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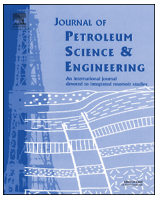

Experimental study on porosity and permeability of anthracite coal under different stresses

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ABSTRACT

Coal porosity and permeability are key factors influencing coal-bed methane well production. In order to investigate the permeability behavior during anthracite coal seam methane production, the porosity and permeability of anthracite coal sample from No. 3 coal seam in Southern Qinshui Basin of China in net confining stress were measured in laboratory. The correlations between porosity, permeability and effective stress were analyzed. Permeability damage rate, stress sensitivity coefficient and pore compressibility factor were proposed to evaluate the effective stress-dependent sensitivity characteristics of anthracite coal. It turns out that, both porosity and permeability of coal sample decrease exponentially with the increase of effective stress. If the effective stress is less than 5 MPa or 6 MPa, stress sensitivity coefficient of coal reservoir changed greatly, and the stress sensitivity coefficient decreases rapidly with effective stress increased. The permeability damage rate increases rapidly with increasing effective stress, the stress sensitivity of coal reservoir enhanced; while in the effective stress is greater than 5 MPa or 6 MPa, the stress sensitivity coefficient of the coal reservoir decreases as effective stress increases slowly, and there is fluctuation, the stress sensitivity of coal reservoir is reduced; while permeability damage rate with the increase of effective stress increased more slowly. With the increase of moisture content and temperature, the permeability damage rate of coal reservoir and stress sensitive coefficient increase, and the stress sensitivity of coal reservoir enhanced.

1. Introduction

Both porosity and permeability are key factors affecting the coal-bed methane production. Porosity of coal usually refers to the sum of matrix porosity and fissure porosity. The dual pore system of coal regulates gas storage capacity, occurrence and transport of methane through coal. Numerous researches on the relationship between porosity and permeability of conventional oil and gas reservoirs have been reported (Louis, 1969; Zimmerman and Bodvarsson, 1996; Zimmerman, 2000). Pore compressibility factor and reservoir stress sensitivity factor were defined to assess the stress-dependent permeability of conventional reservoirs (Lubinski, 1954; Biot, 1956; Louis, 1969; Wu et al., 1995; Jia et al., 1995; Jose, 1997; Min et al., 2004; Wang et al., 2009). Jose (1997) pointed out that permeability loss of the tight sandstone gas reservoir under confining pressure can reach as high as 90% of the initial permeability. As a typical unconventional gas reservoir, coal is a type of low porosity and low permeability porous media and is highly sensitive to effective stress. And coal has a high affinity to gases, i.e. nitrogen, methane, and carbon dioxide. Therefore permeability behavior of coal is more complex than that of conventional oil and gas reservoir. During gas production, coal permeability decreases with the increase of effective stress at early water pumping stage and then increases with the increasing shrinkage effect in later gas extraction stage. A few permeability models were proposed and widely used to describe the stress-dependent effect and matrix shrinkage/expansion effect whereas these models did not take into account the varying cleat compressibility (Shi and Durucan, 2004, 2010; Pan and Connell (2012); Palmer, 2009; Connell, 2009). Experimental studies showed that overall bituminous coal permeability declines exponentially with the increase of effective stress (Enever and Henning, 1997; McKee et al., 1988). Enever and Henning (1997) found the exponential relationship between the permeability of coal seam and the stress. Based on the study of coal seam permeability and its relation to the buried depth in Piceance, San Juan and Black Warrior basins in the United States, McKee et al. (1988) found that the permeability reduces in the law of negative exponential function as the buried depth of coal seam and the effective stress increase and the aperture of coal seam cleat decreases. In order to investigate the permeability behavior of high rank coal during early depletion of CBM

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and its influencing factors, the stress-dependent permeability of anthracite coal was addressed based on laboratory experiments (Meng and Li, 2013; Meng and Hou, 2013). Meng and Li (2013) collected 12 high rank coal samples from the southeast margin of China Ordos Basin and two low and medium rank coal samples from the north margin of this basin and determined their air permeability under a varying effective stress from 2.5 MPa to 20 MPa in laboratory, the correlation models between permeability and stress of high rank coal reservoir were established, and the controlling mechanism of permeability variation was studied. Specifically, variation in in-situ water permeability is likely a function of the maceral composition, mode of deformation, and degree of shearing of the coal seams (Gentzis et al., 2007). However, CBM reservoir has low permeability and strong gas adsorption capacity, which is quite different from the conventional oil and gas reservoirs. CBM reservoir permeability is controlled by coal reservoir stress regime, however researches on the influence of in-situ stress to the coal reservoir permeability were insufficient due to the lack of coal reservoir stress and permeability data. Thus the understanding of the permeability variation during the exploration and development of CBM was still limited to some degree. Previous experimental researches were mainly related to low-medium rank coals, few researches on high rank coals has been reported. This study was undertaken to address the stress-dependent porosity and permeability of anthracite coal at a varying temperature and moisture content. The porosity and permeability of anthracite coal sample from No. 3 coal seam in Southern Qinshui Basin of China in net confining stress were measured in laboratory. The correlations between porosity, permeability and effective stress were analyzed. The results may be applicable in developing strategies in exploration, well completion and production of coal-bed methane.

2. Experimental method

2.1. Experiment samples

The Southern Qinshui Basin, located in Shanxi Province of the Central China, is the most important production base for high quality anthracite in China. The Southern Qinshui Basin measures approximately 120 km from north to south and 80 km from east to west, with an area of about 7000 km^2. Coal seams, generated in Carboniferous and Permian periods, contain abundant methane. Permeability in the coal-bed reservoir is relatively high compared to other coal-bed methane reservoirs in China. The exploration and production tests in this field have been conducted since 1990s. The results show that the Qinshui Basin is a very promising coal-bed methane reservoir with the most exploration wells, the best development prospect, and a higher commercialized production in the China's coal-bed methane reservoirs (Meng et al., 2011).

The coal samples were collected from the No. 3 coal seam in Permian at Sihe coalmine in Southern Qinshui Basin. The burial depth of the coal seam is from 350 m to 1200 m. According to approximate analysis results on air dry basis, the moisture content is 1.36%, volatile yield 8.12% and ash yield 22.63%. The maximum vitrinite reflectance $R_{o,Max}$ is 3.12% and No. 3 coal seam is semi-bright coal in macrolithotype and is banded or homogeneous in coal texture. Cylindrical coal samples were carefully drilled in the direction parallel to the bedding plane. The diameter of coal samples is from 2.51 cm to 2.52 cm and the length from 4.75 cm to 5.11 cm. Dry coal samples were prepared by drying the raw coal samples in the dryer for 48 h. The basic data of the coal samples are shown in Table 1.

Table 1
Basic data of the coal samples.

ID	Diameter (cm)	Length (cm)	Moisture content	Experimental temperature (°C)	Description
1#	2.51	4.75	Dry	20	Fractured
2#	2.52	5.09	Dry	20	Intact
3#	2.52	5.11	Dry	20	Intact
4#	2.51	4.99	Dry	20	Intact
5#	2.51	5.08	Dry	20	Intact
6#	2.52	4.96	Dry	20	Intact
7#	2.50	2.72	30.42%	20	Intact
8#	2.47	3.44	66.8%	20	Intact
9#	2.50	2.60	100%	20	Intact
10#	2.50	5.00	Dry	30	Intact
11#	2.50	5.00	Dry	60	Intact

2.2. Experiment apparatus and procedure

We used an automatic porosity and permeability instrument (AP – 608) to test the porosity and permeability of coal under net confining stress; gas source for confining pressure is supplied by high-pressure air, the high-purity helium acts as the test gas source. The experimental workflow is shown in Fig. 1.

2.3. Experiment conditions

To understand the influence of the coal reservoir stress on coal porosity and permeability, we used the variation of net confining pressure to simulate the variations of coal seam effective stress, and measured the varying porosity and permeability with net confining pressure, and then analyzed the relationships between porosity, permeability and effective stress.

In this paper, the burial depth of coal seams in southern Qinshui Basin ranges from 350 m to 1200 m, so the maximum stress test was designed to 10 MPa, and the temperature test up to 60 °C. To avoid the influence of slippage effect on permeability of coal sample, in the course of the experiment, the displacement pressure is fixed. Confining pressure values were 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0 MPa, and the temperature 20 °C. In order to analyze the influence of temperature on stress sensitivity, experimental temperature is set as 30 °C and 60 °C. To minimize gas slippage effect, the same displacement pressure keeps constant during the test process. Each stress point sustained long enough, at least in balance for 30 min, and then gas permeability at this stress point is measured.

3. Experiment results

3.1. Relationships between coal porosity, permeability and effective stress

3.1.1. The relationship between permeability of coal and the effective stress

The relationship between permeability of coal and the effective stress is shown in Fig. 2. From Fig. 2, we can see that the relationship between the gas permeability of coal and effective stress obeys the negative exponential function as follows:

$$K_i = K_0 e^{-ap} \tag{1}$$

where K_i is the permeability under a specific effective stress, 10^{-3} μm^2; p is the variation value of effective stress from the initial to a certain stress, MPa; K_0 is the permeability under initial effective stress, 10^{-3} μm^2; and a is the regression coefficient, MPa^{-1}.

Regression analysis results for six experimental samples are shown in Table 2. K_0 ranges from 0.0267×10^{-3} μm^2 to 4.2562×10^{-3} μm^2, averagely 0.7819×10^{-3} μm^2; a ranges from 0.26 MPa^{-1} to 0.54 MPa^{-1}, averagely 0.37 MPa^{-1}.