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Changes in pore structure and permeability of low permeability coal under pulse gas fracturing

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A B S T R A C T

In order to enhance effectively permeability of coal seams and increase the efficiency of gas extraction, the pulse gas fracturing is proposed as a new stimulation method. In this study, the pulse gas fracturing experiment of low permeability coal on the laboratory scale was executed and sequential 267 pulse times were preformed. The mercury intrusion porosimetry, scanning electron microscope and permeability measurements were conducted to investigate the changes in the pore structure and permeability caused by the pulse gas injection. The results show as follows. (1) The volume of the coal specimen repeats the swelling-shrinkage process during the pulse gas fracturing which contributes to improve the size and shape of pores and generate micro-cracks in the coal. The deformation of the coal sample has a fatigue threshold in the pulse gas fracturing and its value is near 100 pulse times. (2) The pulse gas fracturing promotes the transfer of smaller pores to larger pores and improves the pore size distribution. After the pulse gas fracturing, the average incremental pore volume of transition pores, mesopores and macropores increases 25.85%, 117.86% and 105.07%, respectively. The total pore volume of the coal sample has an increase of 80.65%. The macropores, mesopores and transition pores volumes increase by 165.22%, 438.33% and 27.27%, respectively. The results indicate that pulse gas fracturing can improve the pore space and the pore distribution, and ultimately increase the permeability of the coal. The change that micropores transfer into larger pores also results that the cumulative pore specific surface of transition pores, mesopores and macropores has an increase of 10.18%, contributing to coalbed methane (CBM) sorption/desorption and diffusion. (3) The crossover network cracks are formed in the coal during the pulse gas fracturing. The porosity and permeability of the coal are obviously improved by the pulse gas fracturing, indicating that the pulse gas fracturing can be used to effectively enhance the permeability of CBM reservoirs. It is worth noting that there is a critical pulse time for the increase of the coal permeability and its value is about 100 pulse times under the stress condition and pulse gas injection method of this research.

1. Introduction

In China, the coal seams have high gas content but they are low permeability, which is unfavorable for production and utilization of coal bed methane (CBM) (Xia et al., 2014; Li et al., 2014; Gao et al., 2016). Currently, hydraulic fracturing has been widely used to enhance the production of CBM reservoirs (Xu et al., 2013; Aguilera et al., 2014); however, hydraulic fracturing has caused many problems, such as polluting groundwater and preventing gas seepage paths-improve due to coal matrix swelling and water locking (Anderson et al., 2010; Holtsclaw et al., 2011; Boudet et al., 2014; Middleton et al., 2015; Wang et al., 2015). Therefore, the idea of non-aqueous fracturing has grown over the last several years as an efficient and environmentally friendly way of performing the hydraulic fracturing (Middleton et al., 2015). The non-aqueous

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fracturing can fundamentally solve the environmental problems relative to water use and pollution, and prevent reservoir damage. Nitrogen is a notable waterless fracturing fluid currently under consideration for use in hydraulic fracturing. In nitrogen fracturing, nitrogen is pumped into a well and then artificial fractures are easily created around the wellbore wall (Mcdaniel et al., 1997; Grundmann et al., 1998). However, just like conventional hydraulic fracturing, the main fractures are formed randomly during liquid nitrogen fracturing, a few branch cracks are produced and extensive fracture networks are not created because that the micro-cracks have no enough time to develop and extend (Huang et al., 2011). In addition, stress concentration can easily form under high gas pressure, which threatens later coal mining (Feng and Kang, 2012). In order to overcome the limitations, pulse gas fracturing is proposed which can improve the effect of gas fracturing on fracture propagation in coal seams because that low pulse loading can produce more secondary cracks and increase the surface areas of coal for promoting gas desorption (Wang, 1987; Li et al., 2011; Liu et al., 2015).

As we know, the pore structure of coal, mainly the matrix pore and the fracture network (cleat system), control the gas flow in coal seams and seriously affect the permeability of coal seams (Cui et al., 2004; White et al., 2005; Chen et al., 2014). Furthermore, gas adsorption and desorption also mainly occur in pores of coal. Therefore, production and utilization of coal bed methane is directly affected by the pore structure of coal (Cui et al., 2004). It can be seen that as the viscosity of gas is smaller than that of water, gas can more easily enter pores of coal and pore gas pressure inevitably affects the micro-pore structure of coal. Wang et al. (2015) investigated changes in coal pore structure and permeability during N_2 injection, the results indicated that N_2 injection improves the pore size distribution and mainly affects macropores, mesopores and transition pores, and permeability markedly rise. Similarly, the pulse gas pressure fatigue can also have effect on the pore structure and permeability of coal.

Accordingly, in this study, a pulse gas fracturing experimental system which based on the laboratory scale was built up. The pulse gas fracturing experiment of low permeability coal was performed. Permeability measurements were conducted to investigate changes in the permeability of coal during the pulse gas fracturing. Changes in the pore structure of coal were analyzed based on the mercury intrusion tests and scanning electron microscope (SEM) experiments. The study results are expected to have a better understanding of the effect of pulse gas pressure on the pore structure of low permeability coal and hence can provide a foundation for the improvement of low productivity CBM wells.

2. Experimental materials and procedure

2.1. Sample preparation

Coal samples were obtained from Shoushan mine in Xuchang, Henan Province, China and the location of coal specimens is shown in Fig. 1. To reduce the discreteness of coal specimens, the coal blocks were taken from a same around 700–800 m depth underground the mining face. This mine is a high gas and outburst mine. Its gas content is 10.46 m^3/t and gas pressure is 1.38 MPa. The coal seam has the characteristics of low permeability, strong adsorption and difficult gas drainage.

The component of the coal was tested by X-ray diffraction (XRD). Through the XRD analysis, the frequency spectrum analysis of coal was conducted on the basis of the peak intensities. The result is shown in Fig. 2. The largest peaks correspond to calcite, kaolinite, and quartz, respectively. The coal consists of calcite, kaolinite, quartz, and other amorphous minerals.

Coal samples were drilled from the original coal blocks along parallel bedding direction. The samples were processed into cylinders with 100 mm in length and 50 mm in diameter. The error of the parallelism of the specimen ends is within ±0.02 mm. The sides of the specimen are smooth and straight within 0.3 mm over the full length of the specimen. Then samples needed to be processed further and a central borehole with 5.2 mm in diameter and 60 mm in length was drilled axially to the sample mid-point. The sketch of the sample design is shown in Fig. 3. Subsequently, the surface and borehole of the specimens were cleaned using the clean water. Then coal samples were sealed and sent to the laboratory for experimental testing. Before the pulse gas fracturing test, the sample was kept in an oven at 50 °C and vacuum for 12 h.

Based on the American Society for Testing and Materials (ASTM) standard (ASTM D3967–08, 2008; ASTM D7012–14, 2014), mechanical parameters of the coal are obtained by the uniaxial compression test, the triaxial compression test and the Brazilian disk splitting test. The details on the experiments show as follows. The uniaxial compression tests and triaxial compression (confining pressure: 8 MPa) tests were performed on the coal samples with Φ50 mm × H100 mm at the vertical loading rate of 0.05 mm/min. As to the Brazilian disk splitting tests, the coal samples with Φ50 mm × H25 mm were prepared and then the vertical loading rate of 0.1 mm/min was maintained until the samples were destroyed. Three specimens were performed in each type of above experiments. The averaged values of the obtained parameters are listed in Table 1.

2.2. Apparatus

To determine the pore structure of the coal, the mercury intrusion porosimeter (MIP) (AutoPore IV 9500) and scanning electron microscope (SEM) (QuantaTM 250) are used to conduct laboratory tests. The pulse gas fracturing experimental system consists of two subsystems: a triaxial loading system and a pulse gas injection system and is shown in Fig. 4. The components and features of the two subsystems are as follows:

(1) The TAWD-2000 electro-hydraulic servo-controlled rock mechanic testing system (Fig. 5a) which is served as a triaxial loading system is used to simulate the crustal stresses, including a triaxial loading platform, two hydraulic power packs and a stress console. This system has following technical parameters: The maximum axial force of 2000 kN, the maximum confining pressure of 80 MPa, the maximum axial displacement of 8 mm, and the maximum lateral deformation of 4 mm. The stress and strain of the sample are automatically and continuously measured by pressure transducers and extensometers and recorded in the computer. The accuracy of this system is ±1% for stress, ±1% for deformation.
(2) The pulse gas fracturing system mainly consists of two air compressors, two air dryers, a gas booster pump, an air tank, a buffer gas bottle, two mass flow meters, two pressure sensors and a console (Fig. 5b, c and 5d). The maximum of output gas pressure and standard flow are 80 MPa and 63 L/min, respectively. The frequency of pulse can be adjusted by the console. The data of the gas pressure and gas flow are automatically monitored and recorded in the computer.

2.3. Experimental methods

Air is mainly made up of nitrogen and the kinetic diameter of air is very closely to that of nitrogen under the same condition. In this