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Parametric Study for Evaluation of Design Parameters of Standing Column Well

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ABSTRACT

While the standing column wells are widely used in practice for its efficiency, the design parameters of the wells are difficult to select. In order to determine the design parameters of standing column well in Korea, parametric study was performed using a numerical model. The properties representative of Korea, including geothermal gradient, hydraulic conductivity, and thermal conductivity were selected and applied in the analyses. The results show that the numerical model can be successfully used in selection process of important design parameters.

1. INTRODUCTION

The ground heat source heat pump system have become popular in Korea as a “green” energy source for heating / cooling of residential and office buildings. Vertical closed-loop heat exchanger is the most widely used geothermal heat pump system, whereas standing column well (SCW) is being newly introduced and applied in Korea.

SCW pumps water from the bottom of a borehole and returns it to the same well after heat extraction and/or rejection. The pumping induces radial groundwater flow into and out of the well, as well as flow within the borehole. The heat is transferred in complex mechanisms involving convection, advection, and conduction. SCW is known to be more efficient than a closed-loop pump since the groundwater is used directly for heat transfer. However, the complex hydro-thermal coupled behavior of the SCW makes it difficult to accurately predict the performance of a SCW. For a wider application of the SCW in Korea, it is important to understand the influence of various parameters on the performance of a SCW and to develop a design guideline considering the local site conditions.

This paper performed parametric study to evaluate the influence of selected parameters using a 2D numerical model. The effects of each variable were discussed and compared in the following.

2. NUMERICAL MODEL OF SCW

Various numerical models have been developed and studied in the past (Braud et al., 1983; Deng, 2004; Mikler, 1993; Oliver and Braud, 1981; Yuill and Mikler, 1995). Deng (2004) developed two-dimensional (2D) hydro-thermal coupled model to simulate the heat transfer within the standing well. It was shown that the numerical model can accurately model the temperature changes within the well. In addition, one-dimensional model was developed to increase the numerical effectiveness. It was demonstrated that the simplified model was also quite accurate for selected case studies.

The development of a new numerical model can be very useful. Rees et al. (2004) performed a comprehensive parametric study using a numerical SCW model and evaluated the design parameters of the SCW. However, development of a numerical code requires extensive amount of time and expertise. Instead of developing a dedicated software for modeling the SCW in Korea, this paper used a commercial finite-volume analysis code to numerically simulate the SCW and to perform the parametric study.

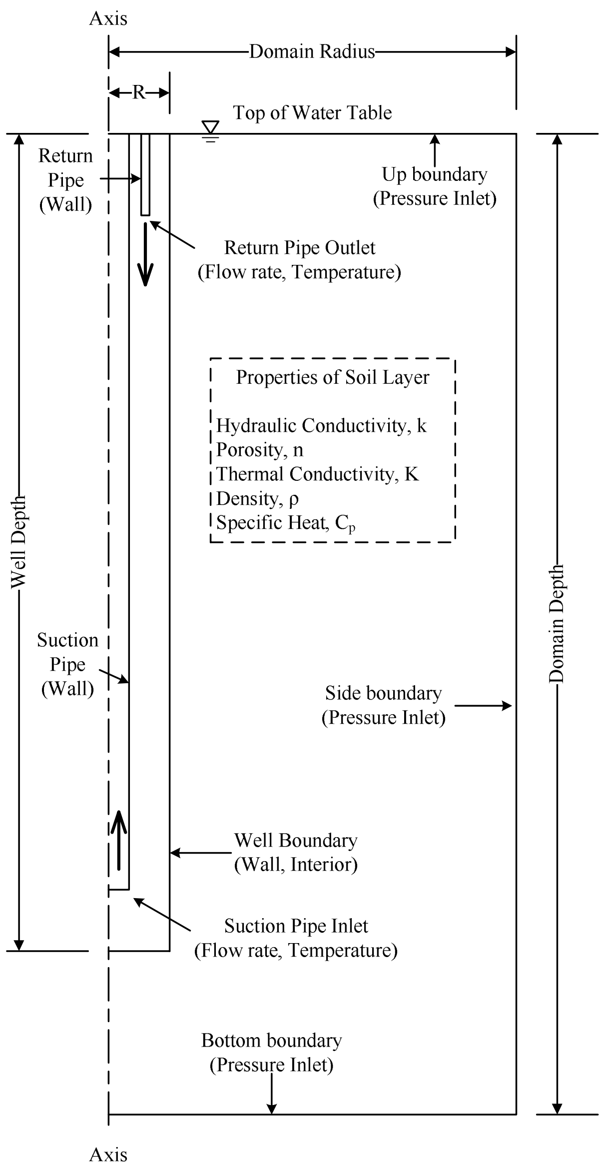

Figure 1: Material properties and boundary conditions used to model a SCW system.

The program used in this study was FLUENT (Fluent Inc., 2006), which is a commercial computer program for modeling fluid flow and heat transfer. FLUENT uses the finite-volume method to solve the governing equations for the fluid flow and heat transfer.

The material and boundary conditions used in the SCW model are shown in Figure 1. It is possible to perform three-dimensional (3D) analysis with FLUENT. However, 2D axi-symmetric analysis was performed to reduce the computational cost. 3D analysis is planned to evaluate the effect of the spacing of the SCW. The flow in the SCW and the ground is initiated by prescribing a flow rate to the suction pipe inlet and discharge pipe outlet.

The borehole, located at the center of the numerical domain, is composed of the well boundary, suction pipe inlet, discharge pipe outlet, suction and discharge pipes. The ground is modeled as a porous medium. The lateral, upper, and lower boundaries of the ground were set to pressure inlet boundaries, at which the total heads were set to zero. Constant temperatures were applied at the boundaries. Input properties for the ground included hydraulic conductivity, thermal conductivity, density, and specific heat. In addition to the properties of the ground, the thermal properties of the pipes were specified. The accuracy of the numerical model of the SCW was thoroughly validated through actual measurements. More details on the numerical model is discussed in the companion paper (Park et al., 2009).

3. PARAMETRIC STUDY

In this paper, a parametric study was performed to evaluate the effect of various parameters on the performance of the SCW system in Korea using the numerical model described in the previous section. The base case of the parametric study was slightly modified from a SCW installed at Euryeong Sports Complex, Korea. The dimensions of the borehole, suction and discharge pipes, and the numerical domain, and the mesh are shown in Figure 2. The input properties for the base case are summarized in Table 1. The domain radius and depth were set to 160 m and 350 m. The depth of the ground below the bottom of the borehole was 50 m, which was the minimum depth recommended to model water flow and thermal conduction in the aquifer without being influenced by the boundary (Deng, 2004). The suction and discharge pipes were made of HDPE. The density, specific heat, wall thickness, and thermal conductivity of the pipes selected in this study were 952 kg/m^3, 1670 J/kg-°C, 5.5mm, 0.22 W/m-°C, respectively. The density of soil layer was assumed to be 2700 kg/m^3.

In the numerical simulation, the water that is returned to the well was used as the input. The resulting change in the temperature of the borehole was simulated and the calculated water temperature pumped from the well is compared with the measured data. The SCW was numerically operated for one day, and the difference between the input (water returned to the well) and output (water pumped from the well) temperatures were compared. To compare of the degree of influence of each parameter, the temperature of the input was set constant throughout the duration of the numerical simulation to 30°C for summer season (cooling mode) and 5°C for the winter season (heating mode). It is of course not realistic that the temperature of the water returned to the well is constant, but it was considered appropriate for the purpose of this study.

A short time increment can improve the accuracy of the analysis, but at the cost of the increased computational cost. In order to determine the optimum time increment for the parametric study, a sensitive analysis was performed. Figure 3 shows the calculated temperatures in the borehole for 1, 6, 12, 24, 48 sec time increments, respectively. The calculated peak temperatures for 48 sec and 24 sec time steps show significant discrepancy compared to the 1 sec interval. Comparisons show that using 12 sec time increment is acceptable and the discrepancy between 1 sec time step result is within tolerable level. In the parametric study, 12 sec time increment was used.

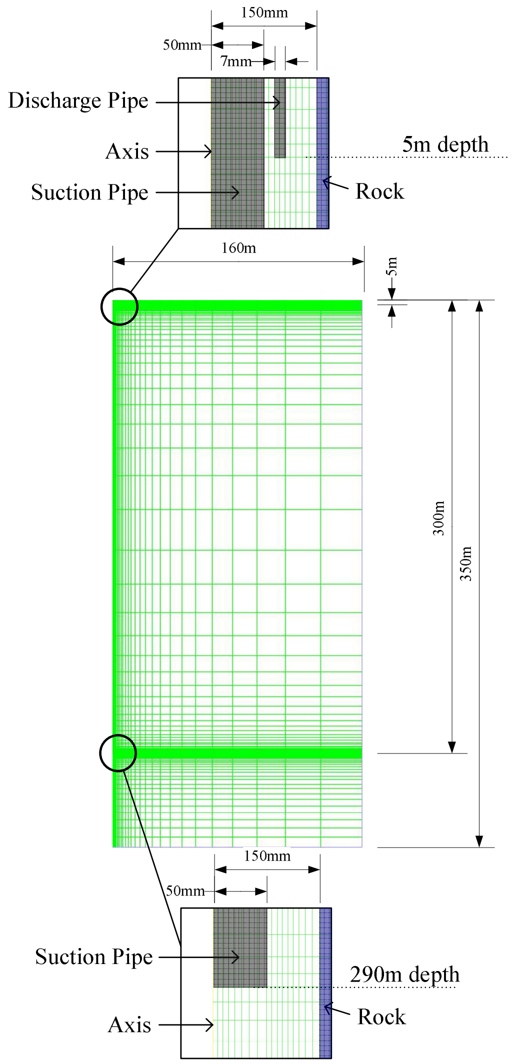

Figure 2: Mesh and numerical dimension of the base case of the parametric study.

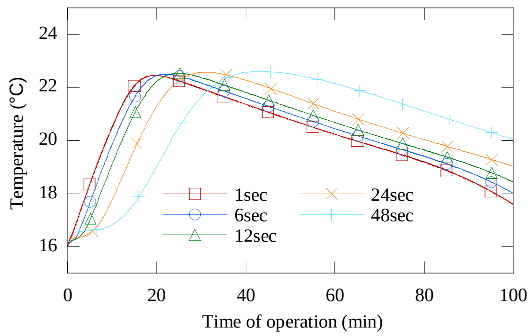

Figure 3: Sensitivity analysis to determine the optimum time step.

Table 1: Property values used in the parametric study.

Parameter	Units	Case					
		Base case	1	2	3	4	5
Porosity	-	0.1	0.025	0.2	0.275		
Hydraulic conductivity	$\times 10^{-5}$ m/sec	1	0.5	5	10		
Thermal conductivity	W/m-°C	3	1.5	4.5	6		
Specific heat capacity	J/kg-°C	800	600	1200			
Geothermal gradient	°C/m	16 + 0.025×depth	16 + 0.015×depth	16 + 0.035×depth			
Flow rate	kg/sec	3	1.5	4.5			
Borehole depth	m	300	200	250	350	400	
Borehole diameter	mm	300	200	250	350	400	
Suction pipe diameter	mm	100	60	140			
Bleeding rate	%	0	1	5	10	20	30

3.1 Variables for Parametric Study

The variables for the parametric study can be classified into two groups, which are a) site dependent variables and b) design variables. A total of five site dependent variables were included in this study, which were the porosity, rock hydraulic conductivity, rock thermal conductivity, rock specific heat capacity, and geothermal gradient. The ranges of the hydraulic and thermal properties of the rock were based on the data of Choi (2004), Deng (2004), Hellstrom (1991), Kwon et al. (2006), and Shin and Kim (1993). Design variables are parameters that the designer of the SCW needs to select considering local geological/hydrological conditions and engineering judgment. A total of five variables were used, which were flow rate, borehole depth, borehole diameter, suction pipe diameter, and bleeding rate. As with the site dependent variables, the variables were varied from the base case.

Table 1 summarizes the cases performed in the parametric study. In each case, only one parameter is changed from the base case. The only exception was the bleeding rate. To clearly demonstrate the effect of the bleeding, the hydraulic conductivity of the ground was increased five times to 5×10^{-5} m/sec.

3.2 Results of Parametric Study

The results of each case in the parametric study are shown in Figure 4 ~ Figure 13. The results are shown in terms of the absolute temperature difference between input temperature (water returned to the well) and calculated temperature (water pumped from the well). If the absolute temperature difference increases, it means that the performance and the effective of the SCW are increasing. The calculated absolute output temperature difference of the base case was 1.98°C for the cooling mode and 3.30°C for the heating mode.

3.2.1 Site Dependent Variables

The site dependent variables considered in this study are porosity, hydraulic conductivity, thermal conductivity, specific heat capacity, and geothermal gradient. The porosity (Figure 4) and specific heat capacity (Figure 5) have negligible influence on the performance of the SCW. Hydraulic conductivity has the most critical influence on the performance, as shown in Figure 6. It is estimated that as the hydraulic conductivity increases, the heat transfer through both advection and convection increases. Another important variable is the thermal conductivity. Increasing thermal conductivity results in enhanced performance. However, the relationship between thermal conductivity and performance is nonlinear. The effect on the temperature difference decreases at thermal conductivities higher than 4.5 W/m-°C, as shown in Figure 7. Figure 8 shows the influence of the geothermal gradient on the SCW system. The temperature difference becomes higher with increasing the geothermal gradient in the heating mode, but shows opposite trend in the cooling mode. It indicates that when the geothermal gradient increases, the temperature at the bottom of the well increases accordingly, causing the water pumped at the bottom to be higher.

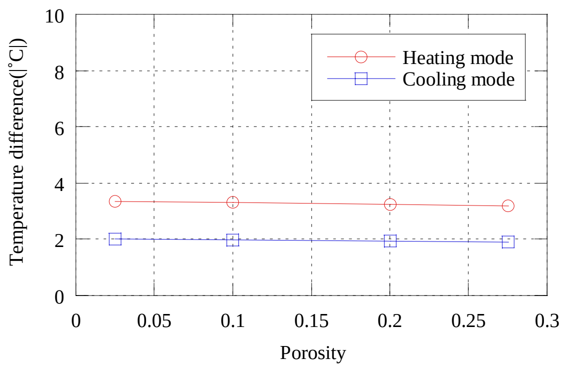

Figure 4: Temperature difference after 1 day operation due to the variation in the porosity of the rock.

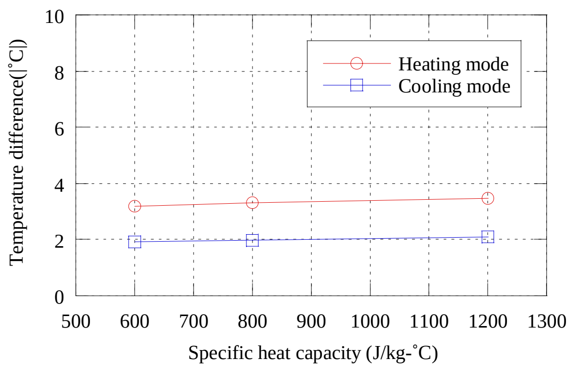

Figure 5: Temperature difference after 1 day operation due to the variation in the specific heat capacity of the rock.

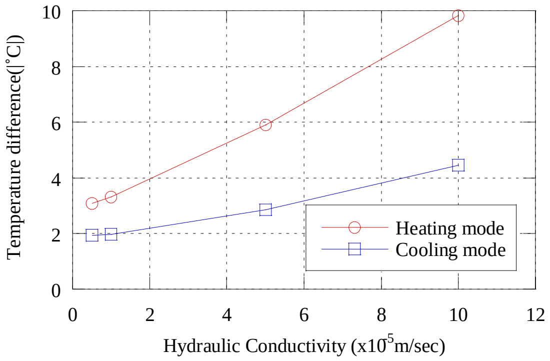

Figure 6: Temperature difference after 1 day operation due to the variation in the hydraulic conductivity of the rock.

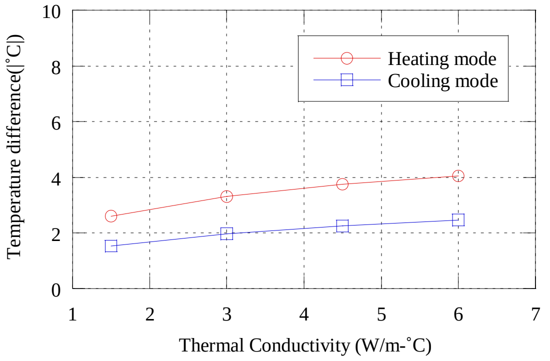

Figure 7: Temperature difference after 1 day operation due to the variation in the thermal conductivity of the rock.

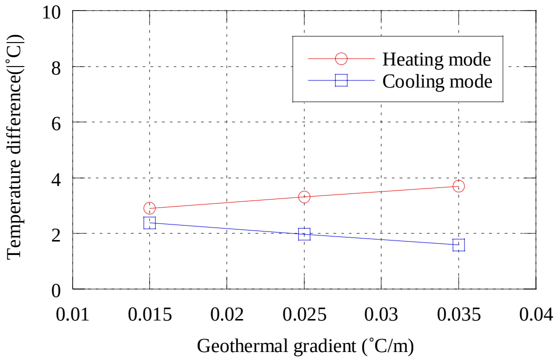

Figure 8: Temperature difference after 1 day operation due to the variation in the geothermal gradient.

3.2.2 Design Parameters

The SCW system has only a few design parameters, which are the flow rate of the system, borehole depth and diameter, pipe diameter, and bleeding rate. Effects of all design parameters were studied in this paper.

Figure 9 shows that decreasing the flow rate increased the efficiency of the SCW system in both the cooling and heating modes. As the flow rate decreases, the water velocity in the borehole becomes slower, and therefore has more time to transfer heat with the borehole wall. If the flow rate increases, the input water from the heat pump is mixed quickly within the borehole, the time for heat transfer is reduced. The simulation demonstrates that the flow rate in the SCW system is important and that it has to be determined considering the efficiency of the SCW and the demand of the building.

The borehole depth also has an important effect on the performance of the SCW system. The effect of borehole depth is shown in Figure 10. Due to the geothermal gradient, the water temperature increases along with the depth of borehole. As the borehole depth increases, the total flow path becomes longer, thereby maximizing the heat transfer with the borehole wall. In addition, the higher temperature at deeper locations allows warmer water to be pumped into the suction inlet. Both mechanisms contribute to the enhanced performance of the SCW in the heating mode for higher borehole depths. In the case of cooling mode, the amount of performance enhancement is less than in the heating mode. The reason for the difference is that as the higher temperature of the water has negative effect on the performance of the heat pump in the cooling mode.

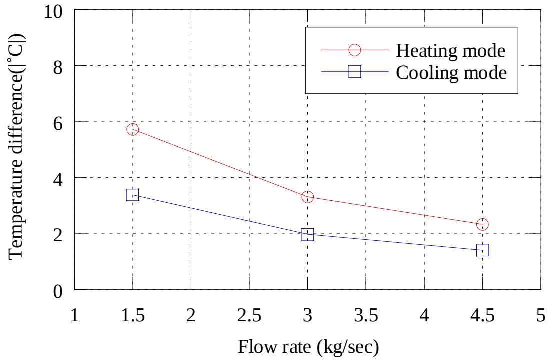

Figure 9: Temperature difference after 1 day operation due to the variation in the flow rate.

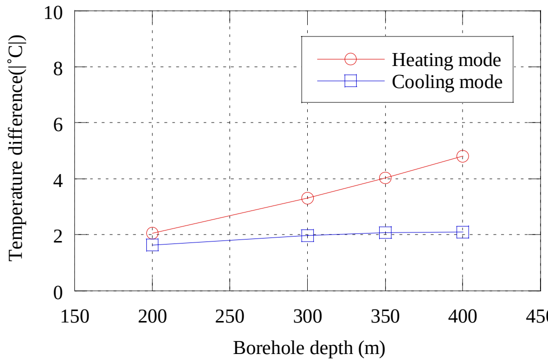

Figure 10: Temperature difference after 1 day operation due to the variation in the borehole depth.

The variation of borehole diameter and suction pipe diameter have limited influence on the performance, as shown in Figure 11 and Figure 12.

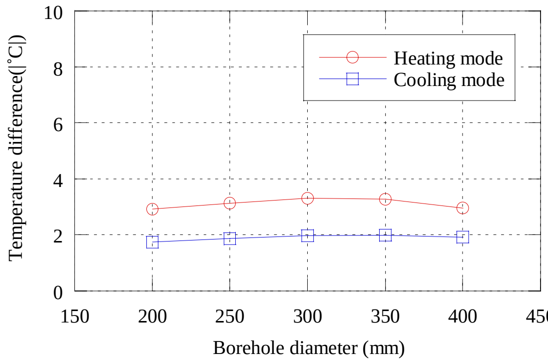

Figure 11: Temperature difference after 1 day operation due to the variation in the borehole diameter.

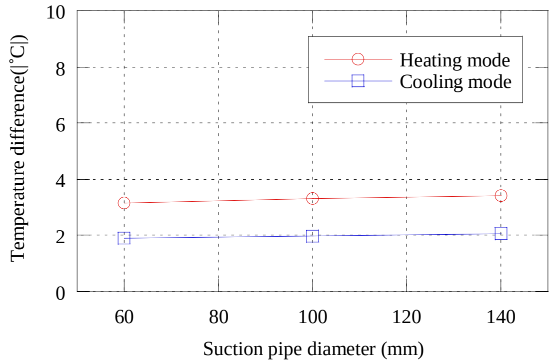

Figure 12: Temperature difference after 1 day operation due to the variation in the suction pipe diameter.

The effect of the bleeding rate is shown in Figure 13. The bleeding had a pronounced influence on the output temperature for both the heating and cooling modes. As the bleeding rate increased, the heat transfer between the ground and the input water increased, and hence improved the performance of the well. However, the effect of bleeding was influenced by the hydraulic conductivity of the ground. If the permeability of the ground was smaller, the influence of the bleed would have decreased accordingly.

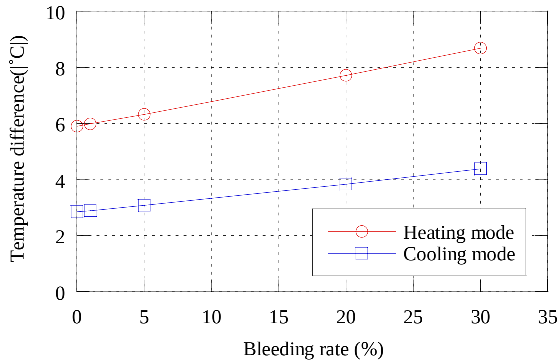

Figure 13: Temperature difference after 1 day operation due to the variation in the bleeding rate.

4. CONCLUSION

A parametric study was performed using a numerical model to evaluate the degree of influence of five site dependent variables and five design variables. The numerical simulation of the SCW was performed using a commercial finite-volume analysis software. The ground water flow and heat transfer were modeled through coupled hydro-thermal analysis. The base case of the parametric study was modified from a SCW installed at Euryeong, Korea. The properties of the borehole, pipes, and the rock of the base case were used as a reference, and the variables were varied to investigate the influence of each parameter. The SCW was numerically operated for a duration of one day, and the difference between the input (water returned to the well) and output (water pumped from the well) were compared for both cooling and heating modes.

The results of parametric study showed that among the site dependent variables, the hydraulic conductivity and thermal conductivity of the rock had the most important effect on the SCW system installed at Euryeong. The geothermal gradient also had non-negligible influence. Porosity and specific heat capacity had secondary influences on the performance of the SCW. Among the design variables, flow rate, borehole depth, and bleeding had important influence on the performance. The bleeding had the most critical influence on the performance, but only for the case in which the hydraulic conductivity is sufficient to allow abundant radial flow.

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