DEVELOPMENT AND APPLICATION OF TEMPERATURE SIMULATOR FOR BOREHOLE HEAT EXCHANGERS OF GEOTHERMAL HEAT PUMP SYSTEMS

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ABSTRACT

To simulate geothermal heat transport associated with the vertical closed-loop geothermal heat pump (GHP) system, a numerical model named "Modified TOUGHREACT" is developed and applied to sensitivity analysis and evaluation of performance of the GHP system in this study. It can simulate temperature changes in borehole heat exchangers with circulating water through the pipe as well as it computes groundwater flow and aquifer temperature changes. The proposed model is based on TOUGHREACT, a widely accepted three-dimensional numerical simulator for heat and water flow and geochemical reactions in geothermal systems. In order to take circulating pipe flow in the BHE and heat flux from the heat pump to the BHE into account, three modules are developed and added to TOUGHREACT. The proposed model is applied to analyze the sensitivities of design parameters that can affect the performance of the vertical closed-loop GHP and to evaluate performance of the GHP system installed at Korea Institute of Geoscience and Mineral (KIGAM). The most sensitive parameters on the system are the thermal conductivity of aquifer and the Darcian groundwater velocity considering acceptable distribution range in the realm of nature. Maximum change of the circulating fluid temperature at the outlet is about 4℃ when thermal conductivity of the aquifer changes from 2 W/m-K to 5 W/m-K and the Darcian groundwater velocity changes from 10^{-8} m/s to 10^{-6} m/s, respectively. Performance of field application at the KIGAM GHP site is under evaluation process by using the developed model.

Keywords: closed-loop geothermal heat pump, numerical simulation, Modified TOUGHREACT

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. A vertical closed-loop GHP system that connects a heat pump to BHEs is the most widely used type of the GHP systems. To avoid over- and under-designing of the BHEs, a quantitative tool for designing the BHEs is necessary. There are several researches on the development of the quantitative tool, using analytical model (e.g. Hellström and Sanner, 2000 and Sutton et al., 2003) or numerical model (e.g. Gehlin and Hellström, 2003, Fujii et al., 2005, Signorelli et al., 2006, and Fan et al., 2007). In this study, a numerical model named "Modified TOUGHREACT" is developed. It can simulate temperature changes in borehole heat exchangers with circulating water through the pipe as well as it computes groundwater flow and aquifer temperature changes. The proposed model is based on TOUGHREACT, a widely accepted three-dimensional numerical simulator for heat and water flow and geochemical reactions in geothermal systems. The Modified TOUGHREACT was verified by comparing the analytical model and data set from an in-situ thermal response test. The proposed model is applied to analyze the sensitivities of design parameters that can affect the performance of the closed-loop GHP system and to evaluate the performance of GHP system.

2. MODEL DEVELOPMENT

The vertical closed-loop GHP system consists of heat pumps and BHEs. Figure 1 shows model conceptualization of the vertical closed-loop GHP system in cooling mode. Heat is moved from indoor to outdoor via the heat pump and from the surface to the subsurface via the BHE.

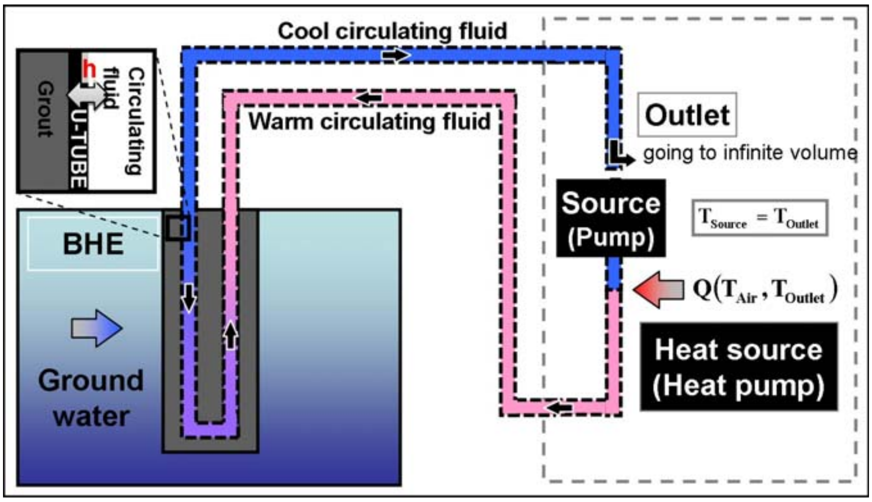


Figure 1. Model conceptualization of the vertical closed-loop GHP system (Kim et al., 2008).

The basic simulator for modeling these systems is TOUGHREACT (Xu et al., 2004). It considers fluid flow occurring under viscous, pressure, and gravity forces according to Darcy's law. Including both sensible and latent heat, heat transport by means of conduction and convection is taken into account. The general form of the basic mass and energy balance equations solved by TOUGHREACT is

$$\frac{d}{dt}\int_{V_n} M \, dV_n = \int_{\Gamma_n} \mathbf{F} \bullet \mathbf{n} \, d\Gamma_n + \int_{V_n} q \, dV_n \quad (1)$$

Where the V_n is an arbitrary subdomain, which is bounded by the closed surface Γ_n. **n** denotes a normal vector on surface element $d\Gamma_n$, pointing inward into V_n. The quantity M denotes the mass or energy per volume and **F** represents the mass or heat flux. q represents sources and sinks.

The mass accumulation term is

$$M_M = \phi\rho \quad (2)$$

Where ϕ denotes the porosity and ρ denotes the density.

The heat accumulation term is

$$M_H = (1-\phi)\rho_R C_R T + \phi\rho u \quad (3)$$

Where ρ_R is the rock density, C_R is the rock specific heat, T is the temperature, and u is the specific internal energy. Fluid and Rock have the same temperature.

Advective mass flux is

$$\mathbf{F}_M = \rho\mathbf{u} = -\frac{k\rho}{\mu}\left(\nabla P - \rho\mathbf{g}\right) \quad (4)$$

Where **u** is the Darcian velocity, k is the permeability, μ is the viscosity, P is the pressure, and **g** is the vector of gravitational acceleration.

Conductive and convective heat flux is

$$\mathbf{F}_H = -\lambda\nabla T + h\mathbf{F}_M \quad (5)$$

Where λ is the thermal conductivity and h is the specific enthalpy.

To take circulating pipe flow in the BHE and heat flux from the heat pump to the BHE into account, three modules are developed and added to TOUGHREACT. We call it Modified TOUGHREACT.

The first module is to calculate heat flux between circulating fluid and U-tube in the BHE. The heat transfer coefficient is used in calculating the convective heat transfer between flowing fluid and solid. Heat flux between fluid and pipe wall is expressed by Newton's law of cooling.

$$\mathbf{F}_H = -h\left(T_w - T_f\right) \quad (6)$$

Where h is the heat transfer coefficient, T_w is the temperature of pipe wall, and T_f is the temperature of fluid. The value of h can be obtained by the Dittus-Boelter correlation that is used for many applications in turbulent flow system (Bennett and Meyers, 1982):

$$h = 0.023\frac{\lambda}{d}\left(\frac{vd\rho}{\mu}\right)^{0.8}\left(\frac{\rho\mu}{\lambda}\right)^{n} \quad (7)$$

Where d is the pipe diameter and v is the flow velocity in the U-tube. The value of n equals 0.3 in cooling mode and equals 0.4 in heating mode.

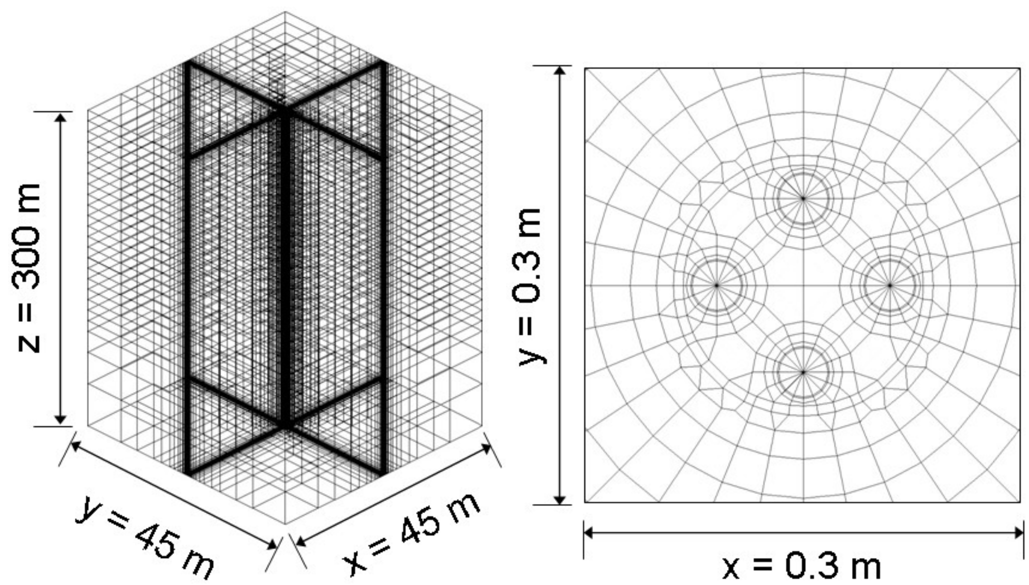
The second module is to consider the movement of the circulating fluid in the BHE. Water pump supplies the power for circulation of the fluid in real system. In this module, "source" (Figure 1) is used to generate the fluid in the inlet of the BHE and its temperature is the same as that of the BHE outlet. The circulating fluid that passes through the BHE outlet is going into the element that has infinite volume and has no effect on the system anymore. The BHE inlet and outlet are only connected thermally.

The last module is to calculate heat flux (Q) from the heat pump to the BHE. This heat flux depends on type of the heat pump, indoor air temperature, and temperature of the BHE outlet. Most heat pumps have a specification data sheet. Relationship between heat of abstract (reject) and entering temperature of two fluids (the circulating fluid and the air) is obtained from the specification data sheet. If the type of the heat pump is determined and indoor air temperature is fixed at some value, then the heat flux at the current time step can be calculated because temperature of the BHE outlet is already known in results at the previous time step. Using the heat flux, temperature of the BHE outlet at the current time step is calculated.

3. MODEL SETUP

Spatial discretization is accomplished from integrated finite difference (IFD) method (Pruess et al., 1999). Figure 2 shows three-dimensional mesh used in simulations. This mesh is automatically generated by the U-Mesh program (Kim et al., 2008). The U-Mesh program generates IFD mesh and input files of the Modified TOUGHREACT, which are suitable to simulate the vertical closed-loop GHP system.

Table 1 shows properties of the BHE, heat pump, water pump and pipe, materials, and boundary conditions for numerical experiments. BHE dimensions, thermal properties of the grout and aquifer, and basal heat flow were measured at the Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea.



(a) (b)

Figure 2. IFD Mesh: (a) complete model domain (x to z ratio = 5), (b) plan view in and around the borehole.

Table 1. Properties of the BHE, materials, and boundary conditions.

BHE dimensions	Depth: 200 m Borehole radius: 82.5 mm U-tube radius (inner): 17 mm U-tube radius (outer): 21 mm
Thermal conductivity (W/m-K)	U-tube: 0.366 (Polyethylene pipe) (Fujii et al., 2005) Grout: 0.800 (Sand – E-plug mixture) Circulating fluid: 0.580 (Water) (Fujii et al., 2005)
Specific heat (kJ/kg-K)	U-tube: 2.09 (Fujii et al., 2005) Grout: 2.20 Circulating fluid: 4.20 (Fujii et al., 2005)
Aquifer parameters	Thermal conductivity: 2.5, 3.0, 3.5 W/m-K Specific heat: 0.80 kJ/kg-K Hydraulic conductivity: 10^{-4}, 10^{-5}, 10^{-6} m/s Porosity: 0.05 Hydraulic gradient: 0.02
Boundary conditions	No flow: top, bottom, front, back Constant head: left, right Flow rate of the BHE inlet: 0.5 L/s Constant temp.: top (15°C) Constant temp.: left, right, front, back (depth dependant) Basal heat flow: 60 mW/m^2

Kim et al. (2008) showed that simulated results matched well with the analytical model (line source model: Carslaw and Jaeger, 1959) and the field data of the thermal response test carried out at one of the BHE in KIGAM.

4. APPLICATION

The proposed model is applied to analyze the sensitivities of design parameters that can affect the performance of the closed-loop GHP system (Kim et al., 2008). Seven parameters that can affect performance of the GHP system are used for sensitivity analysis. Table 2 shows seven cases of the sensitivity analysis. Injected thermal power is 5 kW and duration of the injection is 90 days. Flow rate of the circulating fluid is 0.5 L/s. Figure 5 shows average temperature of the circulating fluid at the outlet of borehole heat exchanger during 90 days of heat injection. The most sensitive parameters on the system are the thermal conductivity of aquifer and the Darcian groundwater velocity considering acceptable distribution range in the realm of nature. Maximum change of the circulating fluid temperature at the outlet is about 4℃ when thermal conductivity of the aquifer changes from 2 W/m-K to 5 W/m-K and the Darcian groundwater velocity changes from 10^{-8} m/s to 10^{-6} m/s, respectively.

Table 2. Seven cases of the sensitivity analysis (Kim et al., 2008).

Classification	Parameter	Unit	Range
Case 1	Thermal conductivity of the aquifer	[W/m-K]	2.0, 3.0, 4.0, 5.0
Case 2	Specific heat of the aquifer	[kJ/kg-K]	0.4, 0.8, 1.2
Case 3	Density of the aquifer	[$\times 10^3$ kg/m^3]	1.00, 2.65, 4.00
Case 4	Thermal conductivity of the grout	[W/m-K]	0.27, 0.55, 0.80, 1.20, 2.38
Case 5	Thermal conductivity of the pipe	[W/m-K]	0.100, 0.366, 0.700, 2.000
Case 6	Heat transfer coefficient	[kW/m^2-K]	0.320, 0.390, 1.067, 1.301
Case 7	Hydraulic conductivity	[m/s]	10^{-9}, 10^{-7}, 10^{-5}, 10^{-4}, 10^{-3}

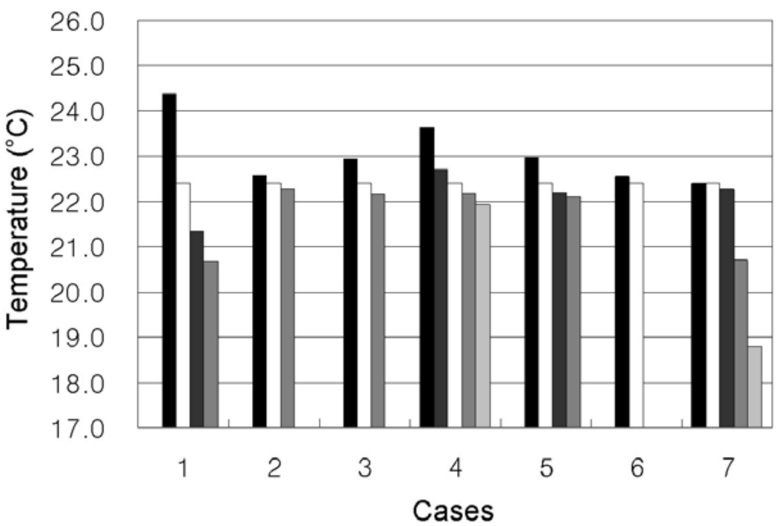


Figure 5. Average temperature of the circulating fluid at the outlet of borehole heat exchanger during 90 days of heat injection (Kim et al., 2008).

5. DISCUSSION AND SUMMARY

The Modified TOUGHREACT was verified by comparing it with the analytical model and data set from an in-situ thermal response test. Simulation results are in good agreement with both the analytical solution and field test data. The proposed model is applied to analyze the sensitivities of design parameters that can affect the performance of the vertical closed-loop GHP. The most sensitive parameters on the system are the thermal conductivity of aquifer and the Darcian groundwater velocity considering acceptable distribution range in the realm of nature.

Using the last module and the specification data of heat pumps, the proposed model is being applied to the optimal design and the evaluation of long-term performance of the GHP system. We can get the proper number of the BHEs, which is suitable for the KIGAM GHP system.

REFERENCES

Bennett, C.O. and Meyers, J.O. (1982) *Momentum, heat, and mass transfer*, Third ed., Wiley, New York.

Carslaw, H.S. and Jaeger, J.C. (1959) *Conduction of heat in solids*, 2nd ed., Oxford Univers. Press, London.

Edwards, A.L. (1972) *TRUMP: A Computer Program for Transient and Steady State Temperature Distributions in Multidimensional Systems*, National Technical Information Service, National Bureau of Standards, Springfield, VA.

Fan, R., Jiang, Y., Yao, Y., Shiming, D. and Ma, Z. (2007) A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection, *Energy*, **32**, 2199-2209.

Freeze, R.A. and Cherry, J.A. (1979) *Groundwater*, Prentice Hall.

Fujii, H., Itoi, R., Fujii, J. and Uchida, Y. (2005) Optimizing the design of large-scale ground-coupled heat pump systems using groundwater and heat transport modeling, *Geothermics*, **34**, 347-364.

Gaia Geothermal (2006) *The Ground Loop Design Version 3.0 User's Manual*.

Gehlin, S. and Hellström, G. (2003) “Influence on thermal response test by groundwater flow in vertical fractures in hard rock”, *Renewable Energy*, **28**, 2221-2238.

Hellström, G. and Sanner, B. (2000) *EED: Earth Energy Designer User manual, Version 2.0.*

Kim, S.K., Bae, G.O., Lee, K.K., Shim, B.O., and Song, Y. (2008) Model Development to Simulate Geothermal Heat Transport and Sensitivity Analyses on the Design Parameters of Closed-loop

Geothermal Heat Pump System. *Korean Society for Geosystem Engineering*. **45**, 326-336.

Narasimhan, T.N. and Witherspoon, P.A. (1976) An Integrated Finite Difference Method for Analyzing Fluid Flow in Porous Media, *Water Resour. Res.*, **12**, 57-64.

Pruess, K., Oldenburg, C. and Moridis, G. (1999) *TOUGH2 User's Guide, Version 2.0*.

Rafferty, K. (2003) Ground Water Issues in Geothermal Heat Pump Systems, *Ground Water*, **41**, 408-410.

Signorelli, S., Bassetti, S., Pahud, D. and Kohl, T. (2006) Numerical evaluation of thermal response tests, *Geothermics*, **36**, pp. 141-166.

Sutton, M.G., Nutter, D.W., and Couvillion, R.J. (2003) A Ground Resistance For Vertical Bore Heat Exchangers With Groundwater Flow, *ASME Journal of Energy Resources Technology*, **125**, 183-189.

Xu, T., Sonnenthal, E., Spycher, N. and Pruess, K. (2004) *TOUGHREACT User's Guide: A Simulation Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media*.

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