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Effects of effective stress and temperature on permeability of sandstone from CO_2-plume geothermal reservoir

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ABSTRACT

Rock is generally complex and heterogeneous, therefore the heterogeneity effects of effective stress and temperature on permeability should be taken into account. In this study, two-part Hooke's model (TPHM) is introduced to understand the influences of effective stress and temperature on permeability of soft and hard parts (two parts) of rock based on coupling thermo-hydro-mechanical tests. Under a fixed temperature level (25 °C, 35 °C, 50 °C, 65 °C, 80 °C, 90 °C and 95 °C), the tests were carried out in a conventional triaxial system whereas the confining pressure was remained at 50 MPa, and the pore pressure was increased to the specified levels step by step, i.e. 8 MPa, 18 MPa, 28 MPa, 38 MPa, 41 MPa, 44 MPa, 46 MPa and 48 MPa. The temperature-dependent relationships for two parts permeabilities are proposed on the basis of the initial test results. We point out that temperature of 65 °C–90 °C is the threshold for the development of CO_2-plume geothermal (CPG) reservoir sandstone cracking under low effective stress (2–9 MPa) based on the relationship between temperature and soft part permeability. Furthermore, we discuss the effect of temperature on the two parts in the rock. The results indicate that as the temperature increases from 25 °C to 65 °C, the flow channel in the hard part has a stronger response to temperature than that in the soft part at a fixed effective stress level, which is opposite to the situation of effective stress. Considering that natural rock is generally heterogeneous with non-uniform pore structure, we suggest a physical interpretation of the phenomenon that before the thermal cracking threshold the two parts have different responses to temperature.

1. Introduction

Rock permeability, which is dependent on effective stress and temperature, plays a critical role in various engineering applications, such as petroleum exploitation, nuclear waste disposal, natural gas exploration, carbon dioxide (CO_2) geological sequestration and geothermal exploration (Ran and Li, 1997; He and Yang, 2005; Zhou et al., 2016). Nowadays, coupling CO_2 sequestration with geothermal energy capture in deep saline aquifers, called the CO_2-plume geothermal (CPG) system, has been widely considered as an effective technology for mitigating CO_2 emissions to the atmosphere (Randolph and Saar, 2011). In the process of cryogenic fluid (CO_2) injection and high temperature fluid (water) drainage, the permeability of reservoir sandstone is influenced by the changing pore pressure and temperature. This has a significant influence on the CO_2 sequestration and mining thermal efficiency. Therefore, it is necessary to explore the effects of effective stress and temperature on the permeability of sandstone from CPG reservoir.

The effects of effective stress and temperature on the permeability of the reservoir rock over a long time, associated with many theoretical studies, have been reported. For example, Ran and Li (1997) suggested that the rock total volume is composed of the matrix volume and the pore volume. The variation of the rock matrix volume is entirely caused by thermal expansion of the solid grain, and the relationship among the permeability, porosity, effective stress and temperature was derived on the basis of the

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Kozeny–Carman equation. In addition, laboratory test results indicated that the permeability decreases with increasing temperature and effective stress before thermal cracking occurred in rock (He and Yang, 2005; Liu et al., 2011; Zhou et al., 2016).

Previous studies have shown that the permeability usually decreases by more than one order of magnitude when the effective stress increases from zero to around 15 MPa (Thomas and Ward, 1972; Jones and Owens, 1980; Kilmer et al., 1987; David et al., 1994). Furthermore, this phenomenon was accompanied with small porosity decreases (David et al., 1994). The deformation of the pores has a significant influence on the rock flow channel. However, the natural rock is heterogeneous and the pores are non-uniform (Berryman, 1992). Walsh (1980) indicated that the rock pores can be divided into two categories: equant dimension pores and flat pores (cracks or low aspect ratio pores). Furthermore, some studies indicated that the microcracks, as a part of the pores, have either closed or experienced large deformation with increasing confining pressure (Brower and Morrow, 1985; Smith et al., 2009).

To explain the stress-sensitive phenomenon of permeability in the low effective stress range for low-permeability rock, Zheng et al. (2015) established a relationship between the permeability and effective stress based on the concept of the two-part Hooke's model (TPHM). The TPHM is a macroscopic model that can deal with microscale mechanisms in a phenomenological manner developed by Liu et al. (2009). The TPHM divides the rock into two categories: the soft part with microcracks and the hard part with general pores. These two parts are subjected to the same stress, but follow different variations of Hooke's law (Liu et al., 2009). Zheng et al. (2015) indicated that the general pores and microcracks have different contributions to permeability, and the derived relationships satisfactorily explain the stress-sensitive phenomenon of permeability in the low effective stress range for low-permeability rock. It was further pointed out that the soft part, while only a small portion of the low-permeability rock, plays a critical role in the relationship between the permeability and effective stress.

The deformation of the pores also acts as a bridge that links the permeability changes and temperature (Zhang et al., 2008). Several attempts indicated that it is necessary to consider the role of the non-uniform pores in the temperature-dependent permeability relationship. For example, test results obtained by He and Yang (2005) showed that at the same temperature level, the permeability is much lower than the predicted result from Ran and Li (1997)'s formula, which is derived on the basis of the capillary bundle model.

Many scholars believe that the non-uniform pores deserve much more attention. For example, Liu et al. (2011) studied the effects of confining pressure and temperature on porosity and permeability for two groups of low-permeability sandstone samples: a "low-porosity group" and a "high-porosity group". Keeping the confining pressure at 5 MPa, and increasing the temperature from 25 °C to 80 °C, the test results showed that the porosity and permeability of low-porosity sandstone samples decreased by 34.7% and 75.1%, respectively; while those of the high-porosity group decreased by 18.4% and 35.2%, respectively. For rock with microcracks, some studies indicated that the microcracks are closed due to the thermal expansion of solid grain (Baldridge et al., 1972; Todd et al., 1973; Cooper and Simmons, 1977). For homogeneous rock with uniform pores, studies showed that the Euler porosity remains unchanged with increasing temperature under the drained condition (Ghabezloo and Sulem, 2009; Ghabezloo et al., 2009; Khalili et al., 2010). Up to now, the relationship among temperature, pore deformation and permeability is still not clear.

As mentioned above, both the pores and the microcracks are influenced by temperature. To address this problem, Hassanzadegan et al. (2014) divided the porosity into two parts: crack porosity and porosity. Results of dynamic modulus tests and temperature unloading tests indicated that for sandstone under the drained condition, the porosity increases with increasing temperature in low effective pressure ranges and decreases with increasing temperature in high effective pressure ranges; while the crack porosity decreases when the temperature increases from 25 °C to 90 °C, and increases when the temperature increases from 90 °C to 140 °C. However, the role of the non-uniform pores in the relationship between the permeability and temperature is rarely reported. This paper attempts to discuss the effects of effective stress and temperature on the permeability of sandstone from CPG reservoir. First, the relationships among rock permeability, temperature and effective stress are obtained from the permeability test. Then the temperature-dependent relationships for two parts permeabilities are established on the basis of Zheng et al. (2015)'s formula and the associated test results. Finally, we discuss the effect of temperature on the two parts in the rock.

2. Brief description of stress-dependent permeability relationship based on two-part Hooke's model

The TPHM conceptually divides the rock into soft part and hard part. These two parts are subjected to the same stress, but follow different variations of Hooke's law due to rock heterogeneity. The soft part is assumed to obey the true-strain-based Hooke's law, while the hard part is assumed to approximately follow the engineering-strain-based Hooke's law, because the deformation of the hard part is small (the true strain is practically identical to engineering strain when the deformation is small). This TPHM can be represented by the hypothesized composite spring system as shown in Fig. 1. Note that in this study, the subscripts '0', 'e' and 't' denote the unstressed state, the hard and soft parts, respectively, and the superscript 'p' refers to pore volume.

For the soft part, Hooke's law can be expressed using the true strain:

$$\mathrm{d}\sigma = K_\mathrm{t}\mathrm{d}\varepsilon_{\mathrm{V,t}} = -K_\mathrm{t}\frac{\mathrm{d}V_\mathrm{t}}{V_\mathrm{t}} \tag{1}$$

For the hard part, using the engineering strain, we have

$$\mathrm{d}\sigma = K_\mathrm{e}\mathrm{d}\varepsilon_{\mathrm{V,e}} = -K_\mathrm{e}\frac{\mathrm{d}V_\mathrm{e}}{V_{\mathrm{e},0}} \tag{2}$$

where σ is the effective stress; K_t and K_e are the elastic moduli of the soft and hard parts, respectively; V_t and V_e are the volumes of the soft and hard parts under the current stress state, respectively; $\varepsilon_{\mathrm{V,t}}$ and $\varepsilon_{\mathrm{V,e}}$ are the true strain for the soft part and engineering strain for the hard part, respectively.

Integrating Eqs. (1) and (2) under initial conditions $V_\mathrm{t} = V_{\mathrm{t},0}$ and $V_\mathrm{e} = V_{\mathrm{e},0}$, we have

$$V_\mathrm{t} = V_{\mathrm{t},0}\exp\left(-\frac{\sigma}{K_\mathrm{t}}\right) \tag{3}$$

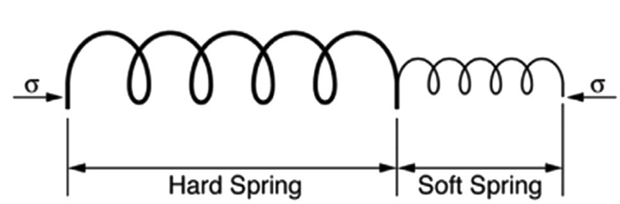

Fig. 1. A composite system of two springs.