. [13] proposed a two-dimensional mixing model (RC2) for U-tube GSHEs and experimentally verified the mixing model under stop-start operating conditions. Santa et al. [14] conducted an experiment to investigate the cyclic thermal stress on the surrounding soil in the operation of BHE in closed loop geothermal systems. The results show that the irreversible compression effect induced by soil increases the salinity and lowers the soil freezing point. Lyne et al. [15] examined high conductivity phase change material (PCM) in the experimental model using annular region packing. The experimental results showed that PCM can reduce temperature fluctuations in annular and soil regions and increase the rate of heat consumption from heater to soil environment. Wang et al. [16] analyzed the heat injection temperature and initial water content during heat storage on the basis of a laboratory experimental setup using BHE. Gordon et al. [2] obtained an experimental study on a vertical coaxial BHE that increasing the inner tube diameter reduces the required length of the heat exchanger and increases the overall performance factor realized by the heat pump. Zhang et al. [17] evaluated the thermal conductivity and specific heat capacity of gravel, sand, sandstone and granite mainly affected by particle size, porosity, density and water content through experiments.

A SCW is a ground heat exchanger that installs a circulating pipe in the well and extracts geothermal energy while circulating fluid. Several experimental and numerical simulation methods have been proposed to study the heat transfer characteristics in SCW. Bu et al. [3] developed a mathematical model describing heat transfer through the underground well as the surrounding rock, based on experimental studies on a single well, and simulated and evaluated the seasonal heat output. The heat output decreases with time, but the imbalance can be adjusted by changing the pouring temperature and speed. Beaudry et al. [18] developed a finite element model that combines heat transfer and groundwater flow with input data collected in a large-scale geothermal laboratory. Simulation results representing conditions of 6-day pumping test, 24-day thermal response test and 25-day dynamic winter operation were consistent with experimental data with mean absolute error of 7.3 cm, 0.15°C and 0.32°C, respectively.

The FECSW is another type of combining the closed loop and open loop. Wu et al. [1] evaluated the influence of different parameters on the output temperature and efficiency of FECSW system through finite element numerical simulation. Thermal conductivity, volumetric heat capacity and porosity have a minor effect on the system sustainability and efficiency, and it has been confirmed that winter-summer (W-S) mode with active cooling has a greater effect than winter (W-S mode). Song et al. [19] designed a sandbox experimental setup for SCW and FECSW experiments. In the experiments, the effect of the outlet water temperature (OWT) and heat absorption (HAQ) of the hot well, especially the OWT improvement of SCW, on the flux of 0-30% was analyzed. Song et al. [20] performed model experiments and numerical simulations on a FECSW. A numerical model of FECSW was developed to analyze the motion of temperature and velocity profiles under flow and thermal breakthrough. When the porosity of the backfill material decreased from 0.35 to 0, the COP of the heat pump unit increased by 1.6% on average, and the thermal breakthrough strength decreased by 45.3% on average within 25 min. Through this quantitative analysis, theoretical suggestions for the heat transfer mechanism near the hot well wall are provided.

Analyzing the results of previous studies, they use laboratory and field experimental data for comparative analysis, focusing on simulation calculations to enhance the performance and heat exchange efficiency of single well modes such as U-tube heat pump system, SCW heat pump system and FECSW heat pump system. In addition, the simulation calculations and experimental results are compared, limited to individual modes, and no three modes are studied in relation to each other. In

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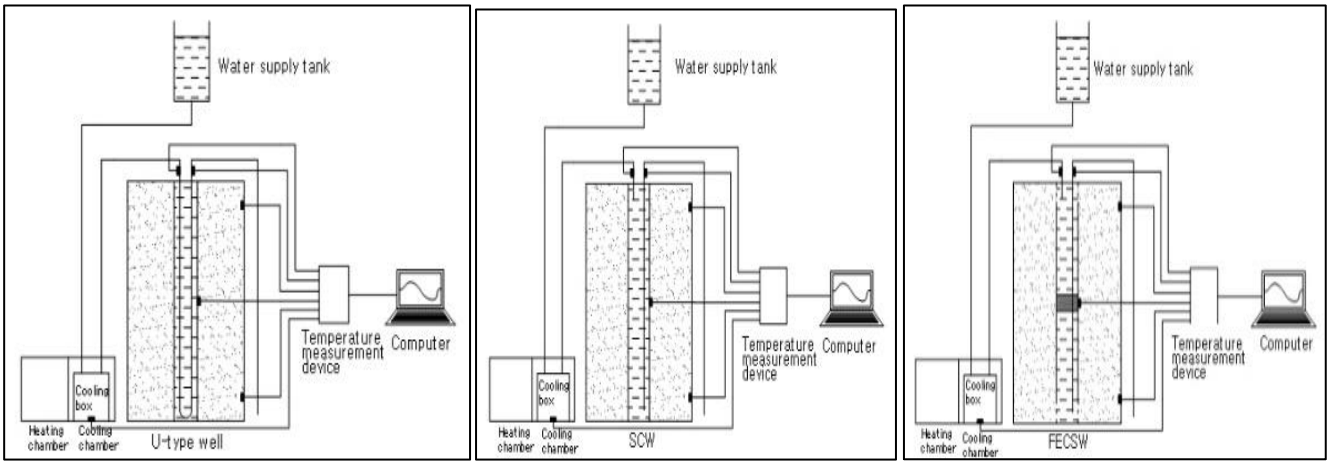
order to study and apply these modes to realistic conditions, the heat extraction efficiency of each mode should be compared with the study of the heat exchange characteristics of individual modes under different environmental conditions. In this paper, we designed a 1:20 scaled model and conducted 10 experimental scenarios considering different experimental conditions such as soil moisture, groundwater convection, heat conduction, abstraction and injection interval selection, and heat extraction experiments according to the scenarios, and compared the effectiveness.

Design and Construction of Single Well Scaled Model

A 1:20 scaled model was designed to perform geothermal extraction experiments. A single well scaled model consists of a well system, a water supply system, a cooling (heating) supply system, a temperature measurement system, and a flow measurement system, and a schematic of each scaled model is shown in Fig. 1.



(a) (b) (c)

Fig. 1. A single well scaled model system configuration

(a) U-tube well, (b) SCW, (c) FECSW

Single well system

U-tube well

In the U-tube well, the heat of the ground is generally extracted in the form of heat transfer, but in the experiments a system was also prepared to study and analyze the convective heat transfer due to groundwater flow. For U- tube well systems, Φ250mmUPVC pipe, Φ20mmUPVC pipe, Φ3.5mmPE tube and insulation materials were used. The Φ250mmUPVC pipe forms the outer wall of the scaled model (Fig. 2). The inner diameter of the pipe is 236 mm and the tube height is 1.5 m. The bottom of the tube is double fixed so that it is not lost by the load of the soil.

The Φ20mmUPVC pipe is the well in the scaled model. In practice, the well wall generally consists of a casing (steel) and a drilled rock. However, there are also cases where poor diagenetic formations, such as Tertiary strata, are made by steel or plastic. In our experiments, we chose to install plastic tubes to replace the role of casings throughout the sample, since we use soil samples. At that time, the porous plastic tube allows the simultaneous convection and heat transfer with the soil and the non-porous plastic tube to examine only the thermal conductivity. The porous plastic tube made about 2,994 holes with Φ2mm to make 10% porosity. The non-porous plastic tube cuts off the water flow between in-hole and out-hole. This provides similar conditions to the practice of filling several impermeable fillers in the well to prevent groundwater contamination during anti-freezing agent leakage accidents.

The Φ3.5mmPE tube is used as the U-tube. A plastic U-ring and Φ3.5mmPE tube were connected to make a U-tube. The tubes were separated by adhesive tape at intervals of 10 cm so that they did not adhere to each other. In practice, a Φ32 mm HDPE tube is used as a U-tube. HDPE (high density polyethylene) pipes are very effective in terms of corrosion resistance, strength and thermal conductivity. UPVC and PE pipes are shown in Fig. 2.

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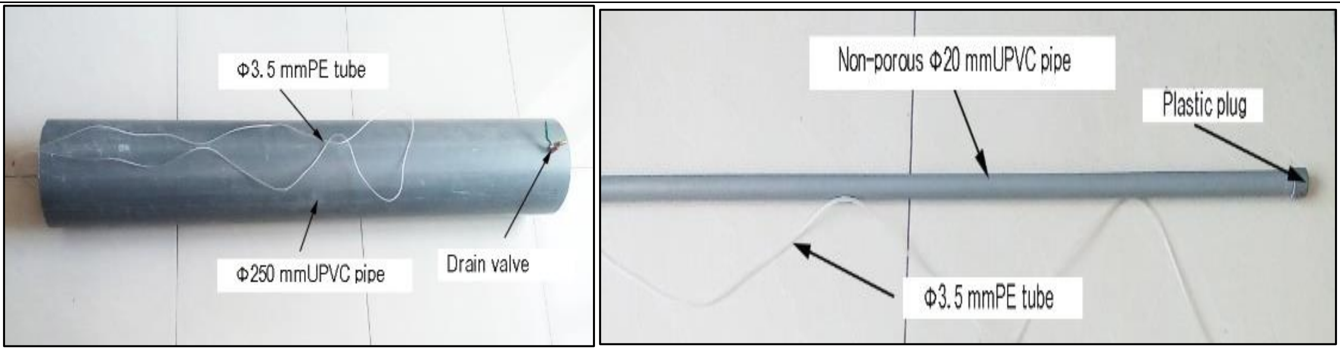

(a) (b)

Fig. 2. UPVC and PE pipes

(a) Φ250mmUPVC pipe and Φ3.5mmPE tube, (b) Φ20mmUPVC pipe

Synthetic rubber insulation is used as insulation material. The Φ250mmUPVC tube, which is the outer wall of the scaled model, is subjected to external temperature during the experiments and may cause errors in the results of heat extraction in the soil, thereby covering the entire pipe (except the upper surface) to the floor with this insulation.

SCW

On the other hand, in the case of non-cracked impermeable rock, the water in the well cannot penetrate and migrate to each other with the surrounding strata (rock), so only heat conduction will affect the heat extraction. Non-porous plastic tube to be prepared for experiments in this case.

The Φ3.5mmPE tube is used as the injection and pumping tube in a SCW model. Two Φ3.5mmPE tubes are inserted into the well, which is located in the upper part and in the lower part. The plastic plug is intended to prevent water from entering the well in case of non-porous plastic pipes.

FECSW

Φ2mm holes are drilled to Φ20mmUPVC pipe section corresponding to inlet and outlet section (10 cm each) with 10% porosity.

In geothermal extraction with a FECSW, the selection of the seal section position and length (interval between the injection section and the pumping section) is very important. In general, it is reasonable that the injection and pumping intervals are in the best position for permeability. That is, it is necessary to select the site for the pumping and reinjection in the ground. If the length of the seal section is reduced, which adversely affects the heat pump operation by rapidly reaching the pumping section and resulting in severe temperature changes. On the contrary, if too large, the arrival time of the injected water is much slow, so that the amount of water in the water-poor zone cannot be provided.

On the other hand, the seal method is also an important technical issue. The seal within the well can be divided into one- and two-barrier. If seal is not good, the injected water may leak through the screen or between the well and the ground soil, causing a loss of heat extraction efficiency.

The problem to consider in seal technology is also how this is technically feasible since the pumping pipe is installed through seal section. In the experiment, a single seal structure was selected, the middle of the 1.5 m long Φ20mmUPVC tube was cut, covered with a seal plug (circular tree) and the seal was completed by passing through the Φ3.5mmPE tube into the tree In order to see if the experimental seal structure actually has a seal function, the Φ20mmUPVC tube was set vertically, filled with water in the upper part (water had a hydraulic pressure of 0.7 mH20) and kept for 48 h, there was no water leakage from the bottom of the tube.

Water supply system

Water supply is ideal to use a mini-pump, but considering the allowable flux 2.5~4 cm/s (0.5 m/s in practice), flux 0.6~1 L/h and cooling (heating) supply load in the scaled model, a very small amount flows into the Φ3.5mmPE tube and is therefore implemented using the static water head without using a mini-pump.

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On the Φ250mmUPVC pipe, a cylindrical water tank of 270 mm in height and 236 mm in diameter (about 10 L in volume) was mounted, drilled at the bottom of the water tank, and a water droplet velocity monitor was installed to enable real-time water supply and flow measurements.

Cooling (heating) system

In practice, to determine the thermo-physical properties of the ground and evaluate the heat extraction capability, thermal response tests are performed to heat the water tank with an electric heater to circulate the heated constant temperature water into the ground. In the thermal response test, the hot water is supplied, but in the present experiment the cold water is supplied from the cold generator.

For the experiments, the inlet pipe for the water supply tank and the outlet pipe for the cooling water extraction into the iron tank filled with water 2L volume are arranged at intervals such that there is no thermal interference and sealed to prevent water from flowing out of the iron tank. Iron box of this structure shall be installed in cooling chamber and covered with synthetic rubber insulation to ensure that cooling is maintained in it (Fig. 3).

Fig. 3. Cooling chamber covered with synthetic rubber insulation

According to the experiments, when the temperature in the cooling chamber was -14°C, the temperature in the cooling box (iron box) was -1.5°C, i.e., the cooling generated from the cooling system was fully transferred into the cooling box.

On the other hand, for heat supply experiments, iron box may be put in heating chamber.

Temperature measurement system

In the experiments, the temperature measurement system is a key part with cold supply.

For temperature measurement, we used the DS18B20 which is a digital temperature sensor that communicates in a single-line access mode. DS18B20 uses a bus communication protocol that implements bus communication using a single control signal bus. The DS18B20 uses a bus communication protocol that implements bus communication using a single control signal bus.

A microcontroller computer (PIC18F452) is used to realize control over the measurement system, such as temperature measurement, display and data communication.

The microcontroller (firmware) was developed in MPLAB IDE v8.5.

The communication circuit uses the Max485 chip to transfer the processed temperature measurement data from the microcontroller to the upper computer in RS485 communication mode.

In the experiments, six temperature sensors are placed in the corresponding position of the scaled model and the temperature in the cooling chamber, the inlet and outlet temperature of the model and the temperature at three locations in the model are measured simultaneously in real time.

The temperature control unit automatically realizes the start and stop of the cooling system at a set time interval, while displaying the temperature at different locations on the LCD and transferring data to the upper computer by PIC control, ensuring the stability of the long-term operation of the cooling system. Using the set key, increment (decrease) key and left and right moving key, the experimental date, time, compressor start and stop time, etc. are set. The data transmitted in the temperature controller is displayed in real time and stored in a computer.

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Real-time measured inlet and outlet temperatures and soil internal temperatures are recorded in the storage medium while graphically displayed on the computer. To accomplish this, the temperature data measured on a single-chip computer were acquired on a computer using USB-485 communications, and then the program for display and recording was written using Qt program.

Flow Measurement System

In order to accurately determine the heat extraction and to provide the inlet and outlet temperature difference to the scaled model, the flow measurement should be performed well.

In the experiments, the flux is very small, with an average of 1 L/h, so a calibrated beaker is used considering the condition that the flux can be measured without the flow meter. Beaker volume is 100 ml.

RESULTS AND DISCUSSION

Soil property assessment test

In the geothermal extraction experiments, fine sand and coarse sand soil were used as materials. Here, fine sandy soil is used as a filling material to fill in the well model.

The characteristics of the sandy soil used in the experiments were determined by experimental methods.

Hydraulic conductivity

The hydraulic conductivity of soil was determined by the fixed head method.

We filled the sample in the sample box, shaken it with constant shaking, and poured water to ensure sufficient humidity. Then, the graduated water supply box was filled with water and placed on the top surface of the sample upside down so that the hole went down. Since the water in the water supply tank is kept to match the water level above the sample, the hydraulic gradient I becomes 1 because of the same length L and water level H of the soil layer, and thus the hydraulic conductivity K can be determined using the flux Q and the cross-sectional area F flowing for time t.

The experimental results for coarse sand, the soil sample filled in the model are shown in Table 1. The average time for three experiments was 38.6 s, and the hydraulic conductivity of coarse sand was determined to be about 81.3 m/d.

Table 1. Experimental results of hydraulic conductivity measurement of coarse sand

№	Time, s	Flux, cm^3	Section area, cm^2
1	41.6	90.8	25
2	37.5	90.8	25
3	36.9	90.8	25

On the other hand, the experimental results for fine sand filled in well are shown in Table 2. The average time was 93.5 s, and the hydraulic conductivity of the fine sand was estimated to be about 33.6 m/d.

Table 2. Results of the hydraulic conductivity Measurement of fine sand

№	Time, s	Flux, cm^3	Section area, cm^2
1	76.6	90.8	25
2	91.7	90.8	25
3	112.1	90.8	25

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Porosity

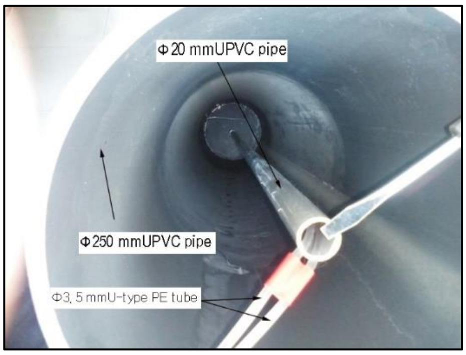
Porosity determination experiments were performed by filling the sand well in the scaled model and supplying water to the bottom of the model to determine the amount of water needed to fill the soil pores. Sandy soil is compacted well at 1.5 m height and filled with water to another model with the same volume as the experimental model and connect the two models to the pipe. When the valve is opened, water flows into the sand filled model in the water filled model. When the water level is balanced, the drawdown value is measured and it is saturated to the top surface of the sandy soil by filling again. At that time, adding the measured drawdown values at each stage results in the water level in the air gap of the soil layer.

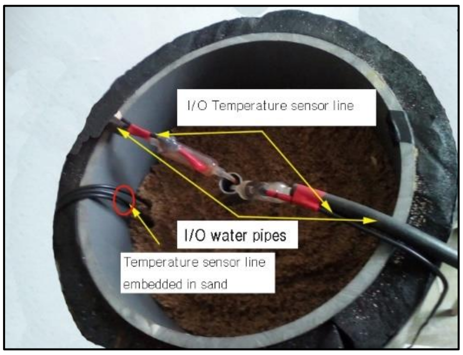
Experimental results showed that when saturated up to the top surface of the soil, the height of the sandy soil was lowered to 1.45 m and the height of water injected was 0.51 m. Since the cross-sectional areas of both models are the same, the porosity of the sandy soil filled in the model is determined to be n=0.51/1.45≈0.35.

Experiments and results using U-tube GSHE scaled model

In order to perform the geothermal extraction experiments in the U-tube GSHE scaled model, the Φ20mmUPVC tube was installed vertically at the bottom center of the Φ250mmUPVC tube and the Φ3.5mmU PE tube was inserted here (Fig. 4-a).

In this situation, the coarse sand used as the formation material was filled with a certain thickness and filled with all by compaction (Fig. 4-b)





(a) (b)

Fig. 4. The U-tube well internal structure

The well internal structure, (b) Internal structure of sand-filled experimental setup

The sandy soil filled with Φ250mmUPVC pipe can be saturated by using the valve at the bottom of the pipe, else drained through it.

Based on the experimental scenarios shown in Table 3, the U-tube GSHE scaled model experiments are conducted and the experimental results are analyzed.

Table 3. U-tube GSHE scaled model experimental scenarios

	Condition	Experimental purpose
Scenario 1	Sand in saturated state, use water as filler inside well, porous well	Evaluation of heat extraction efficiency by heat conduction in the absence of filler
Scenario 2	Sand in saturated sand, use of fine sand as filler inside well, porous well	Evaluation of heat extraction efficiency by heat conduction in case of filler
Scenario 3	Dry sand, use water as filler inside well, non-porous well	Evaluation of heat extraction efficiency by heat conduction in dry impervious ground
Scenario 4	Partially saturated sand, water as filling material	Evaluation of heat extraction efficiency by heat

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	inside well, non-porous well	conduction in weakly permeable strata

Scenario 1

The sandy soil was completely saturated and tested in only water-filled condition without filler inside the well.

The experimental time is 45,360s (about 0.525d), the flux is 0.0228 m^3/d, and the average I/O temperature difference is 5.37°C.

Scenario 2

The sandy soil was completely saturated and the fine sand of size 0.5~1mm inside the well was filled with filler and the experiments were carried out.

The experimental time is 34,560s (about 0.4d), the flux is 0.021m^3/d, and the average I/O temperature difference is 6.67°C.

Scenario 3

The soil is dry sand.

The PVC pipe forming the well is a non-porous pipe and it is not possible to leak the filled water into the surrounding soil instead of the filler between the well and the U-tube.

The experimental time is 30,780s (0.35625d), the flux is 0.0216m^3/d and the average I/O temperature difference is 4.57°C.

Scenario 4

The soil used in Scenario 4 is water-filled and completely removed through the drain valve and partially saturated.

The PVC pipe forming the well is a non-porous pipe, which acts as a barrier to prevent the water filled between the well and the U-tube from escaping into the surrounding soil.

The experimental time is 61,300s (0.71d), the flux is 0.0234m^3/d, and the average inlet and outlet temperature difference is 4.56°C.

The variations of the I/O temperature of the U-tube GSHE scaled model obtained during the experiments are shown in Fig. 5.

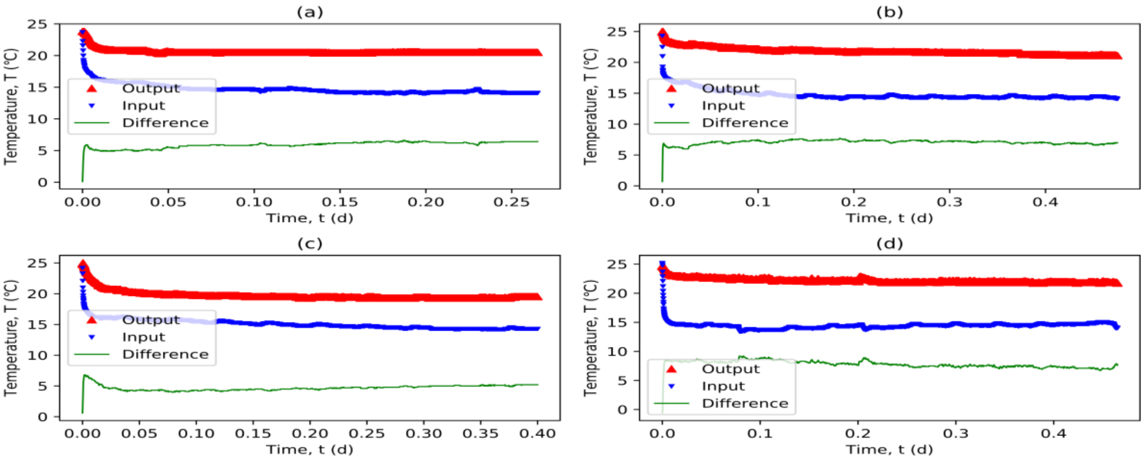

Fig. 5. I/O temperature variation in U- tube GSHE scaled model.

(a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4

The results of the experiments of the scenarios for the U- tube GSHE scaled model were combined to analyze the heat extraction capacity (Table 4).

Table 4. Analysis of heat extraction capacity for U-tube GSHE test scenarios

	Average temperature difference, ℃	Average flux, m^3/d	Thermal Extraction Capability, W
Scenario 1	5.37	0.0228	6.29
Scenario 2	6.67	0.021	6.79
Scenario 3	4.57	0.0216	4.79
Scenario 4	4.56	0.0234	5.38

Experiments and results using SCW scaled model

In order to perform the geothermal extraction experiments in the SCW scaled model, the Φ20mmUPVC tube was vertically installed at the bottom center of the Φ250mmUPVC tube and two Φ3.5mmPE tubes were installed at the inlet and outlet positions. The inlet pipe is located in the upper part of the well and the pumping pipe in the bottom.

In this situation, the sandy soil used as a formation material was filled with a constant thickness between the well and the external wall and filled with all by compaction.

Based on the experimental scenarios shown in Table 5, SCW scaled model experiments were conducted and the experimental results were analyzed.

Table 5. SCW scaled model experimental scenarios

	Condition	Experimental purpose
Scenario 1	Water filled instead of soil, non-porous well	Evaluation of heat extraction efficiency by heat conduction in water
Scenario 2	Wet sand, non-porous well	Evaluation of heat extraction efficiency by heat conduction in ground with constant humidity
Scenario 3	Dry sand, non-porous well	Evaluation of heat extraction efficiency by heat conduction in impermeable rocks
Scenario 4	Saturated sand, porous well	Evaluation of heat extraction efficiency by heat conduction and convection in saturated sand

Scenario 1

In scenario 1, the model was filled with water instead of soil and the experiment was performed.

Since the well model uses non-porous pipes, only heat conduction occurs between the circulating water flowing inside the well and the water filled in the model around the well.

The experimental time is 22,900s (about 0.265d), the flux is 0.0228 m^3/d, and the average I/O temperature difference is 5.87°C.

Scenario 2

In scenario 2, heat exchange experiments were carried out on partially saturated wet sandy soil.

Also, the well is sealed and only heat exchange by the surrounding soil and heat transfer.

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The experimental time is 41,040s (0.475 d), the flux is 0.0214 m^3/d, and the average I/O temperature difference is 7.07°C.

Scenario 3

In scenario 3, heat exchange experiments were carried out on dry sandy soil.

Since a well model is built with non-porous pipes, there is only heat conduction between the well and the surrounding soil as in Case 2.

The experimental time is 34,560s (about 0.4d), the flux is 0.0214m^3/d and the average I/O temperature difference is 4.69°C.

Scenario 4

In scenario 4, heat exchange experiments were carried out on saturated sandy soil.

The use of porous pipes results in convective phenomena, not only heat conduction between the well and the surrounding soil, which increases the heat exchange efficiency.

The experimental time is 40,180s (about 0.465d), the flux is 0.0228 m^3/d, and the average I/O temperature difference is 7.8°C.

The I/O temperature variations in the SCW scaled model during the experiment are shown in Fig. 6.

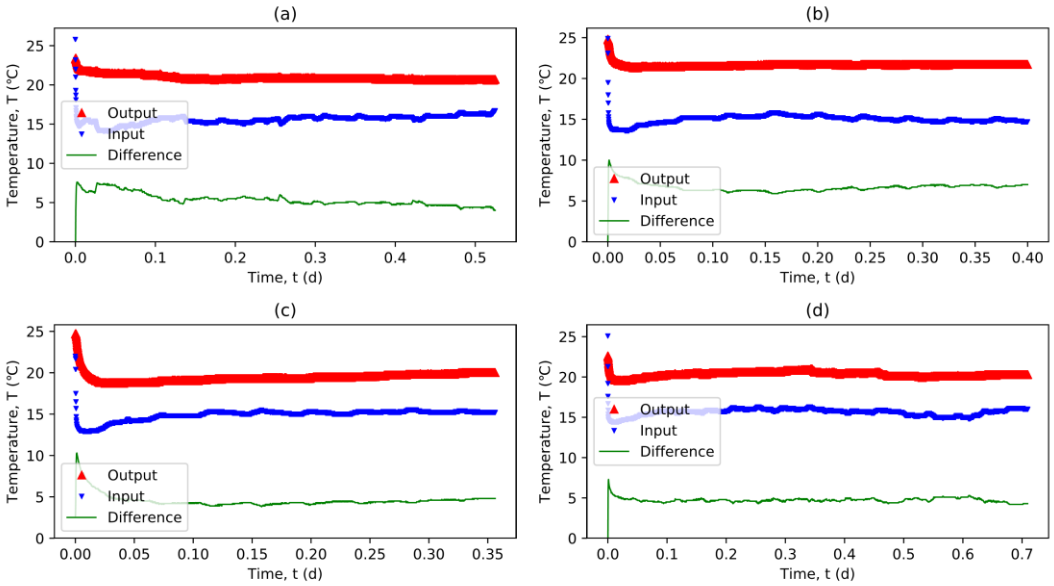

Fig. 6. I/O temperature variations in the SCW scaled model.

(a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4

The experimental results are summarized in Table 6.

Table 6. Analysis of heat extraction capacity for SCW scenarios

	Average temperature difference, ℃	Average flux, m^3/d	Thermal Extraction Capability, W
Scenario 1	5.87	0.0228	6.5
Scenario 2	7.07	0.0214	7.89
Scenario 3	4.69	0.0214	4.71
Scenario 4	7.8	0.0228	8.46

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Experiments and results with FECSW scaled model

In order to perform the geothermal extraction experiments in the FECSW scaled model, the Φ20mmUPVC pipe was vertically installed at the bottom center of the Φ250mmUPVC pipe and two Φ3.5mmPE pipes were installed at the inlet and outlet positions.

The injection pipe is located in the upper part and the pumping pipe passes through the seal section from the bottom of the well and rises to the upper part.

In this situation, the sandy soil used as a formation material was filled with a certain thickness between the well and the outer wall and filled with all by compaction.

We conducted a FECSW scaled model experiment based on the experimental scenarios shown in Table 7 and analyzed the experimental results.

Table 7. Scenarios for FECSW scaled model experiments

	Condition	Experimental purpose
Scenario 1	Injection in upper part, abstraction in lower part, porous well	Evaluation of heat extraction efficiency by heat conduction and convection in the case of pumping under well
Scenario 2	Injection in the bottom, abstraction in the top, and porous wells	Evaluation of heat extraction efficiency by heat conduction and convection in case of pumping in upper part of well

Scenario 1

As the middle part of the well is sealed, the water injected into the upper part penetrates into the surrounding soil through the injection section and enters the well again through the pumping section and is discharged out. The soil material is sand and fully saturated.

The experimental time is 42,120s (0.4875d), the flux is 0.0384 m^3/d, and the average I/O temperature difference is 6.73°C.

Scenario 2

In scenario 2, only the injection and pumping positions of the circulating water are changed, and the other conditions are the same as in scenario 1. Thus, the circulating water is injected into the bottom of the well and permeates into the surrounding soil and moves back to the top and then leaves out.

The experimental time is 82,080s (0.95d), the flux is 0.0323 m^3/d and the average I/O temperature difference is 4.64°C.

The variation of the I/O temperature of the FECSW scaled model obtained during the experiments is shown in Fig. 7.

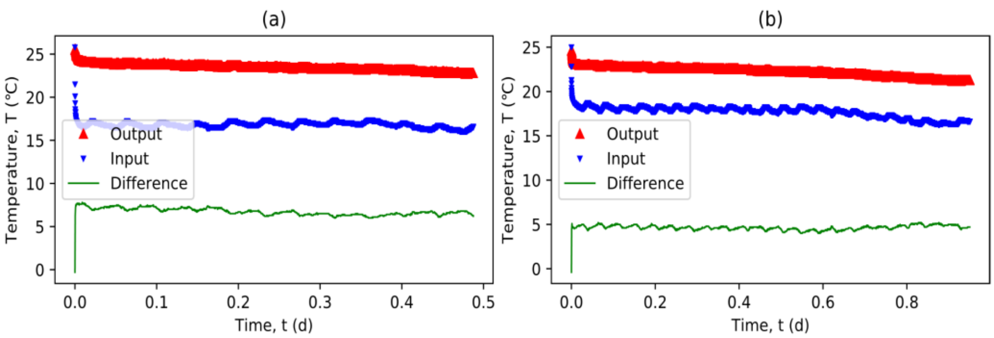

Fig. 7. I/O temperature variation in the FECSW scaled model.

(a) scenario 1, (b) scenario 2

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The results of the experiments on FECSWs were combined to analyze the heat extraction efficiency (Table 8).

Table 8. Analysis results of heat extraction efficiency for FECSW scenarios

	Average temperature difference, ℃	Average flux, m^3/d	Thermal Extraction Capability, W
Scenario 1	6.73	0.0384	12.57
Scenario 2	4.64	0.0323	7.33

CONCLUSIONS

In the U-tube mode, the heat extraction capacity is high in scenarios 2 and 1, and relatively low in scenarios 4 and 3. In scenarios 2 and 1, the use of saturated sand as the formation material and the wells filled with water or fine sand in the borehole were made of porous tubes, so the heat transfer inside the borehole was extended to the ground area, resulting in increased heat extraction capacity. However, in scenarios 4 and 3, non-porous wells were used, and the heat extraction capacity was not high as a result of insufficient heat exchange with surrounding soil. Therefore, it is reasonable to use porous casing or gravel-filled materials because there is no possibility of groundwater contamination in the case of water without antifreeze in the U-tube mode.

The order of magnitude of heat extraction capacity in SCW is scenario 4> scenario 2> scenario 1> scenario 3. Scenario 4 has a high heat extraction capacity compared to scenarios 1, 2 and 3 using non-porous pipes because of the inclusion of saturated sand and porous pipe. This shows that the effect of convection is much greater than heat conduction from the viewpoint of heat extraction. The heat extraction of scenario 4 was about 1.27 times higher than that of scenario 2 in U-tube mode using closed U-tube under similar conditions. This indicates that should increase the convective heat exchange with the circulating water and surrounding ground as much as possible to increase the geothermal extract.

In FECSW, scenario 1 has about 1.7 times higher heat extraction capacity compared to scenario 2. The reason is that the low temperature water is injected in the upper part of scenario 1, so convection is caused by temperature difference in the soil, but convection does not occur in scenario 2 because the low temperature water is injected into the lower part. Therefore, it is considered effective to generate convection by injecting the top of the borehole during heating and injecting it into the bottom of the borehole during cooling.

The results of the scaled model experiments can be applied in practice to select the well structure and operating mode to achieve high heat extraction efficiency.

AUTHOR CONTRIBUTIONS

Tok Gi Choe: Writing-original draft, Conceptualization, Methodology; Jong Su Kim: Investigation, Validation; Dong Guk Kim: Software, Il Jin Ko: Visualization, Review & Edition

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Data Availability

The data that has been used is confidential.

Conflict of Interest

The authors declare that they have no conflict of interest.

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