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# Numerical Simulation of Standing Column Well

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## ABSTRACT

Standing column well is widely used due to its efficiency. This paper describes the numerical modeling of a standing column well. The hydro-thermal coupled analyses were performed using a commercial finite-volume code, and heat transfer through advection, convection, and conduction were modeled. The numerical model results were compared with actual measurements to verify its accuracy. Comparisons demonstrate the close match between the simulated and measured temperatures of the well.

## 1. INTRODUCTION

The use of the ground source heat pump systems has steeply increased in Korea, owing greatly to wide public awareness for global warming and "green technology." Geothermal heat exchanger is one of the most popular "green" technologies that are being used for heating / cooling of residential and office buildings in Korea. Among various types of geothermal heat pumps, the vertical closed-loop heat exchanger (U-loop) is by far the most popular type of geothermal heat pump system. Considerable research is being funded, mostly by the Korean government, to better understand the heat transfer in a U-loop system, to develop more efficient grouting material that encases the pipes, and to develop design guidelines. Another type of geothermal heat exchanger used in Korea, although much smaller in quantity compared to the U-loop pump, is the standing column well (SCW). SCW uses the groundwater drawn from a vertical well and returns it to the same well after heat extraction and/or rejection. The mechanism of heat transfer is much more complex than a U-loop exchanger. The heat is exchanged with the water in the well, surrounding ground, and groundwater through advection, convection, and conduction (Figure 1).

SCW is known to be more efficient and hence, more economical than U-loop systems in regions of favorable geological and hydrological conditions. SCW can be costly for sites in which the depth of the bedrock is greater than 60 m, due to the substantial cost of casing. In Korea, the depth of the bedrock is mostly within 20 m, and therefore the cost of casing is not significant. In addition, abundant groundwater resource and relatively high ground water table depth (5 – 10 m), according to GiMS (National Groundwater Information Management and Service Center, http://www.gims.go.kr/), make Korea ideal for installing and operating the SCW.

Although the SCW has attracted wide attention as a more efficient alternative to the U-loop system, the actual application was limited in Korea. Possible reasons are the lack of a design guideline developed considering the geologic and hydrological conditions in Korea and poor understanding on the mechanism of heat transfer within the well and the surrounding ground. Currently, the design guidelines of New York, USA (Collins et al., 2002) are used without considerations of local conditions. For a wider and more successful application of the SCW, a design guideline based on extensive experience and monitoring is warranted. A numerical model can be used in case a local design guideline is not available or when a site specific estimate is needed. In Korea, however, a numerical model that simulates the SCW has not yet been developed or applied in practice or for research.

This paper used a finite-volume method based software to perform hydro-thermal coupled analysis and to simulate the flow within the borehole and the surrounding ground, and heat exchange within the SCW. The results of the numerical model were compared with measured data in Korea for validation.

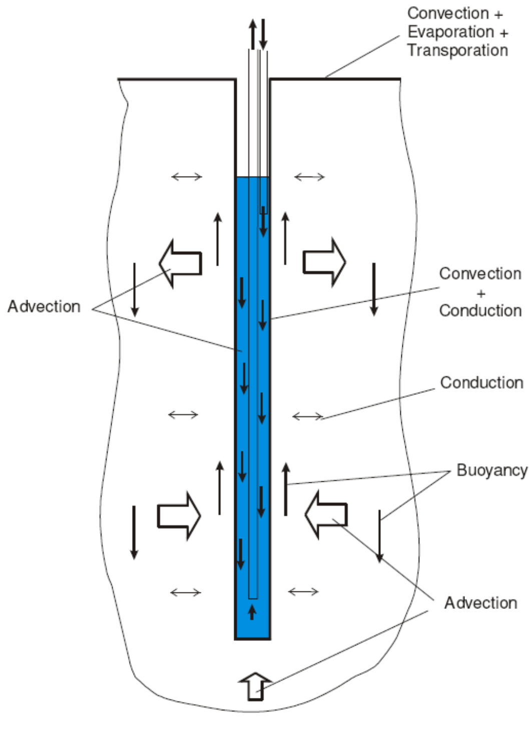


**Figure 1: Heat transfer mechanisms in a SCW (Deng, 2004).**

## 2. NUMERICAL MODELING OF SCW

Various numerical models of SCW have been developed in the past (Braud et al., 1983; Deng, 2004; Mikler, 1993; Oliver and Braud, 1981; Yuill and Mikler, 1995). Deng (2004) and Rees et al. (2004) developed a two-dimensional (2D) hydro-thermal coupled model to simulate the flow and heat transfer within the SCW. Figure 2 shows the schematic representation of the numerical model developed by Deng (2004) and Rees et al. (2004).

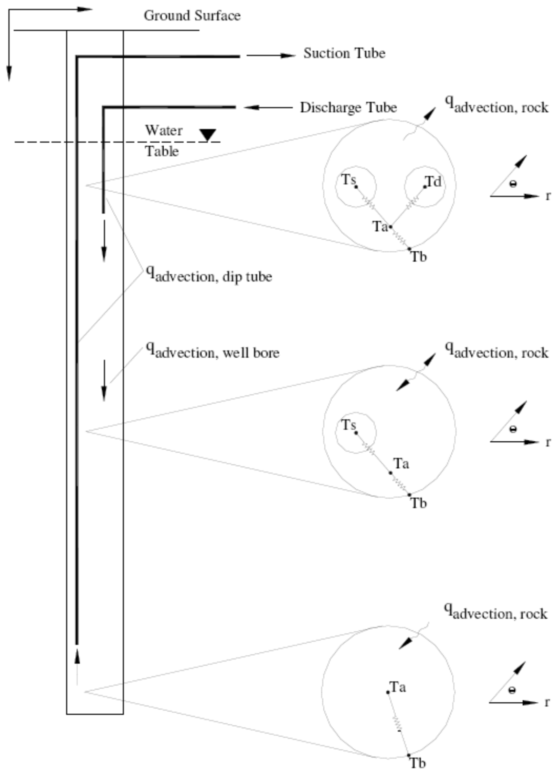


**Figure 2: Schematic drawing of numerical model of Deng (2004).**

The results of the numerical simulations were extensively compared to field measurements for validation. It was shown that the numerical model can accurately simulate the field performance of the SCW.

Deng (2004) also developed a simplified 1D model that is computationally less expensive. In the 1D model, it was assumed that the vertical flow and heat transfer within the well is negligible due to relatively small diameter compared to the length of the well, and only the flow and heat transfer in the radial direction was modeled. The average radial groundwater flow into the well was assumed to be solely determined by the amount of bleed. It was shown that the 1D model was very effective, and was able to reproduce the results of the 2D model for the cases selected.

The main disadvantage of the numerical models by Deng (2004) is that since the program is not a share-ware, its use is not open to engineers in Korea. Other shortcomings are that it cannot be used for layered profiles and since a 2D axi-symmetric model is used for the ground, it cannot be extended to 3D simulations which are needed for evaluation of the performance of multiple SCWs.

This paper used FLUENT (Fluent Inc., 2006), which is a commercial computer program for modeling fluid flow and heat transfer in complex geometries, for the numerical simulation of the SCW. It uses the finite-volume method to solve the governing equations for a fluid. The governing equations that is solved in FLUENT is described in the following.

### 2.1 Fluid Flow and Heat Transfer Model

FLUENT uses conservation equations for mass and momentum for flow model. The general form of mass conservation equation is the following:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \vec{v} \right) = S_m \tag{1}$$

where $\rho$, $t$, $v$, $S_m$ are density, time, velocity, and the mass source added to the continuous phase. The momentum conservation equation is the following:

$$\frac{\partial}{\partial t}\left( \rho \vec{v} \right) + \nabla \cdot \left( \rho \vec{v}\vec{v} \right) = -\nabla p + \nabla \cdot \left( \overline{\overline{\tau}} \right) + \rho \vec{g} + \vec{F} \tag{2}$$

where $p$, $\overline{\overline{\tau}}$, $\rho \vec{g}$, $\vec{F}$ are the static pressure, the stress tensor, the gravitational body force, and external body forces, respectively.

The energy transport equation used in FLUENT for porous media is the following:

$$\frac{\partial}{\partial t}\left( n\rho_f E_f + (1-n)\rho_s E_s \right) + \nabla \cdot \left( \vec{v}(\rho_f E_f + p) \right) = \nabla \cdot \left[ k_{eff} \nabla T - \left( \sum_i h_i J_i \right) + \left( \overline{\overline{\tau}} \cdot \vec{v} \right) \right] + S_f^h \tag{3}$$

where $n$, $E_f$, $E_s$, $\rho_f$, $\rho_s$, $k_{eff}$, $T$, $h$, $J$, $S_f^h$ are porosity of the medium, total fluid energy, total solid medium energy, density of fluid, density of solid, effective thermal conductivity, temperature, sensible enthalpy, diffusion flux, and fluid enthalpy source term, respectively. The first three terms on the right hand side represent energy transfer due to conduction, species diffusion, and viscous dissipation. The effective thermal conductivity is defined as:

$$k_{eff} = nk_f + \left(1-n\right)k_s \tag{4}$$

where $k_f$, $k_s$ are thermal conductivity of water, and thermal conductivity of soil, respectively.

### 2.2 Material and Boundary Conditions

The material and boundary conditions used in the SCW model are shown in Figure 3. 2D axi-symmetric analysis is performed in modeling of the SCW. The SCW model was composed of two regions: the borehole and the surrounding ground. The borehole, located at the center, is composed of the well boundary, suction pipe inlet, return pipe outlet, suction and return pipes. To perform the axi-symmetric analysis, the locations and shapes of the inlet and outlet pipes had to be changed. Figure 4a shows the actual layout of the borehole, while Figure 4b represents the equivalent layout used in the actual numerical simulation. The main difference between the original and the modified layout was the shape and location of the discharge pipe. Although the shape of the discharge pipe was altered, however, the total areas were kept identical. The ground was modeled as a porous medium. The water table was set to be at the upper boundary of the domain.

The lateral, top, and bottom boundaries of the ground were set to pressure inlet boundaries, at which the total heads were set to constant zero. Constant temperatures were applied at the boundaries, following a pre-defined geothermal gradient. All elements of the model were initialized to the temperatures of the site specific geothermal gradient and zero total head before performing the analysis.

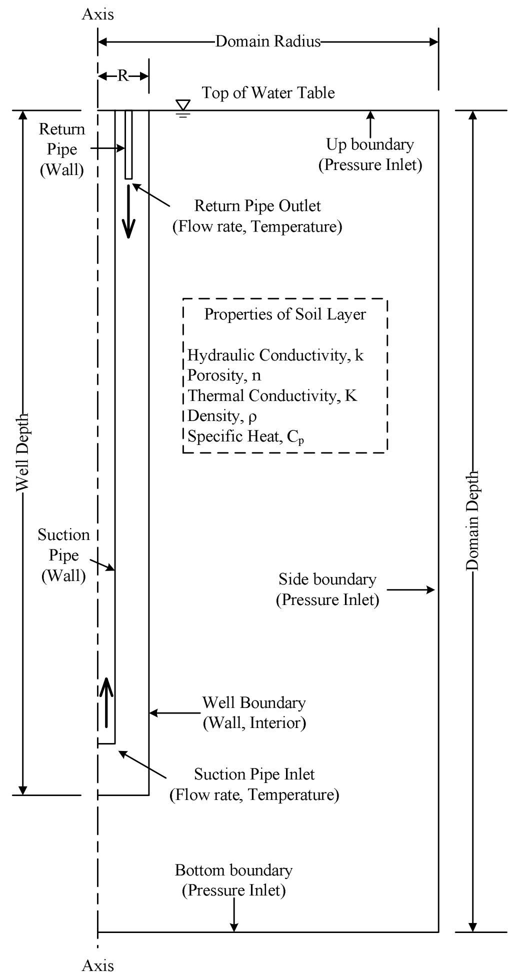


**Figure 3: Material properties and boundary conditions defined in the numerical SCW model.**

Input properties for the ground include hydraulic conductivity, thermal conductivity, density, and specific heat. If the ground is not uniform, variable profile can be specified. In addition to the properties of the ground, the thermal properties of the pipes were specified.

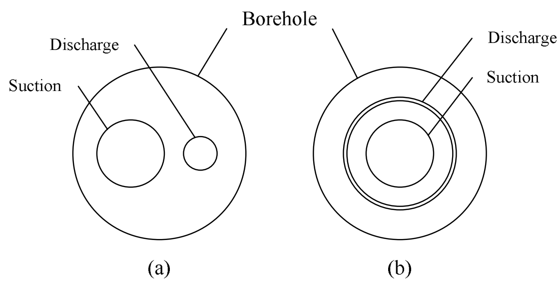


**Figure 4: Borehole model (a) actual shape, (b) equivalent shape used in the axi-symmetric model.**

The flow in the borehole and the ground can be activated by defining the flow rates of the suction pipe and return pipe. If bleeding is used, the flow rate of the return pipe will be smaller than that of the suction pipe. Otherwise, flow rates will be identical. Water was pumped from the suction inlet, and returned through the discharge pipe. The pumping induces flow in the borehole and also in the ground. Since the water is commonly pumped from the bottom and returned at the top of the well, the groundwater is pumped into the borehole in the radial direction at the bottom half of the hole, while the ground water is pumped out at the upper half of the borehole. There exists a location within the borehole at which there is no radial flow.

## 3. VALIDATION OF NUMERICAL MODEL

The numerical model was validated using the measured data obtained from the SCWs installed at Euryeong Sports Complex, located in the inland area of Korea (Figure 5). At the site, both the temperatures of the water returned to the well and the water pumped from the well were measured.

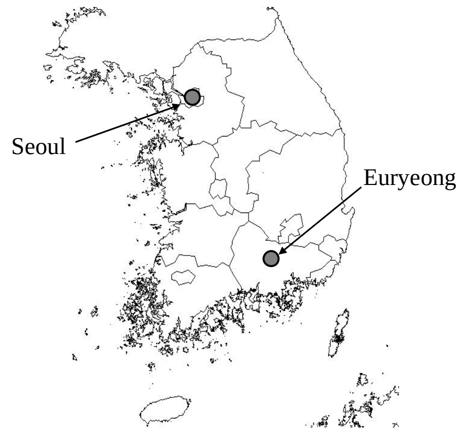


**Figure 5: Location of Euryeong, Korea.**

A schematic drawing of the borehole and the surrounding ground of the Euryeong SCW is shown in Figure 6. The total depth of the borehole was 350 m, while the depth of the casing was 20 m and embedded into the rock. The water table was approximately 18 m below the ground surface. The ground water suction pipe inlet was installed 45 m below the ground surface.

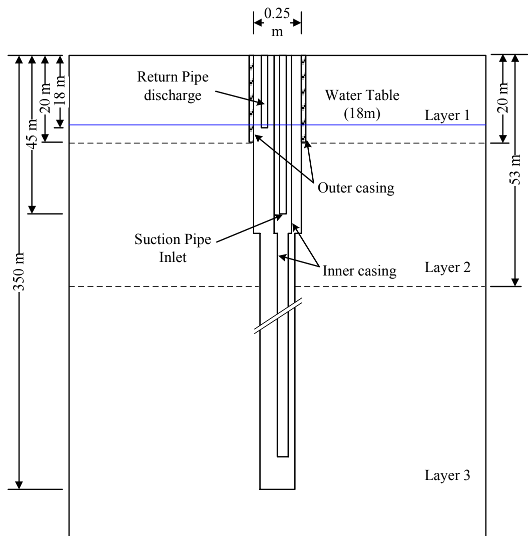


**Figure 6: SCW system applied to Euryeong Sports Complex, Korea.**

The SCW system of Euryeong Sports Complex was usually operated between 20:00 ~ 9:00 during the winter season and between 9:00 ~ 22:00 during the summer season. The SCW was not continuously operated, but in irregular and discrete intervals. Among the database of the recordings, the longest continuous operating periods were selected for the input data for both the cooling and heating modes, as shown in Figure 7. Measured data from 9:00 a.m. to 10:00 p.m. on June 5, 2008 was used for the simulation of the cooling mode, while the data from 11:00 p.m. to 9:00 a.m. on November 4 - 5, 2008 were used for the analysis of the heating mode. The temperature of the pumped water increases during the cooling mode, since the heat is rejected in the heat pump and warmer water is returned to the well. On the contrary, the temperature of the water continuously decreases in the borehole during the heating mode, since the heat is extracted and cooler water is returned to the well.

It should be noted that for accurate validation, the results of the numerical simulation should be compared with the initial measurements before the operation of the SCW, since the temperature distribution within the borehole and surrounding ground is influenced by past operation. However, since the initial measurements were not available, the recordings during the operation had to be used. It was assumed that the in the temperature of the surrounding ground is fully recovered during the non-operation interval. It would also have been ideal if the temperature of the water were measured in the pipe inlet and outlet. However, the temperatures of the water were measured in the mechanical room. The measured data were subject to some amount of distortion, for example by the air temperature. In the analyses, it was assumed that the measured temperatures are directly from the inlet and outlet.

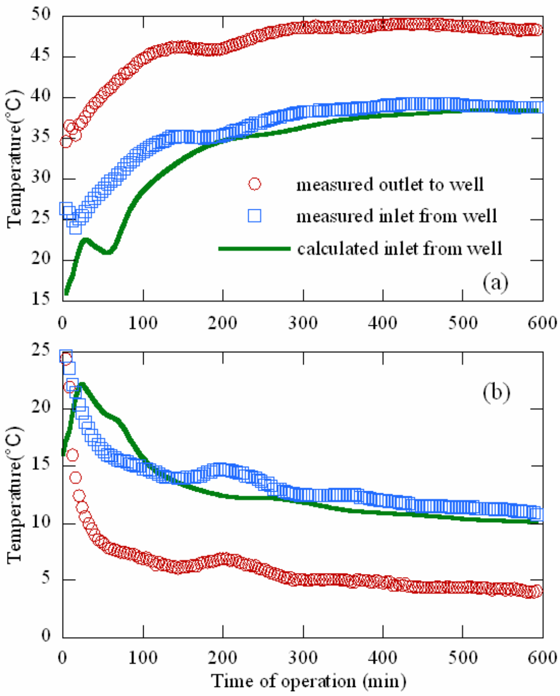


**Figure 7: Measured outlet to well and inlet from well temperature data from Euryeong Sports Complex and calculated temperature data at (a) cooling mode and (b) heating mode.**

The average flow rate of the ground water circulation pump was estimated to be 100 ~ 250 *l*/min. Since there exists a filter on circulation pipe, which reduces the amount of water flow, it was assumed that the flow rate was constant at 2 kg/sec.

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 temperature of the water pumped from the well was compared with the measured data.

Figure 8 shows the mesh and elements used to the model of the SCW system. A total of 10478 quadrilateral elements were used in the numerical simulation. Very dense mesh was used for the borehole and even finer mesh was applied at the vicinities of the pipe inlet and outlet.

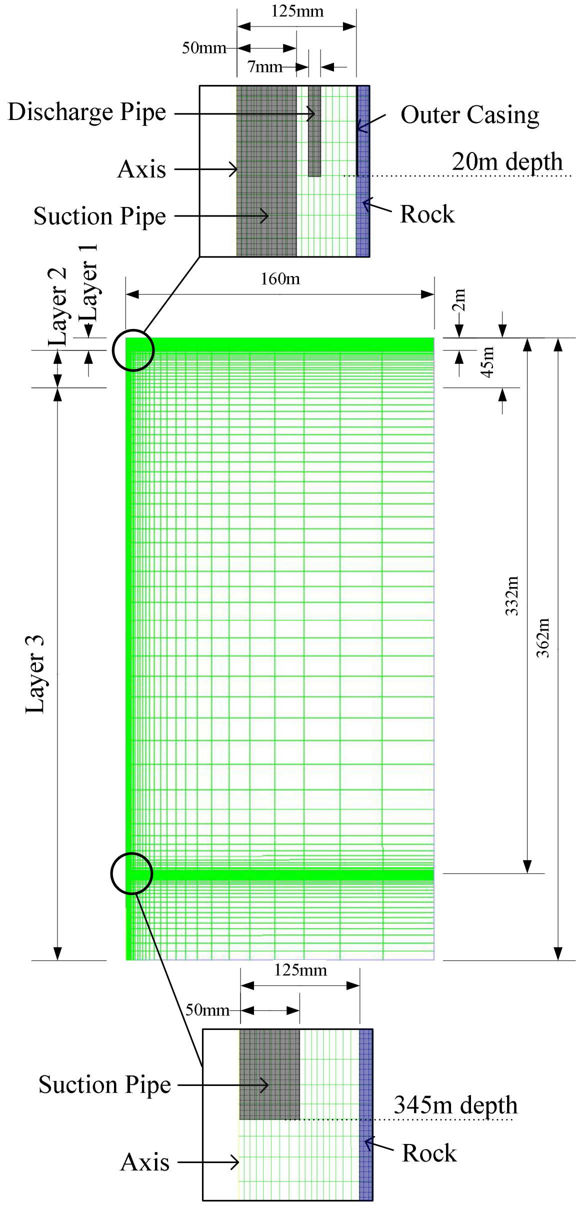


**Figure 8: Mesh of the numerical domain.**

The numerical model only simulated ground and borehole below the ground water table. Hence, the height of the numerical domain was 362 m, and the depth of the borehole was 332 m. The length of the outer casing was 2 m. The suction pipe tip was positioned 5 m above the bottom of the borehole. The radius of the domain was 160 m. The dimensions of the borehole and the pipes are also summarized in Table 1. The radii of the suction and discharge pipes were 100 and 60 mm, respectively. The shape of the discharge pipe had to be changed to perform the axi-symmetric analysis, as shown in Figure 4. The thickness of the transformed pipe was 7 mm. PE pipes were used for both suction and discharge. The thermal conductivity selected for PE is also listed in Table 1.

Due to absence of the accurately measured in-situ properties of the rock, various parameters were assumed based on available information. The hydraulic and thermal properties of the rock used in the analysis are listed in Table 2.

**Table 1: Properties of the borehole and pipes.**

| | Borehole | Discharge Pipe | Suction Pipe |
|---|---|---|---|
| Depth | 350 m | 2 m | 345 m |
| Diameter | 250 mm | 60 mm | 100 mm |
| Wall Thickness | - | 5.5 mm | 5.5 mm |
| Thermal Conductivity | - | 0.22 W/m-K | 0.22 W/m-K |

**Table 2: Hydraulic and thermal properties of the rock layers.**

| Hydraulic Properties | | |
|---|---|---|
| Hydraulic Conductivity (m/s) | $3.52\times10^{-7}$ | |
| Porosity | 0.0525 | |
| Thermal Properties | | |
| Thermal Conductivity (W/m-K) | Layer 1 | 2.5 |
| | Layer 2 | 3.5 |
| | Layer 3 | 5.5 |
| Geothermal Gradient | T(°C) = 16.0+0.0225×depth(m) | |
| Density | 2700 kg/m3 | |
| Specific Heat | 1000 J/kg-K | |

The rock below the depth of 20 m was mostly shale. The hydraulic conductivity of the shale measured from a pumping test performed after boring up to 70 m was used in the analysis. It was assumed that the hydraulic conductivity was constant below a depth of 70 m. The geothermal gradient data measured at a distance of 800 m from the site were obtained from Song (2004) and GiMS (National Groundwater Information Management and Service Center, http://www.gims.go.kr/). Specific heat, thermal conductivity, and porosity were selected based on the data of Hellstrom (1991) and Shin and Kim (1993).

Comparisons between the measured and calculated water temperatures entering the heat pump for a duration of 600 minutes are shown in Figure 7 for both the cooling and heating modes. Even though the predictions were made based on limited input data, the numerical simulations showed reasonable match with the measurements.

At the end of the simulation, the discrepancy between the measured and the calculated temperatures was approximately 1°C for both cooling and heating mode. The air temperature in the mechanical room, variable flow rate, and uncertainties in the hydro and thermal properties of the ground are estimated to have contributed to the difference. The example shows that if site specific data were available, the prediction would have improved.

In addition to short time operation, additional heating mode simulation is performed for a duration of 3 days and 8 hours. The results are shown in Figure 9. The blanks between the measurements represents periods during which the pump is not operated. During the non-operational period, the heat in the borehole and surrounding ground is recovered. Since the temperature of the water within the borehole is not measured during the non-operational period, the rate of heat recovery could not be estimated. However, the amount of the heat recovery could be estimated based on the temperature at the onset of the subsequent operation. Figure 9 shows that the numerical model can reasonably estimate the variation of the temperature during the heating period, but also the amount of heat recovery during non-operational period. The advective heat transfer is expected to be very small when the pump is not in operation and it can be inferred that the heat recovery is mostly due to convective and conductive heat transfers. Considering that the convective and conductive heat transfer is governed by the thermal conductivities of the ground, it can be concluded that the values of the thermal conductivities were appropriately selected.

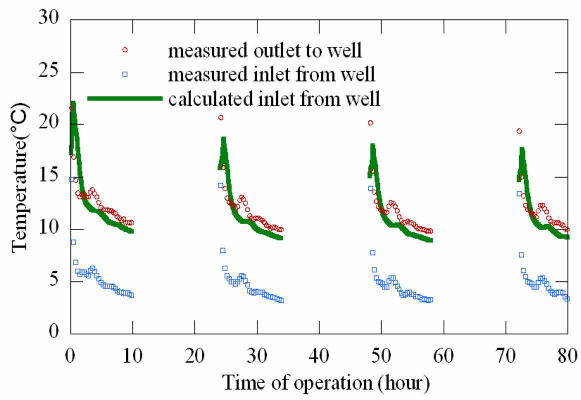


**Figure 9: Comparison of measured and computed water temperature within the borehole at Euryeong Sports Complex for a duration of 80 hours.**

Figure 9 displays that even if the heat is not fully recovered during the period of no operation, and there is a continuous drop in the temperature of the water within the borehole. The numerical simulation can successfully predict the long-term change in the temperature of the ground and the water within the borehole.

The comparisons demonstrate that the numerical model can be confidently be used in the design to estimate the performance of the SCW.

## 4. CONCLUSION

The numerical simulation of the standing column well (SCW) is performed and validated through comparisons with field measurement. The field data was obtained from the SCW installed at Euryeong, Korea. In the numerical simulation, hydro-thermal coupled analysis was performed using FLUENT. The results of the analysis demonstrate that the numerical model can successfully predict the temperature variation in the borehole and the surrounding ground. The discrepancy of the calculated and measured temperatures were within 1.5°C. Considering the incomplete set of input properties, it was concluded that the numerical simulation can be used to predict the performance of the SCW.

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