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Numerical Analysis of Open-Loop and Closed-Loop Geothermal Heat Pump Systems

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ABSTRACT

A choice between a closed-loop and an open-loop geothermal heat pump (GHP) system is not simple. The closed-loop system is more reliable and requires less maintenance in the long-term operation. The open-loop system is more energy-efficient and simple. However, the initial costs of the closed-loop system are comparatively high and the open-loop system is practical only where there is an adequate supply of relatively clean groundwater. The performance and efficiency of the system depend on geologic conditions and cooling and heating loads besides the types of systems. In this study, three different types of systems (the vertical closed-loop system, two-well open-loop system, and standing column well system) are examined at various geologic conditions and cooling and heating loads. The performance of the three-types of systems is analyzed for a year operation simulation results.

1. INTRODUCTION

The GHP system that utilizes shallow geothermal energy resources for heating and cooling purposes has been popular in various parts of the world. Vertical closed-loop GHP systems are one of the most popular GHP systems. It tends to have the highest installation costs of the various geothermal heat pump systems because of borehole heat exchangers (BHEs). The open-loop systems are more energy-efficient and simple. However, they are practical only where there is an adequate supply of relatively clean groundwater. The standing column well (SCW) systems have both characteristics. In this study, three different types of systems (Figure 1) are examined at various geologic conditions and cooling and heating loads by numerical simulations using the TOUGH2-MP (Zhang et al., 2008). The performance (temperature of the production water) of the three-types of systems is analyzed for a year operation simulation results.

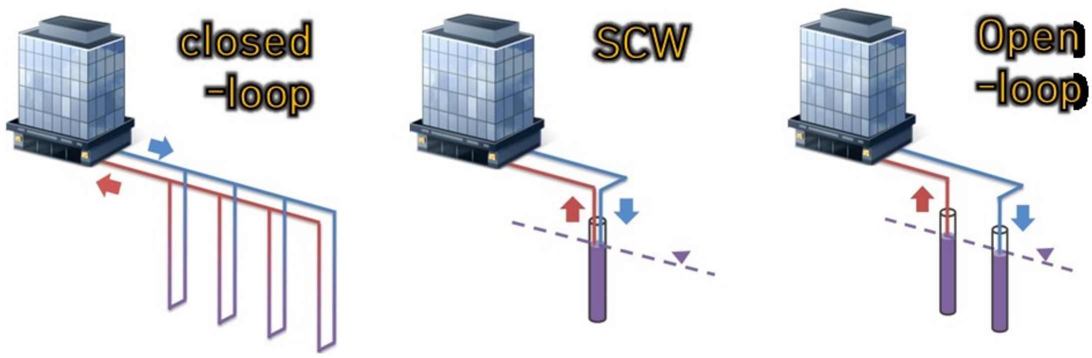

Figure 1: Three-types of GHP systems considered in this study.

2. METHODOLOGY AND MODEL SETUP

The GHP systems consist of heat pumps, fluid pumps and wells. To simulate it, the developed simulator is based on the TOUGH2-MP (Zhang et al., 2008). The TOUGH2-MP is a massively parallel version of the TOUGH2 code (Pruess et al, 1999), a widely accepted three-dimensional numerical simulator for heat and fluid flow in geothermal systems. The developed model is validated by comparing actual data sets with simulated results (Kim et al., 2008, Kim et al., 2010). TOUGH2 [12] and its descendants such as TOUGH2-MP are based on the integral finite-difference (IFD) method (Narasimhan and Witherspoon, 1976). Contrary to typical finite-difference methods, the IFD method has the advantage of irregular discretization in multiple dimensions. Spatial discretization is accomplished by developed mesh generating program. The program generates an IFD mesh and input files that are suitable for simulating the three-types of GHP systems in the modified TOUGH2-MP code. Figure 2 illustrates an IFD mesh used in simulations. Figure 3 shows operation pattern of systems. During a year, 1,000 W of heat is injected (extracted) to the ground in the cooling (heating) season. The GHP systems are operated during the office hours (12 hours) in a day. Material properties, boundary conditions and characteristic of wells are listed in Table 1.

3. RESULTS

The averaged temperature of the production water of each system during the cooling and heating season is analyzed to compare the performance of each system. The performance of three-types of GHP systems is almost same at the standard setting (thermal conductivity: 3 W/m-K, Hydraulic conductivity: 10^{-6} m/s). Simulation results are listed in Table 2.

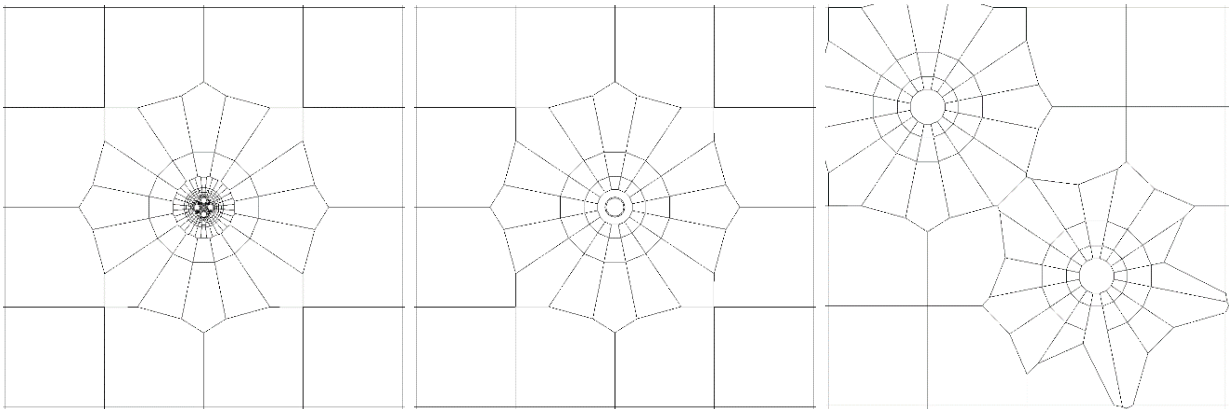

Figure 2: IFD mesh used in simulations: closed-loop (left), SCW (middle), and open-loop (right).

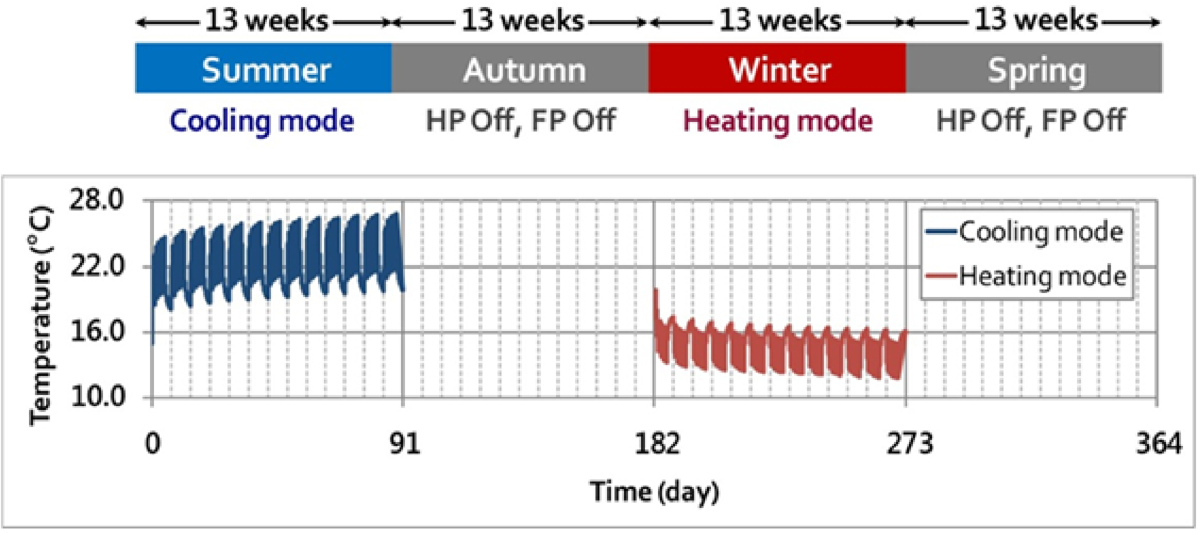

Figure 3: Operation pattern: the HP and FP denote heat pump and fluid pump, respectively.

Table 1. Material properties, boundary conditions and characteristic of wells.

Thermal conductivity of the ground	2, 3, 4 (W/m-K)
Hydraulic conductivity	10^{-5}, 10^{-6}, 10^{-7} (m/s)
Ground parameters (Fixed)	Specific heat: 0.80 kJ/kg-K Porosity: 0.1 Hydraulic gradient: 0.02
Boundary conditions	No flow: top, bottom, front, back Constant head: left, right (hydrostatic pressure) Constant temp.: top (15°C) Constant temp.: left, right, front, back (depth-dependant) Basal heat flow: 60 mW/m^2
Closed-loop system	8 x 200 m BHEs
SCW system	3 x 400 m SCWs
Open-loop system	2 x 300 m wells

Table 2. Simulation results.

Cases	**Thermal conductivity of the ground (W/m-K)**	**Hydraulic conductivity (m/s)**	Closed-loop system	SCW system	Open-loop system
1		10^{-5}	107%	121%	241%
2	3	10^{-6}	103%	98%	100%
3		10^{-7}	102%	71%	37%
4	2		73%	87%	99%
5	3	10^{-6}	103%	98%	100%
6	4		118%	108%	100%

4. CONCLUSION

The performance of the closed-loop system is mainly sensitive to thermal conductivity, while the performance of the open-loop system is extremely sensitive to hydraulic conductivity. The performance of the SCW system is sensitive to both conductivities. Further studies are needed to evaluate the overall costs of each system for a long-term operation.

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