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Experimental study of coal matrix-cleat interaction under constant volume boundary condition

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ABSTRACT

Interaction of coal cleat and matrix plays an important role in determining the dynamic change of coal pore structure and its permeability. Majority of the experimental studies on the cleat-matrix interaction are carried out by measuring the correlation between coal permeability and pore pressure. Under this condition, it is commonly believed that the cleat pressure is equalized with the matrix pressure, in which the permeability is available only for gas flow/adsorption reaching equilibrium state. In this study, the coal cleat-matrix interaction is to uncover during helium unsteady flow from the cleat network to matrix blocks. This objective is achieved by measuring local deformation of coal sample and its permeability under a constant volume boundary. The results show that the incremental of coal strain firstly increases from 184 με for 2.0 MPa to 440 με for 4.5 MPa, resulting from the opening of the fractures and the compression of the matrix blocks, and then recovers to 105 με for 2.0 MPa and 222 με for 4.5 MPa, due to expansion of the coal matrix. Such a transition of the coal deformation reveals that the gas injection process generates a dynamically imbalance pressure between the cleat and matrix, and then gas diffusion around the vicinity of the cleat causes non-uniform expansion of the coal matrix. Recovery ratio of 0.5 for the matrix strain was observed, quantifying the contribution of matrix expansion to the cleat aperture. Through comparing the measured permeability data with two predicted permeability by the constant-volume model and the matchstick model, it is found that the variation of coal permeability is controlled not only by the change of cleat aperture, but also affected by the matrix expansion process. This work offers a new direct observation into the dynamics of gas mass transfer from the cleat to the matrix and a new understanding of coal permeability evolution in response of the transition. It sheds light on the development of new permeability model that incorporate the fracture-matrix interaction.

1. Introduction

Understanding of coal deformation induced by gas extraction is critical for better planning coal bed methane (CBM) production and minimizing coal-gas outburst risks for underground coal extraction. Coal has a typical dual porosity structure: coal cleats are the primary pathway of fluid flow and determine coal reservoir permeability, and coal matrix blocks serve as gas storage site, where gas is stored in various-sized pores (Haenel, 1992). Unlike conventional gas reservoirs, coal can also absorb significant amount of different gasses such as CH_4 and CO_2, resulting in considerable swelling (or shrinkage) deformation of the coal matrix during gas adsorption (or desorption) (Cui et al., 2007; Harpalani and Chen, 1997; Wang et al., 2011; Shi and Durucan, 2005). During CO_2 Enhanced Coalbed Methane operations and CO_2 geological storage processes, the gas inflow can firstly change the cleat aperture and then affects matrix deformation. Under the influences of in-situ stress level, reservoir pressure, gas composition, fracture geometry of coal and water content, the two concurrent processes significantly control coal permeability change in both space and time (Liu et al., 2011). Although is usually attributed to the competing effect between gas sorption-induced swelling/shrinkage and poroelasticity compression (Connell, 2009; Shi and Durucan, 2004), the mechanisms of these complex coal-gas interactions are not still fully understood. It is therefore necessary to further investigate the cleat-matrix interaction in response to the change of pore pressure to more reliably predict coal permeability evolution.

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Numerous experimental efforts have been conducted to investigate evolution of coal permeability with pore pressure. At the case of constant confining pressure, gas permeability is observed to decrease resulting from adsorption swelling in low pore pressure range, and then recover due to predominance of effective stress (Kumar et al., 2015; Wang et al., 2015; Gensterblum et al., 2014; Wang et al., 2011; Robertson and Christiansen, 2005; Li et al., 2013; Pini et al., 2009; Mitra et al., 2012; Seidle and Huitt, 1995). Under constant effective stress, gas permeability is found to decrease with the increasing of pore pressure (Anggara et al., 2016; Pan et al., 2010; Harpalani and Chen, 1997; Chen et al., 2011). Associated experimental methods involve the steady state method (Li et al., 2009; Tanikawa and Shimamoto, 2009) and the pressure transient method (Brace et al., 1968; Zhang et al., 2016). Measured coal permeability is a function of gas flow rate, gas pressures of inlet/outlet of core holder, geomechanics properties and size of coal sample, and gas viscosity. These experimental results are valid only in case of pore pressure of coal sample reaching equilibrium state. Based on in-situ and laboratory experimental results, a variety of coal permeability models have been proposed based on different boundary conditions: (1) uniaxial strain (Palmer and Mansoori, 1998; Shi and Durucan, 2004; Cui and Bustin, 2005); (2) variable stress (Robertson and Christiansen, 2006a,b; Izadi et al., 2011; Connell et al., 2010), and (3) constant volume (Harpalani and Chen, 1995; Ma et al., 2011). It should be noted that the assumptions of these permeability models are not consistent with the actual testing conditions in laboratories. Furthermore, the contribution of the matrix to bulk deformation of coal is attributable to adsorption/desorption-induced swelling/shrinkage. In this case, gas flow primarily occurs in the cleat networks.

In fact, pore fluids migration in the coal matrix requires significant amount of time to get equilibrium state (Zutshi and Harpalani, 2004; Siriwardane et al., 2009; Seidle and Huitt, 1995; Liu et al., 2016), because the matrix permeability is several orders of magnitudes lower than the cleat permeability (Robertson, 2005). This results in the change of matrix pressure lagging behind the change of cleat pressure (Gray, 1987; Liu et al., 2017a,b). Consequently, a dynamic imbalance of pressure exists between coal cleat and matrix in finite time, and can alter the cleat aperture due to the matrix deformation (Liu et al., 2011; Xia et al., 2016). Although some researchers have investigated the impact of coal matrix-cleat interactions on permeability evolution, the relevant permeability models are all based on the assumption of the uniform distribution of gas pressure cleat and matrix (Liu and Rutqvist, 2010; Wang et al., 2012). Under this assumption, both the gas-adsorption-swelling term and poromechanics term of the models are defined by a function of the target pressure (e.g. injection gas pressure in laboratory). It is unable to capture the full evolution characteristics of coal permeability in response to gas mass transfer between cleat and matrix.

Although some dual-porosity models have taken account of impact of the matrix pressure on the coal permeability (Wu et al., 2010; Peng et al., 2014a,b; Wang et al., 2017; Liu et al., 2017a,b), the contribution of the matrix deformation on coal cleat aperture are not fully understood. Considerable experimental studies show the evolution of coal deformation exposing to CH_4 or CO_2 firstly increased and then stabilized at a certain value (Battistutta et al., 2010; Espinoza et al., 2014; Majewska et al., 2009; Liu et al., 2015). It is clear that the measured coal strain is the resultant outcome of cleat open and matrix swelling due to gas adsorption effect, but difficult to differentiate the contribution of matrix strain from total strain of the coal sample. This is because conventional permeability measurements in laboratory do not collect outlet gas flow rate and inlet/outlet gas pressures until the outflow gas reaches the equilibrium state. Hence, investigation of the gas transport characteristics between cleat and matrix is critical for the full understanding fracture-matrix interaction and thus better prediction of coal permeability evolution during gas production.

In our previous work (Wang et al., 2016), the transition process of coal strains associated with helium gas flow in the cleat and diffusion in the matrix was investigated under constant confining stress condition. By adopting this methodology, in this work, a new experimental design is implemented to directly observe the strain evolution of coal sample subjected to the constant volume boundary condition with the injection of helium gas. Under this boundary condition, the change of dimension of coal matrix would be the inverse of the change of cleat width. In addition, gas permeability to coal at the equilibrium state is measured and comparison of the experimental permeability results with the modeling results from the constant volume model and the matchstick model is also conducted. The correlation between permeability and coal fracture-matrix interaction is discussed in detail.

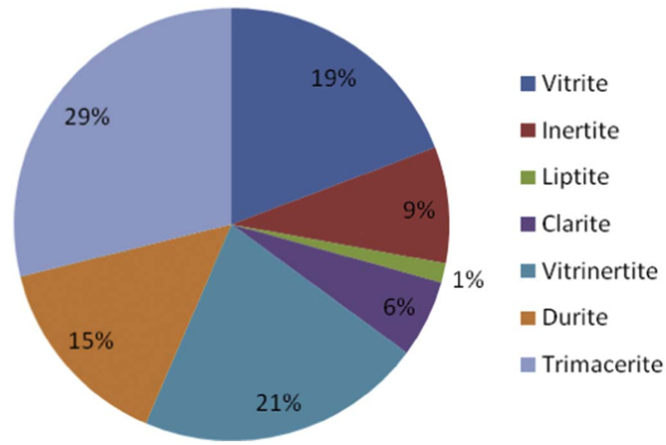

Fig. 1. Pie chart of various macerals of the coal sample.

2. Experimental method

2.1. Sample preparation

A coal block collected from a longwall mining face located at the Juye coal field of eastern China formed in Permo-Carboniferousera. The coal is categorized as high-volatile bituminous (Lv et al., 2015). The compositions of coal macerals are plotted in Fig. 1. The coal sample with diameter and height of 25 mm and 50 mm was drilled perpendicular to the face cleats of the coal block. A series of uniaxial compression tests were conducted to obtain elastic mechanical properties of the coal samples. According to the stress-strain curves of the uniaxial compression, the average Young's modulus (E) and Poisson's ratio (v) of the coal sample is 2.10 GPa and 0.323, respectively.

In order to obtain the pore distribution of the coal sample, the NanoVoxel-2000 X-ray machine was used to scan a 3 mm coal particle cut from the coal block. Scanning parameters were set under voltage of 41 kV and electricity of 240 μA. The NanoVoxel-2000 is able to produce a voxel dataset containing a series of cross-sectional slices of the scanned coal sample with the resolution of 0.5 μm. A three-dimensional image was reconstructed from the voxel data as illustrated in Fig. 2(a), and the three orthogonal cross-sections are given in Fig. 2(b)–(d). The pore characteristics of the voxel dataset were then analyzed by the threshold segmentation module embedded in the *Avizo Software*. It is found that the porosity of each CT slice varies from 5% to 7.5% with an average porosity of 6.27% (Fig. 3(a)). Besides, the majority of the pores are 1 μm–2 μm in diameter, as shown in Fig. 3(b). In order to investigate connectivity of pores in the voxel dataset, a series of cubes with a length of 150 μm were segmented out from the voxel data. Fig. 11 of Appendix shows spatial distribution of various-sized pores in different locations of the voxel data, volume ratios of interconnected pores to closed pores are 0.24, 0.28, 0.63, 0.43, respectively.