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Numerical study on the heat transfer characteristics between supercritical carbon dioxide and granite fracture wall

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ABSTRACT

A two-dimensional numerical model was developed to investigate the flow and heat transfer characteristics of supercritical carbon dioxide ($scCO_2$). The numerical results of flow and heat transfer characteristics of $scCO_2$ through straight granite fracture were found to be in good agreement with the experimental results. Moreover, the heat transfer characteristics between $scCO_2$ and rough granite fractures were also investigated by using the proposed model. The confining temperature outside the specimen was set at 200 °C and the pressure of $scCO_2$ was 8 MPa. Four different case studies with the flow rates of 0.75, 0.51, 0.35, and 0.13 kg h^{-1} were, respectively, designed. The overall and the local heat transfer coefficients (OHTC, LHTC) were used to characterize the heat transfer properties of these cases. Furthermore, the effects of flow rate, fracture roughness, and phase state of CO_2 on the heat transfer characteristics of CO_2 were investigated. The results indicated that increased roughness or flow rate could improve the heat transfer performance of $scCO_2$. Moreover, on the same area of the fracture, the temperature of the fracture wall was found to be always higher compared to that of $scCO_2$; much similar to the water behavior and the OHTC of $scCO_2$ increased with the increase in the injection flow rate. Surface morphology of the fracture significantly influenced the LHTC distribution of $scCO_2$, and LHTC roughly exhibited a negative correlation with the local waviness of fracture. This was pronounced at the sunken positions of the fracture surface, which exhibited significantly larger LHTCs compared to the prominent positions. The heat transfer characteristics of CO_2 were found to be closely related to its phase state. CO_2 in the denser phase showed better heat transfer performance.

1. Introduction

The deep hot dry rock (HDR) geothermal systems are highly-valued worldwide resources with sufficient energy for their great potential, renewability, and cleanliness. Recovery of HDR geothermal resources strongly relies on effectively connected systems of underground fractures which form an enhanced geothermal system (EGS). In traditional EGS, water is employed as the working fluid for heat exchange and looping. In the context of climate change, carbon dioxide (CO_2)-EGS was proposed as an alternative option by Brown (Brown, 2000); however, CO_2-EGS research is still in its infancy stage (Yan-guang et al., 2015). CO_2-EGS has been considered not only to possess outstanding advantages (Olasolo et al., 2016) to harness geothermal energy from HDR due to different thermodynamic and transport properties, but also provides an additional benefit of CO_2 geological storage (Luo et al., 2014), in particular, in water scarce regions (Remoroza et al., 2012). Moreover, supercritical CO_2 ($scCO_2$) is also considered as an alternative to water for its good mobility and heat capacity (Zhang et al., 2014; Zhang et al., 2017a). In order to address the core concerns and issues with regard to CO_2-EGS, comprehensive understanding of the process and characteristics of heat transfer between CO_2 and the HDR fracture during the heat recovery is significantly important (Pruess and Azaroual, 2006).

A fully developed EGS with CO_2 ordinarily consists of the following three distinct zones (Fouillac et al., 2004) (Fig. 1): (1) a central zone or “core” (Zone 1) in which the reservoir fluid is a single $scCO_2$ phase; (2) a surrounding intermediate zone (Zone 2), where in the reservoir fluid consists of a two-phase water-CO_2 mixture; and (3) an outer or peripheral zone (Zone 3) containing the reservoir fluid as a single aqueous phase with dissolved CO_2. Therefore, in CO_2-EGS, CO_2 usually stays in supercritical state. Heat transfer characteristics between water and granite have been extensively investigated till date. At present, extensive research efforts are being devoted to the study on the flow and heat transfer of $scCO_2$ in the pipeline (Jiang et al., 2008; Luo, 2014) or porous media (Luo et al., 2011; Zhang et al., 2016a). Magliocco et al. (Magliocco et al., 2011) conducted a laboratory experimental study of

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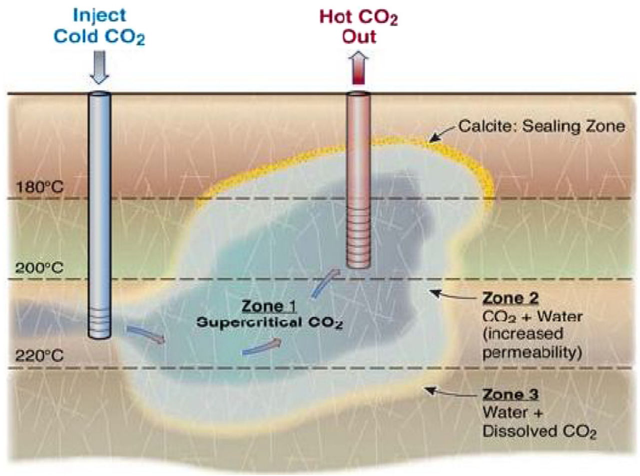

Fig. 1. Schematic illustration of the three zones created by injection of CO_2 into hot fractured rock (Xu et al., 2014).

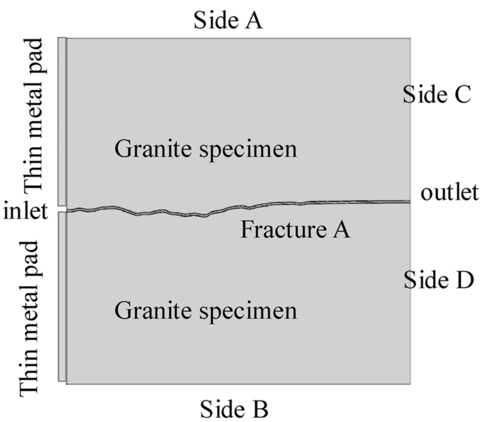

Fig. 2. Conceptual model of $scCO_2$ flow and heat transfer through a single 2D granite fracture.

heat recovery from porous media by means of CO_2 and further performed few simulation investigations on CO_2-EGS at field scale. However, the flow and heat transfer characteristics between $scCO_2$ and granite fracture wall are still poorly understood due to limited research in this area. Recently, Zhang et al. (Zhang et al., 2016b) conducted a preliminary study by performing experiments related to $scCO_2$. They investigated the CO_2 flow and heat exchange in a parallel smooth granite fracture with an aperture of 0.2 mm. The variation characteristics of the temperature of the fracture wall, the inlet and outlet temperatures of $scCO_2$, and the absorbed heat from the rock were analyzed, respectively. Furthermore, the Nusselt numbers for the fully developed flow stage were obtained for $scCO_2$ in the smooth rock fracture. However, the actual rock fracture is usually irregular and the roughness of fracture surface can significantly affect the flow and heat transfer characteristics (He et al., 2016; Zhang et al., 2017b). Moreover, the fracture is usually very narrow; therefore, direct measurement of the thermal parameters is challenging. Noteworthy, the local heat transfer characteristics of $scCO_2$ along rough granite fractures have never been investigated.

The main objective of this study was to numerically investigate the heat transfer process and characteristics between flowing $scCO_2$ and rough granite fracture wall, to contribute in comprehension of heat convection process of $scCO_2$ in rock fractures. In section “Numerical modeling”, the numerical model is described in detail. Then in section “scCO2 heat transfer in straight granite fracture”, the first application of the proposed model is presented. This section provides the model verification, by using the existing test data obtained from a straight granite fracture and simultaneously includes some properties, which cannot be obtained directly from the test. In section “Heat transfer characteristics in rough fracture”, detailed description of a series of simulations conducted in this study is provided, and according to the result, the overall and local heat transfer characteristics of $scCO_2$ are systematically presented. In section “Discussion”, the dependence of the heat transfer characteristics on the phase state of CO_2 is analyzed. Finally, primary findings are summarized in section “Conclusions”.

2. Numerical modeling

The aperture of the rock fracture is usually of micron-scale; therefore, it is technically extremely difficult to install sensors and measure the temperature directly inside the micron-scale fracture. Even if it is possible, it would actually change the surface topography of the fracture, thus disturbing the fluid motion and heat transfer in the fracture. Fortunately, the temperature and pressure distributions inside the fracture can be easily obtained based on the numerical simulation approach. A two-dimensional (2D) model developed by Bai et al. (Bai et al., 2016) was successfully applied to investigate the local heat transfer characteristics of water flow and heat transfer through granite fracture. Model was verified by the test data. According to that model, water was considered to be incompressible at temperatures below 100 °C. However, during actual CO_2-EGS recovery process, the temperature and pressure of the working fluid might undergo a wide range of condition variations. Therefore, it leads to a significant change in the thermal properties of the working fluid, thus influencing the heat transfer effect. Therefore, in this study, the model proposed by Bai et al. was modified for $scCO_2$ flow and heat transfer, by stressing on the compressibility and changes in thermal properties. Fig. 2 illustrates the concept model (Bai et al., 2016).

In this study, the physical parameters of $scCO_2$ were calculated by applying REFPROP9.0 (Lemmon et al., 2010). Owing to the negligible pressure differences between the inlet and outlet of the examined samples, the physical properties of the samples have insignificant effect on the results obtained due to pressure change (Cui, 2014). Therefore, the physical properties of the $scCO_2$ were in accordance with the corresponding values reported in literature (Lemmon et al., 2010). As an example, physical parameters of the $scCO_2$ at the pressure of 8.0 MPa are presented in Fig. 3. Herein, the pressure drop was limited and it exhibited minor effect on the physical parameters of $scCO_2$ as indicated by the comparison between the inlet and the outlet of the fracture. Therefore, the values of the physical parameters of $scCO_2$ corresponding to the experimental pressure, reported by Zhang et al. (Zhang et al., 2016b), were used throughout this study. Fig. 3 depicts the physical parameters of $scCO_2$ at the pressure of 8.0 MPa. The density of $scCO_2$, the specific heat capacity at constant pressure C_p, the thermal conductivity (K), and the viscosity are interpolated from the generated data points, respectively. As the aperture of the fracture is micron-scale, the temperature gradient between the boundary layer and the mainstream is fairly low. Consequently, this leads to a very small density gradient. Therefore, the buoyancy induced by the density gradient is negligible.

The flow and heat transfer processes between $scCO_2$ and granite fracture wall were coupled together. The corresponding coupling numerical model was developed based on the Comsol Multiphysics simulator which requires that the mathematical equations of the processes involved be given first. The single-phase $scCO_2$ flow in the fracture follows the Navier–Stokes equations, as represented below:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0 \tag{1}$$

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \nabla\cdot\left(\mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}\mu(\nabla\cdot\mathbf{u})I\right) \tag{2}$$

Eqs. (1) and (2) are the continuity equation and momentum