

Numerical Study on CO₂-Brine-Rock Interaction of Enhanced Geothermal Systems with CO₂ as Heat Transmission Fluid

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Abstract. Enhanced Geothermal Systems (EGS) with CO₂ instead of water as heat transmission fluid is an attractive concept for both geothermal resources development and CO₂ geological sequestration. Previous studies show that CO₂ has lots of favorable properties as heat transmission fluid and also can offer geologic storage of CO₂ as an ancillary benefit. However, after CO₂ injection into geological formations, chemical reaction between brine and rock can change chemical characteristics of saline and properties of rock such as porosity and permeability. Is this advantage or disadvantage for EGS operating? To answer this question, we have performed chemically reactive transport modeling to investigate fluid-rock interactions and CO₂ mineral carbonation of Enhanced Geothermal Systems (EGS) site at Desert Peak (Nevada) operated with CO₂. The simulation results show that (1) injection CO₂ can create a core zone fulfilled with CO₂ as main working domain for EGS, and (2) CO₂ storage can induced self-enhancing alteration of EGS.

Keywords: EGS, Carbon Dioxide, CO₂-Brine-Rock Interaction

1 Introduction

With the increasing concern of Enhanced (or engineered) Geothermal Systems (EGS) and carbon dioxide sequestration in deep formation, Donald W. Brown^[1] firstly proposed a new concept of an EGS system that may be operated with supercritical CO₂ instead of water as heat transmission fluid. Such a scheme could combine recovery of geothermal energy with simultaneous geologic storage of CO₂. In comparison with water, Brown^[1] noted that CO₂ has three favorable properties: large expansivity, lower viscosity, and much more stable than water as a solvent for rock minerals. He pointed out there are still unfavorable properties, such as lower heat conductivity of CO₂. In recent years, many studies have been undertaken to investigate the CO₂-brine-rock reaction, heat transmission, and rock mechanics of EGS with CO₂^[2, 3, 4, 5, 6, 9]. There are not only the advantages of CO₂-EGS which include increased heat extraction rates and wellbore flow compared to water-based systems and lesser potential for unfavorable rock-fluid chemical interactions^[6, 7], but also the disadvantages that includes the solubility of CO₂ in water has obvious implications for long-term carbon sequestration and water- rock interactions^[2, 8, 10]. The solubility of water

into CO_2 is very important because it affects the reaction of CO_2 with surrounding rocks and the change of porosity and permeability of rock. These effects depend on the time for removal of water and the lithology of rock. Therefore, it is crucial to study geochemical processes and associated changes in permeability and porosity of a CO_2 -EGS system. A great deal of specific and detailed information is required to assess the geochemistry of such a system. In this study, data for mineralogical composition were taken from the Desert Peak (Nevada) geothermal field^[11]. The study is not intended to represent complete flow system of Desert Peak geothermal field, but to understand geochemical process of CO_2 -EGS at this field.

2 Problem Setup

2.1 Geometric and Flow Conditions

In our simulation, a 10 m thick reservoir formation with an injection well was modeled. A one-dimension radial flow model (Fig.1.) was used, consisting of 60 radial blocks with logarithmically increasing radii out to a distance 10000 m. A initial homogeneous porous medium is considered in the model, with the assumption that the fluid exchange with the surrounding low permeability matrix is insignificant. The uncertainty on the permeability specification does not affect modeling results of reactive transport and porosity changes (as long as pressure buildup at the wellbore can be afforded) because a constant injection rate was specified in the present study. Conductive heat exchange with rocks of low permeability above and below simulation domain is an important process when injection temperature differs from the reservoir temperature. The confining layers are modeled as semi-infinite half spaces, and heat exchange is treated with a semi-analytical technique due to Vinsome&Westerveld (1980). Initial reservoir temperature is 210°C and initial hydrostatic pressure is 200 bar (Fig.1.). Hydrogeologic specifications of the one-dimensional radial problem are given in Table.1.

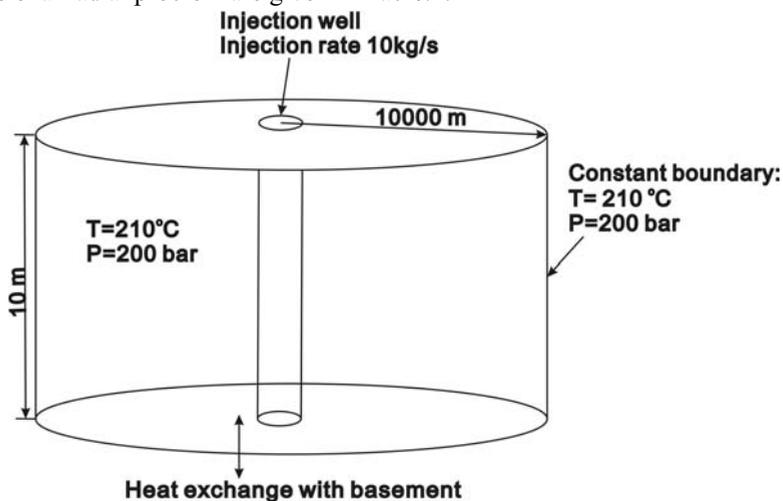


Fig. 1 Simplified conceptual model for one-dimensional radial flow around a geothermal injection well.

Table 1.hydrogeologic specifications for 1-d radial flow problem.

Reservoir properties	value	Initial and boundary conditions		Injection conditions	
		Permeability	$5.0 \times 10^{-14} \text{ m}^2$	Pressure	200 bar
Porosity	0.2	Temperature	210°C	Rate	10.0kg/s
Rock grain	2600 kg/m ³				
Rock specific	1000				
Thermal	2.51				

2.2 Mineralogical Composition and Reaction Kinetics

The initial mineralogical composition used in the modeling is summarized in Table 2. The composition specified was based on the mineralogy of the crystalline rock of pre-Tertiary unit 2 (pT2) from well DP 23-1 of DesertPeak (Nevada) geothermal field, as previously used by Xu et al. (2009). Plagioclase was modeled using 50% low-albite and 50% anorthite. Other trace minerals including epidote, pyrite, and biotite were not considered in the model, because their reactions with the injected fluid are slow and not important for the chemical purpose. Details of the primary mineral composition can be found in Xu et al. (2009). Dolomite, siderite, ankerite, dawsonite, smectite, and kaolinite could be formed after CO₂ injection and are specified as secondary minerals in the simulations. Parameters for the kinetics of mineral reaction used in the mode were taken from Xu et al. (2009 and 2010). The initial waterchemistry is in equilibrium with the initial mineralogy at areservoir temperature of 210°C.

3 Simulation Tool

The present simulations employed the nonisothermal reactive transport code TOUGHREACT (Xu et al., 2006). This code introduces reactive chemistry into the multiphase fluid and heat flow code TOUGH2 (Pruess, 2004). A new fluid property module, ECO2H, based on Spycher and Pruess (2010) work was used. This module provides an accurate description of the thermophysical properties of mixtures of water and CO₂ under conditions typically encountered in CO₂-EGS systems of interest ($12^\circ\text{C} \leq T \leq 300^\circ\text{C}$; $1 \text{ bar} < P \leq 600 \text{ bar}$). Further details on the process capabilities of the TOUGHREACT code are given in Xu et al. (2006).

Table 2. initial mineralogical compositions used in the numerical modeling.

Mineral:	Quartz monzodiorite(% in terms of solid)
Quartz	9
Calcite	12
Albite-Low	12.5
Anorthite	12.5
K- Feldspar	13
Chlorite	8
Illite	7
Others	8

4 Results and Discussion

Fig.2 shows CO₂ saturation as a function of radial distance at different times. Three different zones are formed: (1) a central zone or “core” in which all aqueous phase has been removed by dissolution into the flowing CO₂ stream, so that the reservoir fluid is a single supercritical CO₂ phase; (2) a surrounding intermediate zone, in which the reservoir fluid consists of a two-phase brine-CO₂ mixture; and (3) an outer zone, in which the reservoir fluid is a single aqueous phase with dissolved CO₂. In Zone 1, due to only containing supercritical CO₂, the chemical interactions are weak and the change porosity and permeability are very small. It is the major zone for heat exchange with rock around.

In Zone 2, pH decrease to lower than 5 due to dissolved CO₂. The lower pH causes albite, anorthite, K-feldspar, quartz and chlorite dissolve, and calcite, kaolinite, illite, Na-smectite, Ca-smectite, dolomite, ankerite, and siderite precipitate (Fig.3.). Consequently, the porosity and permeability decrease significantly near the left boundary of Zone 2 (Fig.4.). This is due to (1) CO₂- rich water adds solute mass to the rock matrix and (2) molar volumes of secondary clays are larger than those of the primary minerals. The extent of porosity change is consistent with the mineral alteration mentioned above. The dissolution fronts of primary minerals move over time and occur near the CO₂ source and decreases away from it. The precipitation fronts of secondary minerals also move over time. Precipitation of dolomite, ankerite, and siderite sequesters a significant amount of CO₂. A maximum of about 36kg/m³ of medium were trapped by carbonate precipitation. This zone is the major area that CO₂ is captured by minerals.

Zone 3 only contains water with dissolved CO₂. In this area, the brine-rock interactions are strong due to lower pH, including albite, anorthite, chlorite, K-feldspar and quartz precipitate, and calcite, kaolinite, illite, Na-smectite, Ca-smectite, dolomite, ankerite and siderite dissolve. As a feedback effect, the porosity and permeability increase.

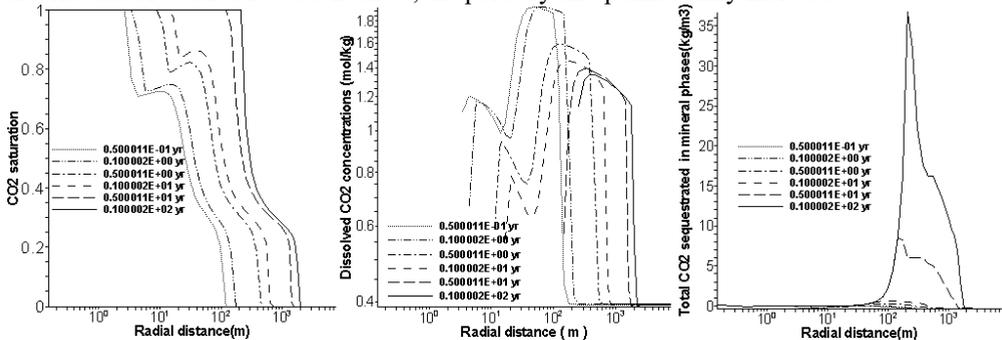


Fig. 2 Different state of CO₂ changes over time in the simulation

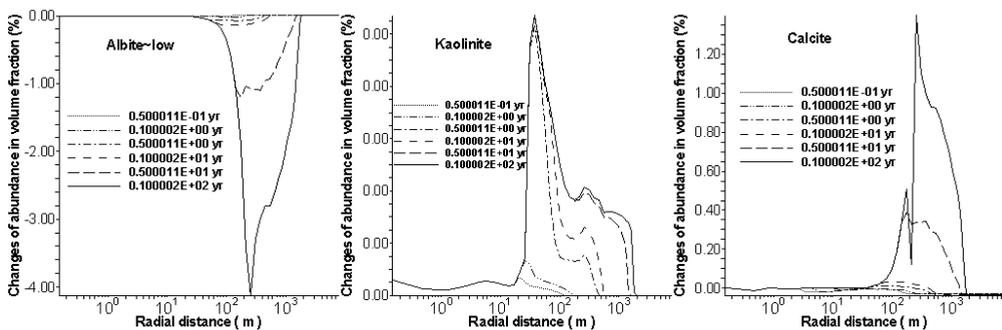


Fig.3 Changes of abundance in volume fraction of minerals over time in the simulation

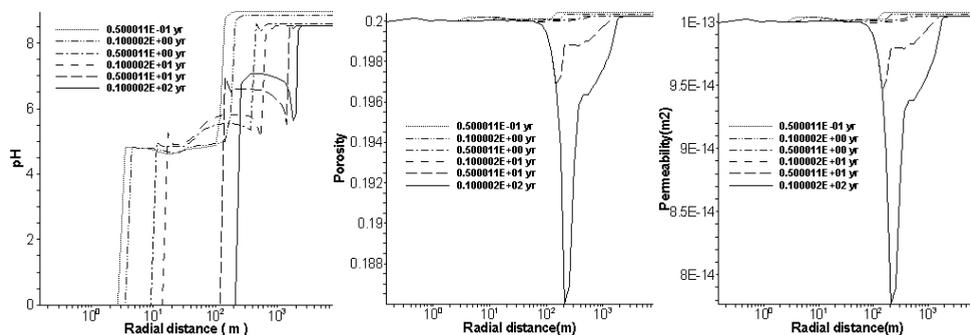


Fig. 4 pH, porosity and permeability changes over time in the simulation

5 Conclusions

Major findings from our simulation are:

In Zone 1, rock-fluid interactions for EGS with CO₂ are weak, which may be more favorable than for water-based EGS but little information is available about chemical interactions between supercritical CO₂ (containing water vapor) and rock minerals.

In Zones 2 and 3, dissolution of primary minerals and precipitation of secondary carbonate and clay minerals are very significant. For Desert Peak mineralogy, the principal minerals undergoing dissolution are albite, anorthite, K-feldspar, quartz and chlorite. Major precipitating secondary minerals are calcite, kaolinite, illite, Na-smectite, Ca-smectite, dolomite, and siderite. Significant CO₂ could be fixed through precipitation of carbonate minerals, which can offer geologic storage of carbon as an ancillary benefit.

Mineral alteration due to dissolved CO₂ generally decreases porosity and permeability which could form a seal that would impact reservoir growth and longevity.

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