Geosciences Journal
Vol. 11, No. 1, p. 83 − 91, March 2007

Application of TOUGHREACT to performance evaluations of geothermal heat pump systems

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ABSTRACT: Numerical simulations were performed with a non-isothermal multi-phase reactive geochemical transport code, TOUGHREACT for predicting changes in temperature, permeability, porosity, and injectivity resulting from a long term operation of a geothermal heat-pump (GHP) system. A one-dimensional model was developed to simulate a GHP system for a potential geothermal reservoir with down-hole water temperature of 200°C. The GHP system was developed for (1) an open-loop system with a set of extraction and injection wells 600 meter apart, and (2) a closed-loop system with a heat exchanger. The same ground water was either injected into the ground through the injection well of the open-loop system or placed in the heat exchanger in the closed-loop system. Injecting water temperature (65°C or 35°C), pressure (+2MPa or +5MPa), chemical composition, and well casing (stainless steel or PVC) for the closed-loop system were varied. The feedback effects of changes in permeability and porosity resulting from mineral dissolution or precipitation on liquid injectivity and heat extractability were evaluated. The results showed that the impacts of the mineral precipitation on liquid injectivity and heat extractability were more significant in the open-loop system than in the closed-loop system. This study also showed the injecting water temperature and well casing material would not be significant to improve the performance of a closed-loop GHP system. For the comprehensive evaluation of a GHP system performance, a system-level modeling considering economic and technical aspects was suggested.

Key words: heat pump, geothermal, TOUGHREACT, groundwater, modeling

1. INTRODUCTION

Geothermal energy, a popular renewable energy form is most commonly used as a direct source or sink of heat for heating or cooling. According to the World Geothermal Congresses (Lund et al. 2005), total geothermal energy use increases 7.5% annually in recent years, and the utilization of the geothermal energy becomes diversified rapidly. Common utilizations include geothermal heat pump, space heating (district heating or home heating), ground (raceway, greenhouse, agriculture pond) heating, snow melting, space cooling, and bathing and swimming. Geothermal (ground-coupled) heat pump (GHP) constitutes the largest portion of the geothermal energy usage in terms of annual energy use and installed capacity (Lund et al. 2005).

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In Korea, the energy utilization for bathing and swimming is estimated as the largest (Song et al. 2005). The Korean government recently launched a project for district heating, and it is expected for the project to stimulate the more utilization of the geothermal energy in Korea. Lee and Hahn (2006) reported that the 48% of deep wells (35m below ground surface) showed nearly no variation in temperature throughout a certain monitoring period, which would make the region with the wells suitable for the GHP system development. Note that the GHP system requires a constant temperature for a stable energy gain and consistent system performance.

The GHP system is essentially a combination of a heat pump and a system for exchanging heat with the ground. The heat exchanging system consist of either a ground heat exchanger (closed loop system), or a system fed by ground water from a well (open loop system). It is found that 46% of the GHP systems in the USA are vertical closed loop system and 38% is horizontal closed loop, while the remaining refers to open loop systems (Lund et al. 2004).

Experimental and theoretical investigations have been conducted over several years to elaborate a basic understanding for the design and performance evaluation of the GHP system (Claesson and Eskilson, 1988; Rafferty 1996, 1998, 2001). The performance of the GHP system depends on the types and operation modes (Pahuda and Matthley, 2001, Inall and Esen 2004), system designs rendering the depth, distance and number of the heat exchangers (Kavanaugh 2000, 2003, Fujii et al. 2005), and the thermal properties of geological formations (Witte et al. 2002, Austin et al. 2000) and backfill materials (Spilker 1998, Allan and Kavanaugh 2000).

Some recent studies on the GHP focuses on the optimization of system performance in various time frames and system scales (Fujii et al. 2005, Kyriakis et al. 2006), and other studies were performed to develop performance prediction tools for the GHP system (Nagano et al. 2006, Zhao et al. 2003). These studies considered technical and economic principals to derive the total costs for optimal performance of the GHP systems. The total cost includes both the operating cost and the capital cost for a given heating and cooling capacity, and the operating cost is attributed to the cost of heat pump operation, energy consumption, heat exchanger capacity, lifecycle cost, and maximum heat load. Li et al. (2006) analyzed heat balance in a GHP system, where the GHP unevenly delivers heat from surface to ground and vice versa, resulting in heat unbalance between ground and surface and the elevated ground temperature (heat island effect). This heat balance analysis is essential in long-term performance prediction.

Few studies are available considering geochemical aspects in the GHP system performance. Xu et al. (2004b) and Xu and Pruess (2004) studied mineral deposition and injectivity loss occurring at a geothermal field where hot brine is injected, using TOUGHREACT (Xu et al. 2004a), a reactive transport simulation program. They predicted significant precipitation of amorphous silica and reductions in porosity and permeability, which were consistent with the estimated field data. In a GHP system, temperature gradient between the heat exchanger surface and ground disturbs the chemical equilibrium in pore water, and this disturbance would cause mineral precipitation (scaling) on the surface of the heat exchanger and surrounding geological medium. This mineral deposition would result in reduced efficiency of the heat changer and modified conductivity of heat and water in the geological medium, thus deteriorate the performance of the GHP system as a result. In the open-loop system where foreign solutions are to be injected into the ground, the impact of chemical reactions on the performance of a GHP system can be larger than that in the closed loop system.

TOUGHREACT was developed by introducing reactive geochemistry into the framework of the existing multiphase fluid and heat flow code TOUGH2 (Pruess et al. 1999). TOUGHREACT is a non-isothermal reactive geochemical transport code, developed for one-, two-, or three-dimensional porous and fractured media with physical and chemical heterogeneity and any number of chemical species present in liquid, gas, and solid phases. TOUGHREACT has been applied to various problems concerning high-level nuclear waste isolation, geological disposal of greenhouse gases, supergene copper enrichment, and geothermal reservoir behavior, and the computer code is already equipped with various functional modules to handle temporal changes in porosity and permeability due to mineral dissolution and precipitation. TOUGHREACT was further enhanced with various addition features including treatment of mineral-water-gas reactive-transport under boiling condition, mineral reactive surface area formulations for fractured and porous media, and porosity, permeability, and capillary pressure changes owing to mineral precipitation/dissolution. TOUGHREACT can be applied to a wide variety of subsurface conditions. The temperature and pressure ranges are controlled by the applicable ranges of the chemical thermodynamic database, and the ranges of the EOS module employed. The ranges in the commonly-used database for EQ3/6 is 1 to 300°C, 1 bar below 100°C and water saturation pressure above 100°C.

Numerical simulation for the GHP system can be a system-level modeling, in which the system performance optimization considering system dimensions, thermal load, initial installation costs, operation expenses, and performance deterioration with potential geochemical interactions would be conducted. TOUGHREACT can be adopted as a geochemical and hydrological process simulator for modeling the GHP system as it can calculate the flow field and simultaneous occurring chemical reactions in the non-isothermal system. TOUGHREACT can provide information related to changes in system performance resulting from geochemical evolution of the subsurface condition.

The purpose of this study is to demonstrate the capability of TOUGHREACT for simulating heat/water flow and mineral precipitations in an open-loop or closed-loop system and the impacts on liquid injectivity and thermal conductivity. Due to limited information on subsurface characteristics including mineral assemblages and chemical composition in pore water, input values are assumed or adopted from previous literatures without validations.

2. MODELING APPROACH

GHP systems utilizing geothermal energy currently provide a renewable form of energy for air conditioning and power generation. Depending on heat load, soil and bedrock condition, landscaping, and climate severity, designing the GHP system varies from ground closed-loop, pond closed-loop to open-loop systems. The performance of the open-loop system, compared to the others, is controlled by more variables that include ambient groundwater flow, geochemical interaction, and heat conductivities. An open-loop heat-pump system typically includes a set of extraction and injection wells, and extracted water is often reinjected into the geothermal system directly or after dilution or concentration at the ground surface. A closed-loop system consists of a heat exchanger installed in the ground, and except heat exchange, its interaction with hosting geological mass is minimal. Major concerns on the development of geothermal energy systems and their long term operation include mineral scaling and clay swelling resulted from the reinjection of extracted water and deteriorating efficiency in time.

This preliminary modeling study was performed to examine the effects of mineral precipitation and dissolution using TOUGHREACT. This study was performed to develop a simple model for GHP systems and to monitor temporal changes in temperature, permeability, and mineral composition resulting from lower temperature water injection (65°C or 35°C) than deep groundwater temperature (200°C) in the GHP systems.

This simulation study considers a deep (about 3000 m) hot water reservoir where (1) a set of injection and production well is installed to develop an open-loop geothermal heat pump system, or (2) a heat exchanger with steel casing is installed for representing a closed-loop system. The two wells in the open-loop system are separated by 600 m to minimize the interference on heat production from low temperature injection water into the injection well. In the closed-loop system, no extraction well was needed. An additional grid block representing well casing covering heat exchanger was situated between the grid block for heat exchanger and the first rock grid block. Only heat flow (no ground water flow) between the heat exchanger (located at injection well) and the neighboring grid blocks was allowed. Due to the assumed symmetry, only one-dimensional (1-D) model was developed to monitor the changes over time in temperature, porosity, permeability, and mineral and water composition in the system. Simulation time for the open-loop system was 10 years, and 100 years for the closed-loop system.

Two basic simulation cases were performed on each GHP system for checking impact of activating porosity-permeability change option: (Simulation 1) a base case without the feedback effect from mineral dissolution and precipitation, and (Simulation 2) a comparable case with the option activated for porosity-permeability changes as low temperature injection continues. The chemical composition of injection water is identical except temperature to those from production well, and the same water was injected for both simulation cases at higher pressure (+2MPa) without artificial pumping at the production well. There was no need of liquid injection into the heat exchanger in the closed-loop system; instead, the temperature inside heat exchanger was fixed at given temperatures (65°C), and heat flow through the steel casing was monitored. The two simulation cases were compared to identify the impact of mineral dissolution and precipitation on water injectivity and productivity using TOUGHREACT. No validation study was performed at the moment.

Additional simulations were performed with varying injection water temperature (65°C or 35°C), pressure at the injection well (+2MPa or +5MPa), chemical composition (diluted by a factor of 10) for the open-loop system. Two different well casing material (stainless steel or PVC) for the closed-loop system were tested as well as two water temperatures(65°C or 35°C) inside heat exchanger.

3. MODEL SETUP

We used a 1-D MINC (multiple interacting continua) model (Xu and Pruess 2001) where three continua represent a fracture with vein alteration, altered and unaltered granite, respectively (Fig. 1). The MINC model resolves global flow and diffusion of chemicals in the fractured rock and its interaction between local continua representing fracture and matrix. Due to assumed symmetry, only one column of matrix block needs to be modeled. Two perpendicular sets of planar, parallel fractures with equal aperture and spacing form a 1-D flow tube between injection and production well. The matrix is refined into 72 grid blocks representing 600 m distance. The block size gradually increases from 0.1m at the injection side to 20 m at the production side. No extraction well was installed in the closed-loop system case. A heat exchanger represented by an injection well with well casing was placed in the model instead of the injection-extraction wells. The well casing allows heat conduction but no water or gas flow through the casing.

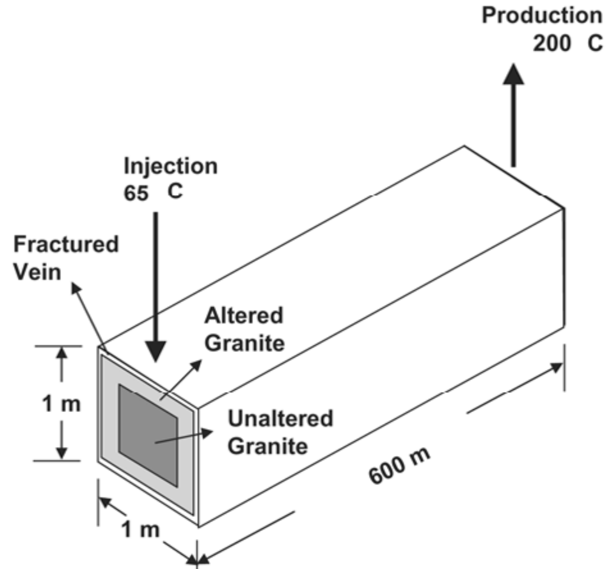

Fig. 1. Schematic of the MINC model consisting of three continua representing fractured vein and altered and unaltered granite.

The regional groundwater flow was not considered in the model because in this 1-D tube model, the ambient flow was assumed to have the same flow direction and flow velocity between the wells caused by applied pressure gradient is representing both ambient and injected flow. No flow boundary was rendered on lateral boundaries and constant head boundary is on the injection well.

Detailed information on water chemistry and mineralogical composition of each continuum is required to assess the chemical impact on heat pump operation. Because this study is not intended to any particular sites, however, the data were taken from the European Hot Dry Rock research site (Jacquot, 2000, Durst, 2002, and Bächler, 2003). The particular site was chosen because of its potential similarity of the geological conditions to those in Korea. Three different mineral assemblages were reported. The first represents strongly altered minerals from a highly fractured vein filled with clays, carbonates, and secondary quartz mineral. The second assemblage is composed of altered granite rocks partially altered to clay minerals and carbonates. The inner most area in the matrix is unaltered granite where fracture density is nearly zero, and the chemical interactions in the unaltered granite zone were not considered. The ini-

Table 1. Initial mineralogical composition of the three zones used in the simulations

Mineral	Volume percentage of solid rock		
	Fractured vein Alteration	Altered granite	Unaltered granite
Quartz	43.9	4.09	24.2
K-feldspar		13.9	23.6
Plagioclase			42.5
Biotite			4.2
Hornblende			3.1
Chlorite		4.8	2
Calcite	4.3	3.3	0.3
Dolomite	0.7	0.8	
Illite	40.2	24.6	
Na-smectite	7.392	7.469	
Ca-smectite	2.208	2.231	
Pyrite	1	0.7	
Galena	0.3	1.3	
Other minerals (not reactive)		36.81	0.1

Data were taken from Jacquot (2000), Durst (2002), and Bächler (2003).

tial mineral compositions were listed in Table 1.

Initial water chemical compositions (Table 2) for the fractured vein and altered granite zones were obtained by equilibrating the sample water (column 1 in Table 2) with their corresponding mineral compositions (Table 1) at a temperature of 200°C. Chemical composition of injection water (column 4 in Table 2) corresponded to the native water but with a lower temperature of 65°C or 35°C, and the injection water was not allowed to change over time in terms of temperature and chemical composition. The same water chemistry and mineral compositions were applied to both the open- and closed-loop system.

Hydrological and thermal parameters used for the three mineral zones and the well casings of the heat exchanger were listed in Table 3. The data were basically obtained from Durst (2002) and Bachler (2003), however, the values were adjusted to represent general geothermal reservoirs.

Temporal changes in porosity and permeability due to mineral dissolution and precipitation were considered in this study. The changes in porosity were directly calculated from changes in volume of minerals that were precipitated or dissolved. Permeability was estimated using the newly calculated porosity. For the porosity-permeability relations to estimate the effect on permeability changes, TOUGHREACT offers five options, among which we chose the simple cubic Kozeny-Carman grain model (Eq. 1):

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)\left(\frac{1-\phi_0}{1-\phi}\right)^2 \quad (1)$$

where ϕ is the porosity, k is the permeability in m^2, and the subscript 0 denote the initial values of variables. The simple cubic Kozeny Carman porosity-permeability equations may not reflect the complex relationship of porosity and permeability in geological media that depends on interplay of many factors, such as pore size distribution, pore shapes, and connectivity (Verma and Pruess, 1988), however it provides information on the relative changes of porosity and permeability in geological media.

Kinetic mineral dissolution and precipitations were calculated with the general form of rate law (Steefel and Lasaga,

Table 2. Initial water chemical compositions (mol/l) used in the simulations

		Fractured vein	Altered granite	Injection Water
Chemical components	Well CPK1 At 3500 depth at 165°C	Equilibrium with the minerals at 200°C	Equilibrium with the minerals at 200°C	at 65°C or 35°C
Ca	1.820×10^{-1}	1.810×10^{-1}	1.706×10^{-1}	1.810×10^{-1}
Mg	4.610×10^{-3}	5.874×10^{-3}	5.540×10^{-3}	5.874×10^{-3}
Na	1.213	1.213	1.212	1.213
K	7.180×10^{-2}	7.179×10^{-2}	9.439×10^{-2}	7.179×10^{-2}
Fe	1.491×10^{-6}	2.191×10^{-5}	1.996×10^{-7}	2.191×10^{-5}
Cl	1.72	1.72	1.72	1.72
SiO_2(aq.)	3.500×10^{-3}	4.129×10^{-3}	4.131×10^{-3}	4.129×10^{-3}
HCO_3	7.500×10^{-3}	7.795×10^{-3}	1.727×10^{-3}	7.795×10^{-3}
SO_4	2.020×10^{-3}	2.062×10^{-3}	2.392×10^{-3}	2.062×10^{-3}
Al	5.656×10^{-9}	5.655×10^{-9}	1.518×10^{-6}	5.655×10^{-9}
Pb	1.000×10^{-12}	1.296×10^{-6}	3.391×10^{-8}	1.296×10^{-6}
pH	5.03	5.55	5.92	5.55

The composition given in the second column was from a Soultz Well CPK1 sample (Durst, 2002). No measurements for Fe, Al, and Pb concentrations in the sample were reported, and small values were assumed for consistency because of the presence of minerals with these components.

Table 3. Thermal and hydrological properties of three zones and steel casing of the heat exchanger

	Fractured vein Alteration	Altered granite	Unaltered granite	Stainless Steel casing	PVC casing
Volume	10%	60%	30%		
Density [kg/m^3]	2650	2650	2650	8027	920
Porosity	0.2	0.1	0.02	0	0
Absolute Permeability [m^2]	2.00×10^{-12}	2.00×10^{-15}	2.00×10^{-18}	0	0
Thermal conductivity [W/m °C]	2.9	3.0	3.0	14.9	0.42
Specific Heat [J/kg °C]	1000	1000	1000	502.4	1760
Tortousity	0.3	0.1	0.05		

Table 4. List of kinetic rate parameters used in Eqs. (2) and (3) for minerals considered in the present paper

Mineral	k_{25} (moles m^{-2}s^{-1})	E_a (KJ/mol)	n	Surface area (cm^2/g)
calcite	6.4565×10^{-7}	62.76	0	98×10^{-1}
	6.9183×10^{-2}	18.98	1	98×10^{-1}
quartz	1.2589×10^{-14}	87.50	0	98×10^{-1}
K-feldspar	1.0000×10^{-12}	57.78	0	98×10^{-1}
	3.5481×10^{-10}	51.83	0.4	98×10^{-1}
dolomite	1.2589×10^{-9}	62.76	0	98×10^{-1}
	1.0233×10^{-3}	20.90	0.9	98×10^{-1}
Na-smectite	1.0000×10^{-13}	62.76	0	1516×10^{-1}
	4.3652×10^{-12}	62.76	0.17	1516×10^{-1}
Ca-smectite	1.0000×10^{-13}	62.76	0	1516×10^{-1}
	4.3652×10^{-12}	62.76	0.17	1516×10^{-1}
illite	1.0000×10^{-13}	62.76	0	1516×10^{-1}
	4.3652×10^{-12}	62.76	0.17	1516×10^{-1}
pyrite	4.0000×10^{-11}	62.76	0	129×10^{-1}
galena	4.0000×10^{-11}	62.76	0	129×10^{-1}
chlorite	2.5119×10^{-12}	62.76	0	98×10^{-1}

Note: A reaction order **n** (acid catalyzed) greater than zero is used for mineral dissolution, while n=0 (no catalysis) is used for precipitation. For minerals with only one set of the parameters with n=0, it is used for both dissolution and precipitation.

1994, Eq. 2) using the rate parameters listed in Table 4.

$$r_m = \pm k_m A_m a_{H^+}^n \left|1 - \frac{Q_m}{K_m}\right| \quad (2)$$

where m is the mineral index, r_m is its dissolution/precipitation rate, k_m is the rate constant (moles per unit mineral surface area and unit time), A_m is the specific reactive surface area per kg of H_2O, a_H^+ is the activity of H^+, and n is an empirical reaction order accounting for catalysis by H^+ in solution. K_m is the equilibrium constant for the mineral-water reaction written for the destruction of one mole of mineral m, Q_m is the ion activity product. The temperature dependence of the reaction rate constant can be expressed as

$$k = k_{25}\exp\left[\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] \quad (3)$$

where E_a is the activation energy, k_{25} is the rate constant at 25°C, R is the gas constant, and T is absolute temperature. Details on the mathematical formulation on the calculation of mineral dissolution and precipitation are available from the TOUGHREACT manual (Xu, et al., 2004a).

4. RESULTS AND DISCUSSION

4.1. Open-Loop System

Injection rates with two basic simulation cases were shown in Figure 2. The injection rate without the feedback effects of porosity-permeability changes decreases over the time as flow and reaction front approach the production well. The decreasing trend is more obvious when the porosity-permeability changes were incorporated into the model (Simulation 2 in Figure 2).

Porosity and permeability increases near the injection well, and temperature drop propagates toward the production well as injection continues (Fig. 3). Later, the porosity and permeability sharply drops as the reaction front moves to the production well. The initial increase of porosity and permeability was directly caused by mineral dissolution, particularly, with calcite, which has a highest solubility at 65°C. Dissolution takes place at near the injection well because calcite is under-saturated in the injection water at 65°C. As the water is mixed with the ambient hot water,

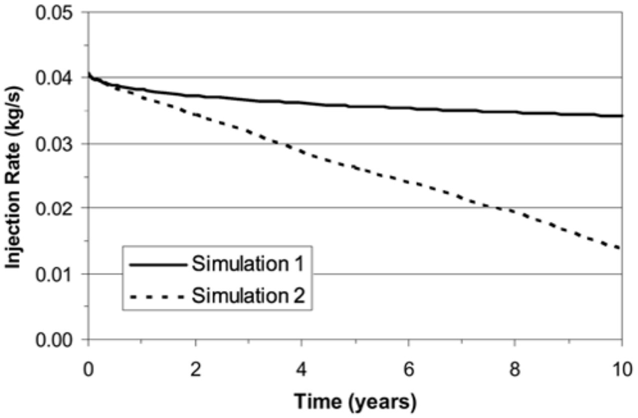

Fig. 2. Injection rate (kg/s) variations over time in the open-loop GHP system with 3000 m depth, 50 MPa pressure, 200°C base temperature, and with 65°C injection water temperature. Simulation 1: base case; 2: porosity-permeability changes were incorporated.

temperature goes up and solubility goes down, in turn, calcite precipitation starts occurring (Fig. 4). Highest precipitation occurs at near 50 meter (134°C) from the injection with a maximum 3.6% volume increases. The calcite precipitation increases again near at 254 m and reaches a peak at near 354 m (200°C), even yet to be understood clearly, it may be related to increasing pH in the groundwater. The pH drops quickly as cold water invades and calcite dissolves

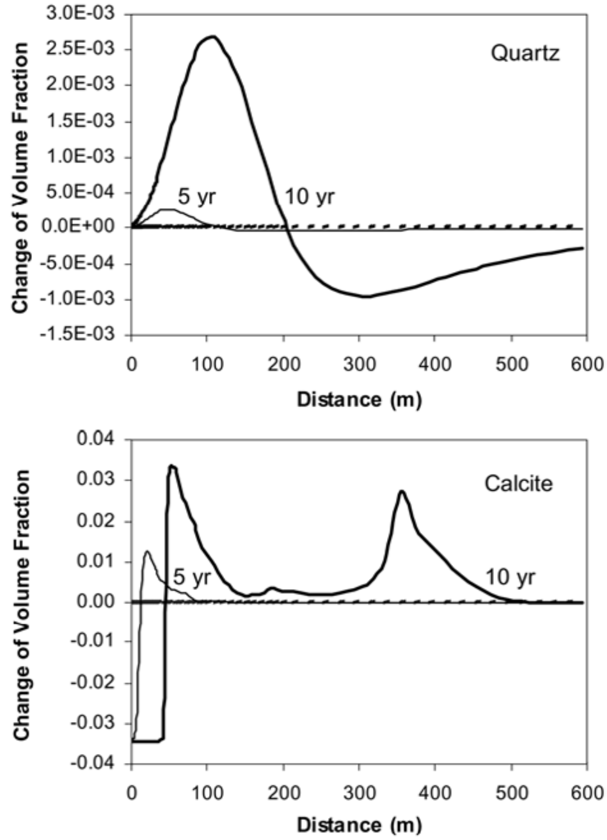

Fig. 4. Changes of mineral abundances (quartz and calcite) from Simulation 2 of the open-loop system.

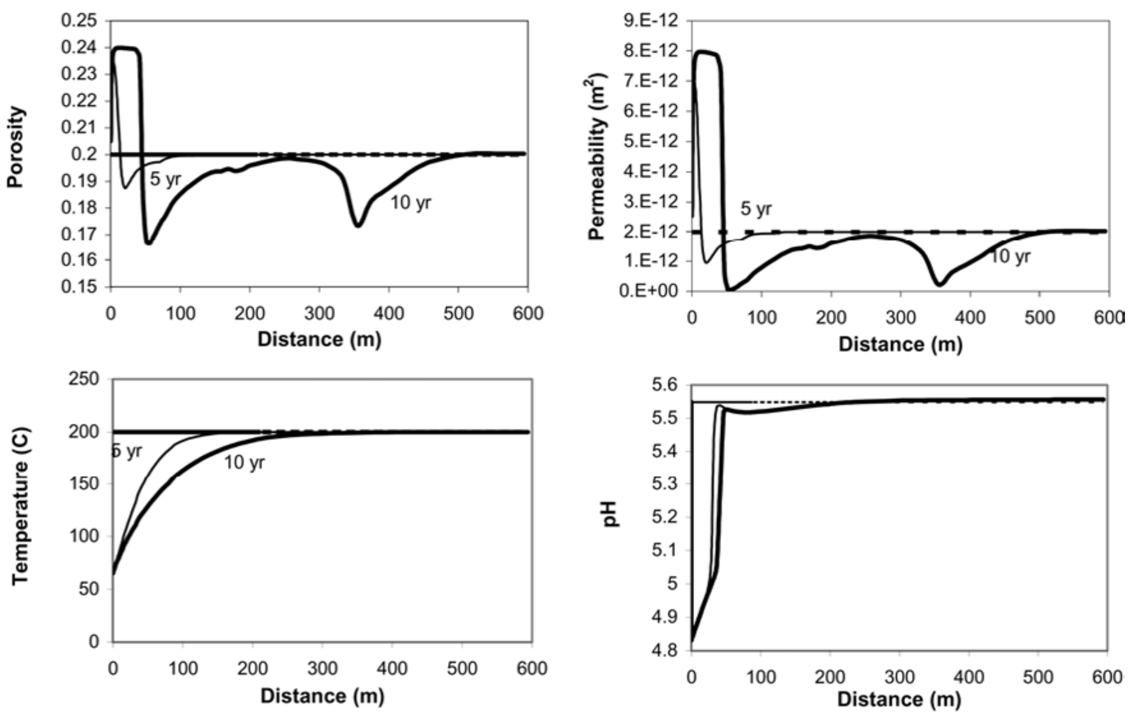

Fig. 3. Distribution of porosity, permeability, temperature, and pH with distance from injection well for Simulation 2 considering porosity-permeability changes in the open-loop system.

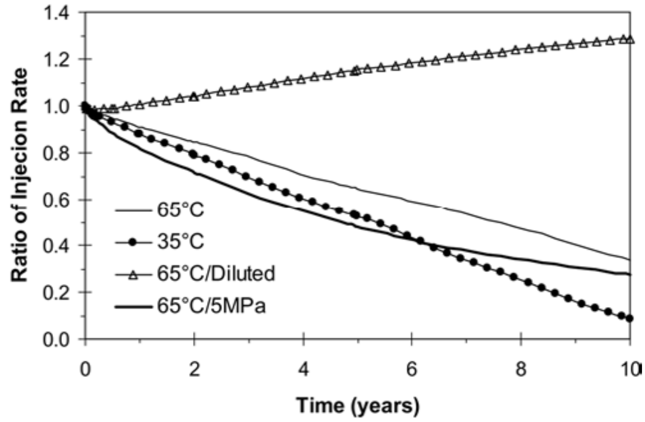

Fig. 5. Injection rate (kg/s) variations over time in the open-loop GHP system with various conditions: (1) 65°C injection water temperature, (2) 35°C injection water temperature, (3) 65°C injection water temperature and diluted water by a factor of 10, and (4) 65°C injection water temperature and 5 MPa over-pressure at injection well. For all cases, porosity-permeability changes was incorporated.

(Fig. 4). But as water moves from the injection well, temperature increases fast and as a result oversaturated calcite rapidly precipitates. The calcite precipitation results in increasing pH. This slowly increasing pH eventually passes the initial pH (5.55) at near 254 m and calcite at equilibrium becomes oversaturated and precipitated.

While calcite precipitates rapidly, quartz precipitation takes place rather slowly due to kinetics even though the injection water is supersaturated with quartz. Precipitation slows down as temperature increases, and at 200°C, quartz becomes under-saturated and dissolution occurs.

Results from three additional simulations with varying conditions were shown in Figure 5 where the ratio of injection rates was used to compare varying injection rates with different overpressure on the injection well. The diluted injection water cases show rapid increase injection rates due to under-saturated chemical composition, while the other two cases (35°C and 65°C with higher overpressure) showed similar decreasing pattern of injection rates to the base case. The cases with higher overpressure (+5MPa) would be beneficial in a long term operation as it reaches steady injection rates faster with less deduction.

4.2. Closed-Loop system

Heat loss to the heat exchanger caused temperature drop in surrounding matrix near the heat exchanger, which initially decreases pH with calcite dissolution but the dropped pH in the pore water increased as other minerals precipitates with lowered temperatures. The lowered temperature resulted in lowered solubility of most minerals, causing mineral precipitations and porosity decrease. However, the changes in the permeability and porosity due to the temperature drop and pH increase were minimal with no liquid injection and minimal inflow from surrounding domain, and the impact of the reduced permeability and porosity on heat flow from the matrix to the heat exchange was negligible during the simulated time (Fig. 6).

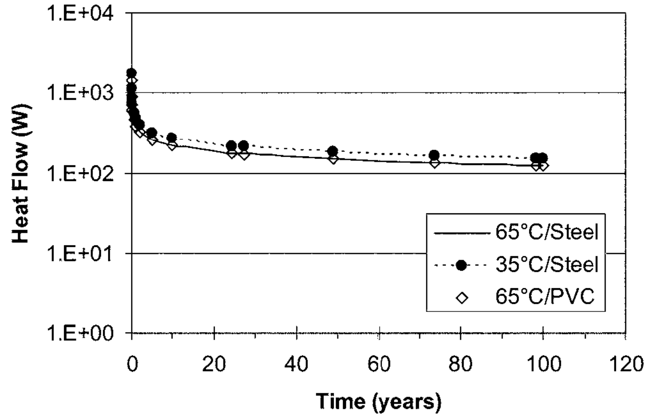

Fig. 6. Heat flow rate variation over time at the heat exchanger steel casing in the closed-loop GHP system. Simulation 1: base case; 2: porosity-permeability changes incorporated.

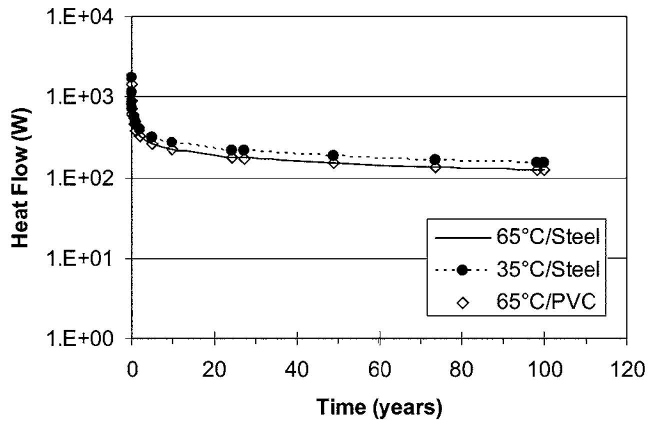

Fig. 7. Heat flow rate variation over time at the heat exchanger with various conditions: (1) 65°C injection water temperature with stainless steel well casing, (2) 35°C injection water temperature with stainless steel well casing, (3) 65°C injection water temperature with PVC well casing in the closed-loop GHP system. For all cases, porosity-permeability changes were incorporated.

As in the open-loop system, two additional runs were performed to see the impact of varying conditions such as temperature inside heat exchanger and well casing materials (Fig. 7). As expected, no significant impact from those conditions were found. Particularly, PVC well casing did not show impacts on heat transfer rates in the long term operation of 100 years. Note that material degradation and surface interaction for mineral precipitation and sorption were not considered in the simulations.

5. SUMMARY AND DISCUSSION

A GHP system with an open-loop or closed-loop setup was examined using TOUGHREACT in terms of the variation in injectivity and heat flow. The changes in porosity-permeability resulted from mineral dissolution and precipitation and impacted the performance of the system differently depending on the GHP system setup. TOUGHREACT offers various options to delineate the relations between porosity and permeability, and provides insights into the geochemical, hydrological, thermal processes that may occur concurrently. However, there are many processes yet to be developed and incorporated into the code, and clay-swelling effect on permeability changes is one of them.

Current study on the GHP system performance is limited to evaluating TOUGHREACT as a tool to predict the system response to lower temperature injection water using general geochemical information. This study showed TOUGHREACT was capable of simulating the heat and water flow in the GHP systems where mineral precipitations and dissolution were considered. However, the processes simulated here were very complicated, and detail analysis should be executed to understand the processes better. For better simulations, it is important to characterize the potential geothermal sites to obtain the information required by the code. Therefore, further study should be focused on to the site characterization as well as designing optimal geothermal heap pump system for the potential site. The optimization requires a system-level modeling including cost analysis (installation cost, operation expenses, system requirement to meet the heating or cooling load, system depreciation, etc), heat balance analysis (reduction in heat source availability, long-term response of the reservoir to heat pumping activity, etc), and geochemical interaction between the GHP system and hosting geological medium (mineral precipitation/dissolution, thermal conductivity alteration, flow field changes, etc.). The system-level modeling involves both the economic and technical analysis, and the TOUGHREACT can provide technical information on the flow of heat and water, as well as thermal and geochemical responses of the ground system to the disturbance from the GHP system.

ACKNOWLEDGEMENTS: This study was supported by the Korea Energy Management Corporation (KEMCO).

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Manuscript received June 7, 2006
Manuscript accepted January 4, 2007