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Experimental comparisons of gas adsorption, sorption induced strain, diffusivity and permeability for low and high rank coals

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ABSTRACT

Because of coal pore structure, the adsorption and diffusion behaviors are quite different for low and high rank coals. Differences of gas adsorption-diffusion and adsorption deformation of low and high rank coal and its permeability evolution were carried out in isothermal adsorption experiment and desorption-seepage testing system. The law of adsorption and adsorption induced strain, diffusion of low and high rank coal and its influence on the coal permeability were revealed. It turns out that, the methane adsorption-diffusion and adsorption induced-strain of low and high rank coal increase with the increase of the adsorption equilibrium pressure. Because of the control of pore structure, the diffusion property of low rank coal sample is higher than that of high rank coal sample. And the strain perpendicular to the bedding plane is higher than that parallel to the bedding plane. Sorption-induced strain of high rank coal is higher than that of low rank coal, which is related to the amount of gas adsorption in coal. The Langmuir volumetric strain is about twice as high as that of the low rank coal. The law of gas adsorption deformation of coal can be described by a Langmuir isotherm adsorption equation. The influence of methane adsorption-induced swelling strain on the permeability of high rank coal is higher than that of low rank coal. At a constant effective stress, the permeability of low rank coal is higher than that of high rank coal, and with the increases of adsorption equilibrium pressure, the permeability decline by a negative exponential function of different rank coals; the rate of permeability reduction of high rank coal is higher than that of low rank coal.

1. Introduction

Coalbed methane (CBM) has been successfully extracted from both low and high rank coal reservoirs. The CBM resource in China is estimated to $\sim 36.8 \times 10^{12}\,m^3$. Based on the national resource estimation, 23% and 43% of the total resources occur in the high rank and low rank CBM reservoirs, respectively [1]. In China, commercial gas production in the southern Qinshui basin of high metamorphic anthracite coal was achieved and the large-industrial-scale CBM development was implemented. Compared to the high-industrial-scale CBM development of high rank coal, the CBM development of low rank coal is relatively slow. This has provided an opportunity to further increase the CBM production in China from low rank coal reservoirs, since low rank coal reservoirs have been technically approven for CBM extraction worldwide. CBM production is a continuous process of desorption, diffusion and seepage. The development of CBM is to reduce the reservoir pressure by drainage, so that the adsorbed methane gas desorbed and release, and diffuse in the pores and fractures to CBM wells. In the process of CBM extraction, methane adsorption-diffusion and sorption-induced deformation of low and high rank coal are two key factors for CBM production. The deformation of coal matrix will influence permeability of coal reservoir [2,3]. During the development of CBM, on the one hand, with the extraction of water and gas, the reservoir pressure gradually decreases which results in an increase of effective stress. The fractures/cleats in coal are mechanically compacted and tend to close. Therefore, the elastic and plastic deformations of the coal lead to a significant decrease of the permeability of coal formation. On the other hand, in the process of CBM production, with the decrease of reservoir pressure, the adsorbed-phase methane is gradually desorbed from coal causing the shrinkage deformation of coal matrix. This matrix shrinkage results in the fracture opening after the reservoir pressure is depleted beyond the critical desorption pressure. It may lead to an increase of the permeability [4–6]. Adsorption-induced swelling deformation and desorption induced matrix shrinkage have been reported

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Table 1
Results of vitrinite reflectance, proximate analysis, coal composition.

Sample ID	Proximate analysis (%)				Coal composition(%)				$R_{o,max}$(%)
	M_{ad},%	A_{ad},%	V_{ad},%	FC_{ad},%	Vitrinite	Inertinite	Exinite	Mineral	
No. 1	26.41	5.01	33.91	47.11	81.0	17.0	0.0	2.0	0.35
No. 2	2.40	11.97	5.69	79.94	78.4	17.2	—	4.4	3.42

by several researchers [7–10]. Many scholars have conducted a lot of studies on adsorption/desorption [7,11–19]. Moffat and Weale [11] carried out experiments on the adsorption-induced volumetric strain of coal and found that the swelling volumetric strain increase ranging from 0.2% to 1.6% with ranks from low volatile bituminous to semi-anthracite with methane pressure in range of 0–15 MPa. However, when methane pressure exceeds 15 MPa up to 71 MPa, the volume of coal either declined or remained somewhat constant. Gray [20] quantitatively evaluated the effect of matrix shrinkage on the permeability of coal and in his study, he made these assumptions: the CBM desorption leads to shrinkage of coal matrix and the shrinkage results in the increase of the fracture aperture and thereby the permeability of coal increases. Harpalani and Schraufnagel [12] studied the differences of volumetric strains of coal induced by carbon dioxide and methane gas adsorption. Harpalani and Mitra [18] measured coal matrix volumetric strain for both the Illinois and San Juan Basin coals. For Illinois bituminous coal, the volume of coal matrix increased by approximately 0.58% with methane at 5.5 MPa. For San Juan subbituminous coal, the matrix volume increased by approximately 0.64%, with methane at approximately 7 MPa. Seidle and Huitt [15] conducted adsorption experiments of methane and carbon dioxide with the coal samples from San Juan Basin and found that the coal strain caused by adsorption is directly proportional to the amount of adsorbed gas and that the volumetric strain and the adsorption isotherm have similar trends. The characteristics of coal reservoir are closely related to the degree of coal metamorphism. There are some differences in origin of coalbed methane, reservoir physical properties and reservoir forming process, which lead to significant differences in the adsorption-induced deformation of different coal ranks. The amount of adsorption, pore structure and size distribution change with the rank of coal, and the amount of adsorption increase with increase of coal rank; The high rank coal has a larger surface area than the low rank coal, so the amount of adsorption gas is also relatively high [21–22]. According to the energy conservation assumption that the variation of surface energy caused by gas adsorption is equal to that of the elastic energy of media, Pan and Connell [8] established a mathematical model to calculate the strain of coal matrix. Based on the variation of surface energy caused by adsorption, Liu et al.[9] established a mathematical model of adsorption-induced strain of coal matrix, taking into account the physical-mechanical and adsorption parameters. These can provide the theoretical basis for estimation of adsorption-induced deformation. In the literature, many efforts has been devoted on the adsorption-induced deformation of low rank coal, but the high rank coal sorption induced deformation is rarely reported.

In this study, both low and high rank coals were studied. Two coal samples were collected from the southern Qinshui Basin and the southeastern Yunnan Basin, China. Both coals were prepared into cylindrical cores. Differences of gas adsorption-diffusion/adsorption deformation of high and low-rank coals and their permeability evolutions were carried out by a isothermal adsorption apparatus and desorption-seepage testing system. The laws of adsorption-diffusion/adsorption induced-strain of low and high rank coals and their influences on the coal permeability were compared and analyzed, which can provide the theoretical basis for future CBM well extraction optimization.

2. Experimental setup and conditions

2.1. Specimen preparation

Coal samples were collected from the southern Qinshui Basin and the southeastern Yunnan Basin, China. Low rank coal sample (No. 1 coal) is lignite coal and high rank coal sample (No. 2 coal) is anthracite with maximum vitrinite reflectance ($R_{o,max}$), 0.35% for No. 1 coal, 3.42% for No. 2 coal. The coal specimens are mainly semi-bright and semidull coal with a primary structure. The coal samples were prepared into cylindrical cores with dimensions of ~50 mm in length and ~25 mm in diameter. The cores were drilled in direction of parallel to the bedding plane. Proximate analysis and petrographical data were listed in Table1.

2.2. Experimental method

(1) In order to evaluate the difference of adsorption capacity between low and high rank coals, the isothermal adsorption experiment was carried out on both coal samples by using the TerraTek isothermal adsorption apparatus (ISO-300). According to the *in situ* reservoir pressure and temperature conditions, the experimental temperature was set at 27 °C and the maximum adsorption pressure was 12 MPa. The experimental apparatus is fully automated, with computer controlled gas injection, pressure measurement and data acquisition. For isothermal adsorption test, 100–120 g coal sample with the size of 0.2–0.25 mm (60–80 mesh) was selected. In this study, the testing procedure followed the national standard of "Experimental Method of High-Pressure Adsorption Isothermal to Coal-Capacity Method" (GB/T19560-2008 [23]).
(2) The diffusion property is based on the isothermal adsorption experiment and calculated by isothermal diffusion model, and the diffusion coefficient was estimated based on the linear relationship between the adsorption capacity and time (Details are presented in the Section 3).
(3) The testing system of coal-gas desorption-seepage is composed of a gas flow-rate measurement unit, a strain measurement unit, a gas injection and monitoring unit and a loading unit. Permeability measurement is carried out according to a China national standard SY/T 5336-2006(2006) [24] Core Analysis Method. The testing fluid is methane and the experimental temperature is constant at the room temperature (~20 °C). During the experiment, the effective stress was kept constant at 3.5 MPa. The experimental program is shown in Table 2.

The coal matrix swelling can be directly measured with a linear strain gauge with the data acquisition system. The matrix swelling leads to the decrease of coal permeability and the permeability can be estimated by the measured flow-rate at each injection gas pressure.

The experiment simulates gas adsorption swelling deformation and the process of gas transport with a progressive increase of gas injection pressure under the constant external stress condition. In order to ensure the stability of the experimental process, the gas pressure, axial and confining stresses were continuously monitored and recorded.

The experimental procedure is as follows: (1) specimen was gradually stressed to desired axial and confining stresses; (2) constant