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Full Length Article

Coal cleat reconstruction using micro-computed tomography imaging

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HIGHLIGHTS

- A method for identifying face and butt cleat families based on CT images is developed.
- An advanced image analysis method is presented to extract statistics of fracture structural parameters.
- Discrete fracture network models are constructed that are representative of bright coal.
- Permeability is calculated directly on voxelised DFN models to evaluate coal heterogeneity and anisotropy.
- The developed framework resolves CT imaging resolution limitation and segmentation errors.

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ABSTRACT

Coal seam gas (CSG) is gaining global interests due to its natural abundance and environmental benefits in comparison to more traditional energy sources. However, due to its significant heterogeneity and complex porous structure, it is challenging to characterise and thus predict petrophysical properties. Moreover, the fracture network of coal poses a major challenge for direct numerical simulations on segmented images collected from X-ray micro-computed tomography (μCT). The segmentation of coal images is problematic and often results in misclassification of coal features that subsequently causes numerical instabilities. This paper aims to develop an advanced image analysis method and a novel discrete fracture network model to circumvent these issues. Coal μCT data are utilised for the acquisition of structural parameters and then discrete fracture networks are built to reconstruct representative coal images. The modelling method mimics the cleat formation process and reproduces particular cleat network patterns. The reconstructed network preserves the key attributes of coal, i.e. connectivity and cleat structure, while not being limited in terms of size and/or resolution. Furthermore, direct numerical simulations based on lattice Boltzmann method are performed on the cleat network realisations to evaluate coal permeability. We find that directional permeabilities result in different system scaling effects because of the dependence on the underlying structure of the cleat network. The developed method facilitates the evaluation of the relationship between coal cleat structure and resulting flow properties, which are steps forward in the evaluation of coal petrophysical properties at the core scale.

1. Introduction

Coal seam gas (CSG), also known as coal bed methane (CBM), is a form of unconventional natural gas extracted from coal reservoirs. In the past, methane was vented during mining operations for safety concerns, but now it makes a significant contribution to powering both industry and households [28,63]. As a result, the study of coal structure is considered crucial, because CSG production is mainly controlled by coal permeability [23,58], which in turn is related to the underlying fracture network, called 'cleats'. Coal cleats theoretically occur in two main sets of sub-parallel fractures, "face cleats" and orthogonal "butt cleats" as demonstrated in Fig. 1 [66]. In most circumstances, face cleats are formed first during coalification, whereas butt cleats occur later and terminate at face cleats, resulting from the relaxation of the original stress field [24,66]. In other words, for an organised cleat set, the connectivity pattern mostly presents "T-junctions" between face cleats and butt cleats. Generally, the 3D description of cleats includes spacing, geometry, orientation, aperture size, connectivity, degree of mineralisation and topology, all of which can influence methane production [38].

There are three main models proposed to characterise fracture systems and simulate fluid flow: (1) equivalent continuum model

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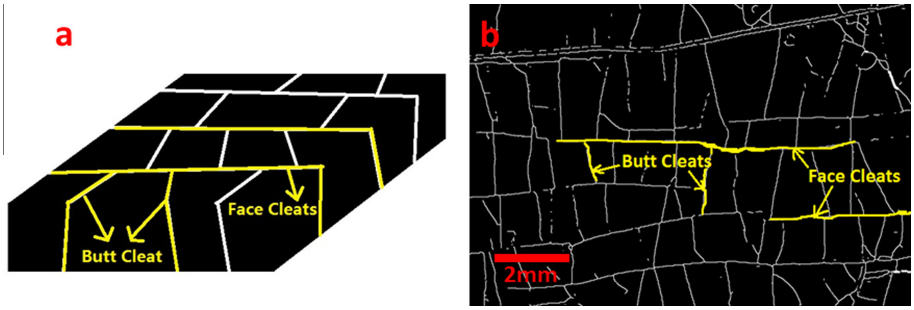

Fig. 1. An illustration of face and butt cleats in a conceptual model (a) and real cleat system (b). Face cleats are orthogonal to butt cleats, and butt cleats terminate at face cleats.

(ECM) [9,57,70]; (2) dual-continuum model (DCM) [34,76]; and (3) discrete fracture network model (DFN) [10,16]. ECM is the most simplified model, where the porous medium is divided into a number of regions where physical properties, e.g. transmissibility and storage, are defined to be uniform. These physical properties are computed from a fracture network realisation and then volume averaged for the total rock size, including matrix and fractures [30]. The DCM, also known as the dual-porosity model, originates from the study of Barenblatt et al. [4] and was introduced by Warren and Root [76]. This model is comprised of primary porosity and secondary porosity. Flow can occur between the primary and secondary porosities through an exchange term, but no flow is considered in the primary porosity. Later, the model was developed to account for flow in both domains, i.e. the dual permeability model [6,29]. The DCM is commonly limited to simple fracture configurations. In a recent study, Sakhaee-Pour and Wheeler [64] developed a fracture-cell model to simulate multiple intersecting curved fractures. Similar to DCM, each cell is assigned with porosity and permeability values to model the flow behaviour: the effective porosity is almost identical to matrix porosity while the effective permeability is determined by the flow path direction and fracture geometry. Their model is able to resolve complex fracture geometries and can be implemented into a reservoir simulator to simulate flow in ultralow permeable reservoirs, such as shales. Both ECM and DCM are prevalent in industry due to their simplicity and computing efficiency. They are however extremely simplified representations of complex fracture networks and inherent non-physical abstractions often make them inadequate for the accurate determination of flow properties in fractured reservoirs.

In contrast to continuum models, DFN assumes that fluid transport in fractured rock is dominated by a number of unique pathways formed by discrete fractures. Therefore, instead of average or effective medium properties, DFN describes the geometry and attributes of discrete fractures explicitly [18]. Thus, it is the most accurate approach for modelling fracture systems [25]. Advantages of DFN modelling are summarised as follows: (1) it can account for physical geological parameters, such as fracture orientation, length, aperture size and depth; (2) it can be upscaled to a dual medium model, which can be solved using conventional computational methods, such as finite difference; (3) it can assess larger scale connectivity, such as faults and large fractures; and (4) it can quantify the uncertainty and heterogeneity of porosity and permeability using stochastic methods [45]. However, DFN also suffers some drawbacks. For instance, it requires more computational time in comparison to ECM and DCM [40,57] and mesh generation for arbitrary fracture networks can be complex and challenging [25].

The first use of DFN models for flow in fractured porous media was in the early 1980s and these models consisted of discrete planes in 3D or line segments in 2D. Baecher et al. [3] established a DFN model based on the statistical description of rocks, in which fractures were circular disks, based on the findings of Robertson [61]. They assigned random centre points following Poisson distribution, log-normal distributed radii and weighted frequency distributed orientations to the disks, while neglecting aperture size distribution. Afterwards, Cacas et al. [10] further developed DFN modelling by applying the Fisher von Mises distribution on fracture orientation and classifying the orientation into different families. In addition, they used a lognormal distribution to characterise fracture aperture sizes. Cacas's method of building DFN models is still widely used, while the distributions may vary according to the observed field data. Apart from conventional fractured rocks, DFN modelling is also feasible for coal reservoirs [15,24,41,66,79]. Nevertheless, most of the coal studies simply generate DFN models stochastically based on statistical descriptions of the cleat network and thus disregard the underlying connectivity of face and butt cleats. Only a limited number of studies consider the potential spatial organisation of the cleat system. For example, Gao et al. [24] built a DFN model for coal cleat systems, which consists of three orthogonal discontinuity sections: (1) bedding planes; (2) face cleats; and (3) butt cleat. This DFN model seems to describe coal rather well, but the independent orientation statistics of the face and butt cleats were not included. Therefore, they failed to reproduce the characteristic “T-junctions” that are common in fractured coal seams [43]. Herein, a novel DFN model is designed specifically for coal cleat networks that includes the independent distribution statistics of face and butt cleats and then generates networks in a way that mimics the geological formation of the cleat network.

DFN models can be constructed for a large range of length scales, ranging from field scale (>1 km) to core scale (1–10 cm). Cleats on different scales require different approaches to obtain the necessary statistical data for DFN reconstruction. For instance, cleat network reconstruction on larger scales (m to km) combines seismic, well logging, outcrop analysis, and coring data. But such quantitative field data are not always available and often extremely expensive. In this paper, we characterise fractures at the core scale using a non-destructive imaging technology called X-ray micro-computed tomography (μCT). This technique has the capability of detecting cleats at the micrometre length scale in core plugs that are many centimetres in diameter. There are several relevant works on the application of μCT scanning for coal characterisation and modelling. Mazumder et al. [47] applied μCT to analyse cleat spacing, aperture sizes and orientation. However, they lacked a comprehensive way to determine cleat spacing statistics. More specifically, fractures of non-desirable directions were suppressed manually, then a set of parallel lines perpendicular to a pre-defined direction were added to the image, finally only line segments that were connection from one cleat to another were measured. This manual measurement approach is not practical for hundreds or