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Permeability and Porosity of Tight Rock Materials under Conditions of High Temperature and High Pressure

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Abstract. Experiments were performed by using an improved test system of physical parameters of rock materials. Influence of effective stress, temperature and flow velocity of fluid on permeability or porosity of tight rock materials under high temperature and high pressure was investigated. A micro-mechanism was given to interpret changes of the permeability or the porosity by means of a microscopic imaging method. Results show that the permeability decreases with an increase in effective stress or temperature and increases with an increase in flow velocity of fluid, and that relative change of the porosity increases with an increase of effective stress and is not detectable with an increase in temperature. The main reasons for the above changes are nonlinear flow and narrowing of micro-cracks under action of effective stress or thermal effects. Changes of the micro-cracks play a more important role in the permeability than in the porosity. The results can provide engineering geological disposal of high level radioactive waste with basis.

Introduction

Permeability and porosity are important physical property parameters of rock materials. Several researchers have investigated permeability or porosity of porous media such as Collins [1] and Scheidegger [2]. Brace *et al*. [3] studied permeability of granite under high pressure. Laurent *et al*. [4] discussed pore-pressure influence on elastic behavior of rocks. Peng *et al*. [5] analyzed permeability of sandstone under different confining pressures. Guo *et al*. [6] described microscopic characteristics of flow of physical chemistry fluid in porous media. The rock physical parameter automatic testing system is the first system in the world [7] to measure simultaneously rock mechanics parameters and ultrasonic velocities under formation conditions.

In this paper, an improved test system of physical parameters of rock materials was employed to test permeability and porosity of tight rock materials under high temperature and high pressure. Influence of effective stress, temperature and flow velocity of fluid on the permeability or the porosity was considered. A micro-mechanism was given to interpret changes of the permeability or the porosity by means of a microscopic imaging method.

Improvement of Equipment and Flow Chart

The experimental instrument was developed technically by the state key laboratory of Chengdu University of Technology with the help of loans of the World Bank.

Technicians of the state key laboratory researched and developed independently a pressure monitoring device of cooling water of hydraulic source and a deionizer of heat-shrinkable tubing.

The schematic diagram of flow chart of experimental facility is shown in Fig. 1.

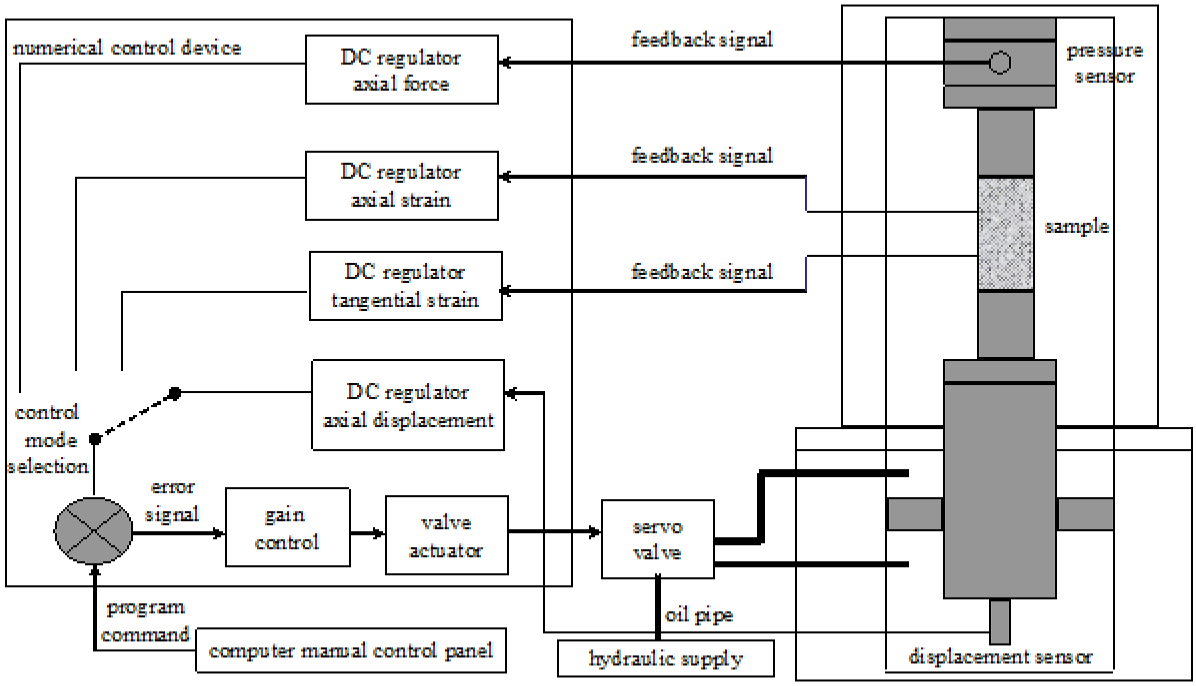


Fig. 1 Schematic diagram of flow chart of experimental facility

Experimental Materials and Method

The main experimental materials were tight rock and distilled water. Experiments were carried out under conditions of high temperature and high pressure. The experimental conditions were selected according to formation conditions (temperature: 20ºC - 200ºC, confining pressure: 1 MPa - 140 MPa, pore pressure: 0 MPa - 70 MPa, axial load: 0 kN - 1000 kN).

The experiment included the following procedures: (1) to check pressures of all the water sources; (2) to switch a hydraulic source, a controller and a computer selectively; (3) to select and install related devices; (4) to switch a controller and a control computer; (5) to adjust and maintain appropriate initial pressure; (6) to seal up a rock sample; (7) to close a tri-axial chamber; (8) to run a test procedure; (9) to heat; (10) to terminate a test according to the procedure; and (11) to empty oil after the temperature of the tri-axial chamber below or equal to 70ºC.

Formulae for Permeability and Porosity

A formula to calculate permeability of rock for the improved test system can be expressed as

$$K = \mu\beta V \frac{\ln\left(\Delta p_{\mathrm{i}} / \Delta p_{\mathrm{f}}\right)}{2\Delta t\left(A_{\mathrm{s}} / L_{\mathrm{s}}\right)}. \tag{1}$$

where, K is permeability, μ is dynamic viscosity of fluid, β is the coefficient of compressibility of fluid, V is volume of a standard chamber, $\ln(\cdot)$ is natural logarithm, Δp_{i} is initial differential pressure, Δp_{f} is final differential pressure, Δt is time of the corresponding differential pressure, A_{s} is sectional area of rock materials and L_{s} is length of rock materials.

A formula to calculate porosity of rock for the improved test system can be written as

$$n = \frac{V_{\mathrm{po}} - \left(\Delta V_{\mathrm{pt}} - \Delta V_{\mathrm{pm}}\right)}{V_{\mathrm{To}}\left(1 - \varepsilon_{v}\right)} \times 100\%. \tag{2}$$

where, n is porosity, V_{po} is initial pore volume, ΔV_{pt} is measurement value of pore volume change under current pressure, ΔV_{pm} is system volume variation under current pressure, V_{To} is initial total volume of rock materials, ε_v is volumetric strain.

Results and Discussion

The permeability and the porosity were obtained. Fig. 2 shows that the permeability of tight rock materials decreases with an increase in effective stress. Fig. 3 shows that the permeability decreases with an increase in temperature. Fig. 4 shows that the permeability increases with an increase in flow velocity of fluid. Fig. 5 shows relative change of porosity increases with the increase of effective stress. It is found that the porosity of tight rock materials has no detectable changes with an increase in temperature under high temperature and high pressure.

In most circumstance, flow of water in high-permeability rock follows Darcy's law so that permeability is a constant value which has nothing to do with flow velocity of fluid. But it is noted that Fig. 4 gives a new phenomenon. The main reason for the phenomenon should be the nonlinear flow in tight rock materials.

Both permeability and porosity are a macroscopic and statistical average value. However, a micro-mechanism of the above results can be analyzed by a microscopic imaging method.

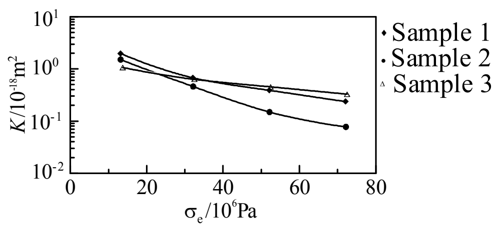


Fig. 2 K changes with σ_e (effective stress)

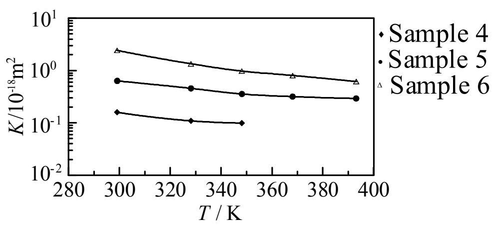


Fig. 3 K changes with T (temperature)

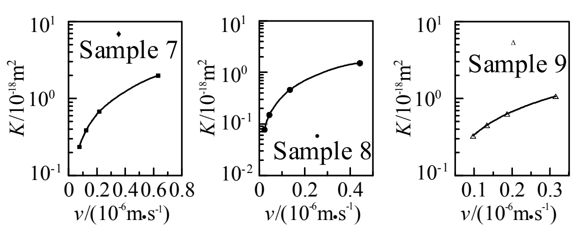


Fig. 4 K changes with v (flow velocity)

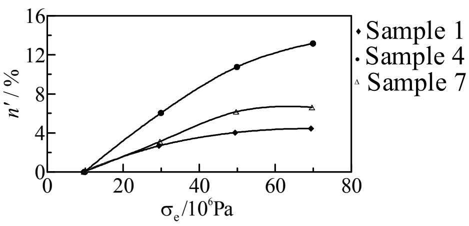
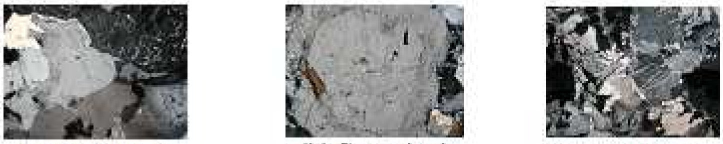


Fig. 5 Relative changes of n with σ_e

Fig. 6 shows microstructure of tight rock materials. Results show that there are some micro-cracks in the tight rock materials although the experimental model samples of tight rock materials have no macroscopic cracks. The micro-cracks can be closed gradually under the action of the effective stress. Moreover, thermal expansion exists in tight rock materials because of thermal effects so that the micro-cracks become narrowed. The changes of the micro-cracks are of great importance to permeability and they are of little importance to porosity of tight rock materials under high temperature and high pressure. Therefore, there are some differences between changes of the permeability and the porosity of tight rock materials under high temperature and high pressure.



(a) Sample 1 (b) Sample 4 (c) Sample 7

Fig. 6 Microstructure of tight rock materials

Conclusions

Results show that the permeability of tight rock materials decreases with an increase in effective stress or temperature and increases with an increase in flow velocity of fluid, and that relative change of porosity increases with the increase of effective stress and has no detectable changes with an increase in temperature under high temperature and high pressure.

There are several main reasons for the above changes: (1) the nonlinear flow of fluid; (2) closing of micro-cracks under the action of the effective stress; and (3) narrowing of micro-cracks under the action of the thermal effects. The changes of the micro-cracks play a more important role in permeability than in porosity of tight rock materials under high temperature and high pressure.

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