Journal of Natural Gas Science and Engineering 35 (2016) 131–143

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

# Experimental study on physical structure properties and anisotropic cleat permeability estimation on coal cores from China

Xiaomeng Xu [a, b], Mohammad Sarmadivaleh [b], Chengwu Li [a, *], Beijing Xie [a],
Stefan Iglauer [b]

[a] Faculty of Resources and Safety Engineering, China University of Mining & Technology, Beijing 100083, China
[b] Department of Petroleum Engineering, Curtin University, Perth, WA 6102, Australia

## ARTICLE INFO

*Article history:*
Received 9 March 2016
Received in revised form
15 August 2016
Accepted 19 August 2016
Available online 21 August 2016

*Keywords:*
Coal bed methane
Coal cleat
X-ray CT images
Plane and volume porosity
Anisotropic cleat permeability

## ABSTRACT

Knowledge of the natural structure properties of coal seams is essential for the coal bed methane (CBM) production because of their great influence on the inner flow characteristics and permeability features of hydrocarbons and water. In this paper, a series of laboratory tests, including nondestructive low-field nuclear magnetic resonance (NMR), scanning electron microscopy (SEM), X-ray computed tomography (CT) and core tests were carried out to characterize the physical structure properties of coal. The pore size distribution, pore type, morphological features and three-dimensional rendering of coal cleat structures are presented. The permeability changes of 7 cylindrical coal cores investigated under a varying effective stress range (0–35Mpa) reveal that coal porosity decreased linearly and coal permeability declined exponentially with the rise of stress; while under higher stress conditions, the occurrence of internal crushing and mechanical damage will result in irreversible change for porosity and permeability. Through the comprehensive analysis based on linking permeability to porosity and CT result, a basic estimation on directional cleat permeability is also realized. This method provides a preliminary but satisfactory estimation for local directional cleat permeability, which reflects that both bedding and non-bedding direction permeability owns great heterogeneity for an individual sample; but face cleat permeability always found to be the largest, and the mean bedding plane permeability value is found usually 3.01–11.68 times lower than face and butt cleat permeability.

## 1. Introduction

Gas permeability of coal is a controlling factor for the productivity of coalbed methane (CBM) (Tao et al., 2012) and is also of key relevance in terms of carbon geo-sequestration, where carbon dioxide is stored in coal seams deep below the earth's surface (Tsotsis et al., 2004). Coal permeability has been verified both experimentally and numerically that it is usually sensitive to changes in many factors including effective stress (Jasinge et al., 2011; Li et al., 2014), gas sorption effect (Fitzgerald et al., 2005; Nie et al., 2014), coal rank (Gray, 1987), pore pressure (Palmer and Mansoori, 1996) and slippage effect (Wang et al., 2014a), however there is another factor – the internal structure of coal, is relatively neglected (Majewska et al., 2010). Knowledge of the natural structure properties of coal beds is essential for engineering practice because of their great influence on the inner flow characteristics and permeability features of hydrocarbons and water (Laubach et al., 1998). The structure of coal has been reported as special for its dual-porosity system and diverseness in comparison with some other conventional rocks (Thararoop et al., 2012). As the detailed characterization of coal structures in different ranks is extremely difficult (Haenel, 1992), the effects of coal structure on coal permeability is still a challenging task to be pursued intensively.

Structurally, coal is a complex material and conceptually consists of two main pore systems: pores and cleats. Pores are smaller, and pores less than 10 nm in size are usually defined as micropores, pores larger than 1000 nm are called macropores, and of course there are some mesopores between the mentioned size (Harpalani and Chen, 1997; Nie et al., 2015). Micropores are mainly unconnected inside the coal matrix, while macropores contribute to the natural network of fractures, called cleats. The cleat system can be classified into three orthogonal classes: face cleat, butt cleat and

---

[*] Corresponding author. Faculty of Resources and Safety Engineering, China University of Mining & Technology, Beijing 100083, China.
*E-mail address:* fslcw2000@163.com (C. Li).

http://dx.doi.org/10.1016/j.jngse.2016.08.050

bedding planes (Wang et al., 2014a). As depicted in Fig. 1, face cleats are laterally extensive and continuous avenues for gas and water flow in coal; Butt cleats are perpendicular to the bedding planes and face cleats, though they are mostly discontinuous and end at an intersection with just one face cleat; however, butt cleats also act as important flow channels (Laubach et al., 1998). Due to the existence of different types of pores (especially cleats), coal is considered a dual-porosity material, and the permeability of coal is easily affected by pore features (e.g. pore size distribution, pore types and connectivity) and cleat properties (e.g. cleat size, cleat spacing, cleat orientation, cleat network and connectivity) (Gash et al., 1992). The influence of coal structure on coal permeability is in all aspects, i.e. the special stress response feature in the perspective of mechanics, volume changing effect due to adsorption effect and anisotropy of permeability in different directions, but all of these are not clear enough in mechanism to some extent.

As coal cleats are the main flow channels inside this material, it is believed that coal cleat characteristic is the decisive element to anisotropic coal permeability. Adams et al. (2013) believed that the vertical permeability for a reservoir is generally lower than its permeability in horizontal directions and the ratio between non-bedding and bedding direction permeability also rises with burial depth increasing (Adams et al., 2013). To make a simplicity, in previous permeability modelling work vertical permeability is either supposed to be negligible or assumed that vertical permeability was 1/10 of the horizontal permeability (Shi and Durucan, 2008). However, the characteristics and effects of permeability anisotropy, and how this depends on the coal's structural attributes are only poorly understood. We concluded that there are two reasons for this situation: the absence of quantitative analysis on coal structure and the lack of effective measurement technology for anisotropic permeability. Coal permeability anisotropy is typically measured either on core plugs recovered from coal seams in different directions (perpendicular or parallel to the bedding direction), or directly multiple test on cubic samples. The first method suffers from coal heterogeneity, i.e. even coal samples from the same block will have different permeability features, while in the second approach sometimes the internal damage of coal body is irreversible and thus affect the final result.

As modelling the permeability of a coal seam with inadequate consideration of coal structure and structural anisotropy can lead to misleading predictions and high uncertainty, it is important to have a better understanding of these aspects. We thus designed a series of laboratory tests, including nondestructive low-field nuclear magnetic resonance (NMR), scanning electron microscopy (SEM), X-ray computed tomography (CT) and core tests were carried out to examine coal structures and coal cleat characteristics. The pore size distribution, pore type, morphological features and three-dimensional rendering of coal cleat structures are also presented. Then, on the basis of coal cleats analysis, a preliminary method is proposed to estimate anisotropic cleat permeability of coal.

## 2. Methodology

### 2.1. Coal specimen preparation

Coal blocks were obtained from the exposed Wu$_9$-20180 workface of the underground Pingdingshan Colliery, Henan Province of China. The burial depth of this coal seam is approximately 650 m with a 1.6–2.3 m thickness and 14 m$^3$/t gas content, the maximum gas pressure is 1.14 MPa. The working face was exposed to the mine air for more than half a year before the sample blocks were collected after blasting. As a result, the samples had enough time to outgas methane they originally contained. Thus permeability measured in this study can be seen as absolute permeability and we believe that the permeability change was solely caused by external stress loading (no sorption). All coal blocks were drilled into cylindrical shape with a 37.46 ± 0.14 mm diameter and 76.64 ± 0.40 mm length, paralleling to bedding direction and face cleat direction. Before conducting any other experiments, the dimension of each cylindrical core was carefully measured. Subsequently the statistic elastic modulus and Poisson's ratio were tested by sending compressive (P wave) and shear waves (S wave) along the axial direction of the samples (Eberhart-Phillips et al., 1989). The coal rank was identified following Chinese Standard GB/T 212-2008 and DL/T 1030-2006: coal powder from the same block as the core samples was collected and used for analysis. These results are listed in Table 1; all specimens were quite similar, owing to the same coal seam origin. However, it is noticeable that the Poisson's ratio and Young's modulus showed a relatively larger variation, which is caused by the high sensitivity of the seismic velocity to internal fractures (cleat orientation and/or coal bedding

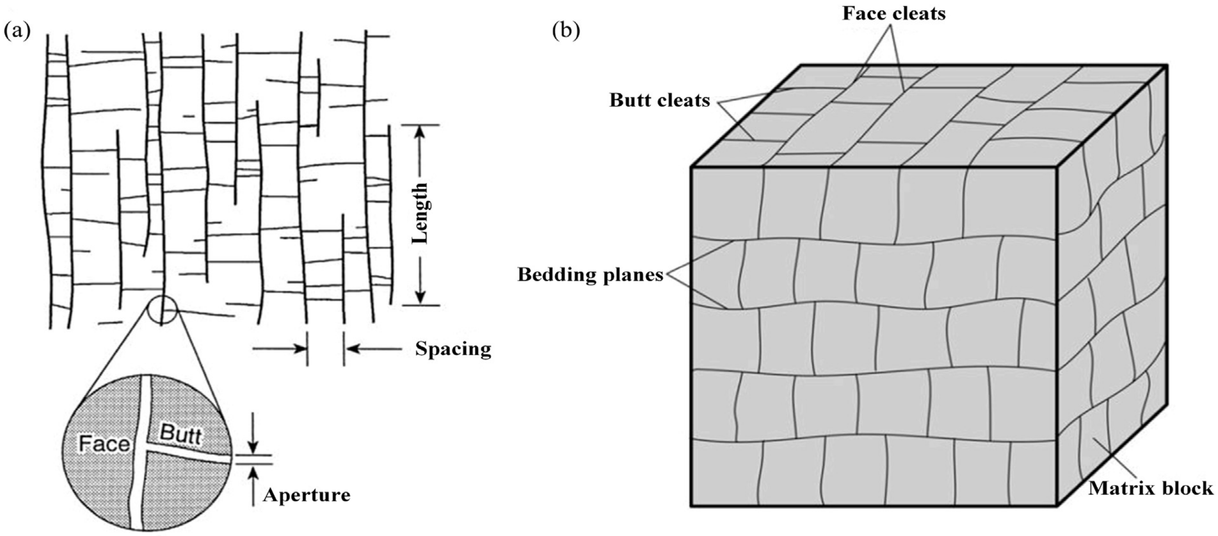

**Fig. 1.** Schematic illustration of coal cleat system and its geometry. (a) Cleat trace pattern in a plane view (Adapted from Laubach, et al., 1998.); (b) Coal cleat system and matrix block (After Wang et al., 2014b).