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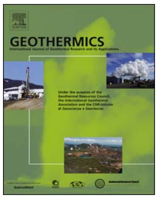

Injection of supercritical CO_2 for geothermal exploitation from single- and dual-continuum reservoirs: Heat mining performance and salt precipitation effect

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ABSTRACT

The geothermal exploitations from the single-continuum (i.e. sandstone here) and dual-continuum (i.e. hot dry rock here) reservoirs using CO_2 have unique advantages and huge application potentials. However, the salt precipitation caused by the evaporation can damage the reservoir and reduce the heat mining rate. In this paper, two comprehensive simulation models are established to analyze the fluid flow, salt precipitation, and its effects on the reservoir properties and heat mining rate during the geothermal exploitation using CO_2 from the sandstone and hot dry rock reservoirs. For the sandstone reservoir, the formation water will flow back to the injection well under the actions of the gravity and the gas-liquid capillary pressure driven by evaporation, which can result in a lot of NaCl precipitating in the injection well. The salt precipitation in the sandstone reservoir can make the steady heat mining rates decrease by about 1/3. For the hot dry rock reservoir, the formation water in the matrix system can be drawn to the fracture through the fracture-matrix interface due to the capillary pressure, which complicates the distribution of the salt precipitation in the fracture system. Under the actions of the back flow in the fracture and flow exchange between fracture and matrix, the salt precipitation mainly occurs in the areas near the injection and production wells, which makes the steady heat mining rate decrease by about 1/2. Both the low-salinity water injections prior the CO_2 injection and after the salt precipitation occurred can effectively reduce the salt precipitation for the sandstone, but only the low-salinity water injection after the salt precipitation occurred can dissolve the precipitated salt and effectively recover the heat mining rate.

1. Introduction

In recent years, with the development of the CO_2 capture and geological storage (Rochelle, 2009; Nghiem et al., 2004), the utilization of CO_2 has received more and more attention and the CO_2 has been suggested as a heat transmission fluid to exploit geothermal energy (Brown, 2000; Pruess, 2006, 2008; Randolph and Saar, 2011; Adams Benjamin et al., 2014; Cui et al., 2016a,b). Compared to water, the conventional heat transmission fluid, there are many advantages for CO_2 during geothermal exploitation (Pruess, 2006, 2008; Randolph and Saar, 2011; Adams Benjamin et al., 2014; Cui et al., 2016a). Firstly, under geothermal reservoir conditions, CO_2 will be in its supercritical state with low viscosity and high mass density, which can increase the production and heat mining rate for any given pressure gradient (Pruess, 2006, 2008). Secondly, CO_2 has larger compressibility than water, which can generate a thermo-siphon effect and buoyancy force between injection and production wells to reduce the power consumption in fluid circulation systems (Pruess, 2008; Adams Benjamin et al., 2014). Thirdly, combined with the CO_2 geological storage technology, almost all the injected CO_2 can be sequestrated in the reservoir after geothermal exploitation (Pruess, 2006, 2008; Randolph and Saar, 2011; Cui et al., 2016a,b), which can effectively reduce the emission of the greenhouse gas.

The research on the CO_2-based geothermal exploitation has been very active in recent years. The concept of using CO_2 as a heat transmission fluid was first proposed to exploit geothermal from hot dry rock by Brown (CO_2-EGS) (Brown, 2000), subsequently, a lot of research has been conducted to study the fluid flow and the heat mining rate in the CO_2-EGS in detail (Pruess, 2006, 2008; Xu et al., 2008; Zhang et al., 2014). Pruess et al. quantitatively analyzed the thermophysical and dynamic properties of the CO_2 and showed that the heat mining rate of CO_2 is 50% higher than water (Pruess, 2006, 2008). Xu e al. and Cui et al. also performed simulation to evaluate the heat mining rate and conclude that CO_2 is more efficient than water during geothermal exploitation (Xu et al., 2008; Zhang et al., 2014). In 2011, Randolph et al. proposed a new concept called as the CO_2-plume geothermal (CPG)

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system (Randolph and Saar, 2011), in which CO_2 is used to exploit geothermal form a natural high-permeability reservoir that is overlain by a low-permeability cap rock. Natural high-temperature reservoirs are ubiquitous throughout the world and have larger pore volumes than tight hot dry rocks, which means more CO_2 can be sequestrated and more geothermal can be exploited (Adams Benjamin et al., 2014; Xu et al., 2014). In addition, the CPG system can reduce or eliminate the need for complex and expensive hydraulic fracturing that is typically required in the EGS system (Randolph and Saar, 2011; Adams Benjamin et al., 2014; Xu et al., 2014). All of this research has fully shown that geothermal exploitation using CO_2 from hot dry rock and sandstone reservoirs has great application prospect and development potential.

However, the water will evaporate into the injected dry CO_2 during geothermal exploitation and results in the NaCl precipitating from the formation water, which can affect the porosity and permeability and then the fluid flow (Zhang et al., 2016) and heat mining rate of $SCCO_2$ (Muller et al., 2009; Bacci et al., 2011; Peysson et al., 2011; Ott et al., 2015; Zeidouni et al., 2009; Borgia et al., 2012, 2013). Many laboratory experiments have been conducted to analyze the salt precipitation and its influence on the fluid flow (Muller et al., 2009; Bacci et al., 2011; Peysson et al., 2011; Ott et al., 2015). A core flooding experiment showed that the small reduction in porosity caused by the salt precipitation can reduce significant impairments in permeability (Bacci et al., 2011). Further, many core scanning experiments demonstrated that a locally high salt precipitation can occur near the injection well due to the back flow of the formation water (Peysson et al., 2011; Ott et al., 2015). In the numerical simulation aspect, many multiphase reactive flow simulations (Cui et al., 2016a; Ott et al., 2015; Zeidouni et al., 2009; Borgia et al., 2012, 2013) suggest that evaporation of formation water caused by CO_2 can cause salt precipitation and reduce the flow and heat mining rate. Cui et al. performed a two-dimension simulation to assess the heat mining rate and the influence of salt precipitation during geothermal exploitation from a typical high-temperature gas reservoir using CO_2, and concluded that a lot of NaCl will precipitate in the injection well area due to the back flow of the formation water (Cui et al., 2016a). Nicolas Spycher et al. analyzed the salt precipitation and its effect during geothermal exploitation from hot dry rock, and observed that significant clogging caused by salt precipitation can occur in the region close to production well after less than 10 years injection of CO_2 for a low-salinity system, and clogging can occur near the injection well in less than one year for high salinity water (Borgia et al., 2012, 2013). All of these works suggest that salt precipitation can significantly impact the formation porosity and permeability and fluid flow in the porous media. This would severely compromise the geothermal exploitation efficiency eventually.

Usually, the geothermal reservoirs are divided into two types according to the fluid flow characteristic in the porous media, which are single-continuum and dual-continuum geothermal reservoirs, respectively (Cui et al., 2017b,c). Such as the sandstone, a typical single-continuum reservoir, it has a natural pore structure which acts as the channel for the fluid flow as well as the heat source. However, there are many fractures (natural or hydro-fracturing) in the dual-continuum reservoir in which the fracture mainly acts as the channel for flow while the matrix porous structure mainly acts as the sources for fluid and heat (Borgia et al., 2012; Yamamura and Ogino, 2002). Hot dry rock is a typical dual-continuum reservoir, in which the hydraulically created fracture has high permeability and provides the channel for flow while the tight matrix provides the heat for heat exchange. The variations of reservoir properties and fluid flow in different types of geothermal reservoirs may cause different salt precipitation when CO_2 is used to exploit geothermal, which in turn can affect the flow behavior and heat mining rate.

However, there is a lack of systematic research work on the salt precipitation and its effect on the heat mining in different types of reservoirs. Therefore, it is necessary to analyze the difference of the salt precipitation and its influence on the heat mining rate through putting single- and dual-continuum reservoirs together. In this study, the sandstone and hot dry rock reservoirs were analyzed to represent the single- and dual-continuum reservoirs due to their wide distributions and typical single- and dual-continuum characteristics (Cui et al., 2017b; Yamamura and Ogino, 2002). Through the compared study, the characteristics of salt precipitation in the different types of reservoir can be more easily clarified, and some specific measures to reduce the salt precipitation can be more easily developed.

The main objective of this study is to evaluate the salt precipitation occurred and its effect on reservoir property and heat mining rate in different types of reservoirs during geothermal exploitation using CO_2 as a heat transmission fluid. Therefore, two comprehensive models were firstly established for geothermal exploitation from the sandstone and hot dry rock reservoirs, which can model the water evaporation, the salt precipitation/dissolution, the changes of the porosity and permeability, and the flow and heat mining rates. Using these models, the fluid flow, salt precipitation, and its influence on reservoir properties and heat mining rate in different types of reservoirs were analyzed, which can help people to understand the characteristics of salt precipitation and heat mining in different types of reservoirs. Meanwhile, three kinds of measures to reduce salt precipitation were simulated and their effectiveness in sandstone and hot dry rock reservoirs were evaluated, which can enhance the utilization potential of the CO_2.

2. Comprehensive models for geothermal exploitation

The CO_2 injection can cause the continuous evaporation of H_2O, which can increase the salinity of the formation water and make the NaCl precipitate from the formation water eventually. Usually, the process of the formation water evaporation is relatively fast and can be considered as a thermodynamic process (Cui et al., 2016b; Cui et al., 2017b), so it is reasonable to assume its equilibrium can be reached instantaneously in the simulation. Therefore, in this study, the evaporation of formation water into the CO_2 phase is simulated through inserting the gas-liquid K-value tables under different pressure and temperature (Tian et al., 2008). The gas-liquid K-value is defined as the gas phase mole fraction of the component divided by the liquid phase mole fraction of the component in the phase equilibrium, which is generated using the equation of state.

2.1. Math model of salt precipitation and dissolution

The dissolved NaCl starts to precipitate from the formation water only when the concentration of NaCl is higher than its solubility. Otherwise, the precipitated salt starts to dissolve. The rate of salt precipitation/dissolution is slower than the rate of water evaporation, and its equilibrium can not be achived instantaneously, so a kinetic model is adopted to simulate the salt precipitation and dissolution in this study (Cui et al., 2016a).

$$v = ke^{-E_a/(T_{abs}\cdot \mathrm{R})}\cdot C_{NaCl} \tag{1}$$

where v is the rate of salt precipitation or dissolution in unit pore volume, mol/(s m^3); k is the reaction constant and in here is set to 10 based on the experiments results (Alkattan et al., 1997; Jin et al., 2016), s^{-1}; E_a is the activity energy and is set to 2000 based on the experiments results (Alkattan et al., 1997), J/mol; T_{abs} is the reference temperature, °C; R is the universal gas constant, J/(mol °C); C_{NaCl} is the apparent quantity of NaCl (in water phase) in unit pore volume, mol/m^3, and it is defined by the following equation:

$$C_{NaCl} = \rho_l \cdot S_l \cdot (x_{NaCl} - x_{sat}) \tag{2}$$

where S_l is the saturation of the liquid phase, dimensionless unit; ρ_l is the mole density of the liquid phase, mol/m^3; x_{NaCl} is the real-time concentration of NaCl, mole fraction in formation water; x_{sat} is the NaCl saturation concentration in the liquid phase (i.e. the solubility of NaCl), mole fraction in formation water. When c_{NaCl} is higher than 0, salt