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Full Length Article

Rough-walled discrete fracture network modelling for coal characterisation

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HIGHLIGHTS

- A method for extracting fracture surfaces from micro-CT images is developed.
- The roughness of fracture surfaces is quantified.
- Rough-walled discrete fracture network models are developed.
- Overestimation of permeability based on conventional DFN models is addressed.

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ABSTRACT

Coal seam gas (CSG), an unconventional resource of energy, is gaining global interests due to its natural abundance and environmental benefits in comparison to more traditional energy sources. Its production is mainly controlled by the underlying fracture network of coal, called “cleats”. The discrete fracture network (DFN) model is widely applied for characterising fracture networks due to its ability of accounting for physical geological parameters of cleats. However, common discrete fracture network (DFN) models fail to preserve the local heterogeneity by assuming planar and smooth cleat surfaces, while real cleats have rough walls and variable opening apertures. This paper aims to characterise the roughness of cleat surfaces at the core scale by developing a novel framework: rough-walled discrete fracture network (RW-DFN) model. The model integrates the pore-scale roughness obtained from micro-computed tomography (micro-CT) imaging of coals into the discrete representation of fracture networks. Analysis of the fracture surfaces obtained from micro-CT imaging demonstrates random, isotropic surfaces following a Gaussian distribution. RW-DFN gives lower permeability than that of the traditional DFN by up to 30%, and its permeability estimation is more accurate with significantly fewer errors (6.5%) than traditional ones (25.1%). This indicates that, to be able to characterise these reservoirs, traditional DFN models may over-estimate the production while our proposed RW-DFNs provide more deterministic results. Overall, the method applies micro-CT imaging to obtain the internal surfaces of coal fractures in a non-destructive manner and reconstruct representative RW-DFN models. The developed RW-DFN models are not restricted by the imaging resolution, so that they are favourable for direct numerical simulation of permeability. In addition, RW-DFN models can be constructed with extended domain size, so they can be incorporated into existing reservoir characterisation frameworks for the prediction of coal properties.

1. Introduction

Coal seam gas (CSG) is a form of unconventional natural gas extracted from coal bed reservoirs, whose production is mainly controlled by the underlying fracture networks, known as “cleats” [20,58]. In these reservoirs, the matrix is usually regarded to be relatively impermeable [62,48], while the fractures contribute as the main hydraulic conductivity of the rock mass [17]. To represent the subsurface fracture system more realistically, discrete fracture network models (DFN) [16,11] are widely applied, where geometrical parameters, such as orientation, length, aperture size and density, are described explicitly and assumed to be statistically distributed. For example, centre points of fractures follow Poisson distributions, radii and aperture sizes exhibit lognormal distributions, and orientations follow weighted frequency distributions

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or von Mises Fisher distributions [3,11,15,61,71,22,76,43]. Apart from assumptions, statistical data can also be obtained from field data for the generation of fracture networks on the field scale (m to km), or by using a non-destructive imaging technology on the core scale (1–10 cm). In this work, the fracture characterisation at the core scale is studied applying X-ray micro-computed tomography (micro-CT). The fracture characterising framework on the core scale generally consist of the following steps: (1) micro-CT imaging of the core to provide a 3D fracture system; (2) analysing the geometrical properties of discrete fractures obtained from images to extract the statistical data; (3) reconstruction of DFNs where fracture geometries follow the measured statistics; and (4) solving for fluid flow using analytical or numerical methods to predict petrophysical properties [7,49,69,32].

DFN models are commonly assumed to have smooth and parallel (zero dilation) planar fractures [50,31]. While in real rocks, natural fractures have variable opening widths and rough walls with possible contact between the wall boundaries at discrete points [21,8,13,78,19]. When the area of contact between fracture surfaces is greater than approximately 30%, effects of fracture roughness cannot be neglected [65]. Because the fluid tends to avoid the constrictions and contact areas of the fracture, so the flow through a single fracture is divided into several tortuous flow channels [66]. As a result, the hydraulic transmissivity calculated based on simplified DFN models is overestimated in comparison to that of a rough plate model of an identical mean aperture [13,19]. Therefore, fracture roughness is significantly important in determining the hydraulic behaviour of coal samples [68].

To include the effect of fracture roughness, several methods have been developed based on the cubic law for flow where the average flow rate of a fracture is assumed to be proportional to the cube of mechanical aperture width [21]. For example, the aperture term is redefined by replacing the mechanical aperture with the smaller hydraulic aperture, which is a function of surface roughness [8,72,77]. Because the flow in rough fractures is nonlinear, the permeability is lowered due to the induced frictional loss. Roughness can also be accounted for by introducing a multiplicative factor in the cubic law [74,54]. Apart from that, aperture heterogeneity can be accomplished by discretising the DFN model into equal grids, where equivalent permeabilities are calculated using the cubic law with different aperture values [28]. However, the one-dimension cubic law is not accurate for three-dimensional data, e.g. non-uniform and tortuous flow fields [10]. Also, three-dimensional Navier-Stokes (NS) equations are challenging and time-consuming to be solved on irregular geometries, such as rough-walled fractures, since NS equations have a set of coupled nonlinear partial derivatives of varying orders [10,41]. Therefore, the direct inclusion of roughness to the DFN geometries can be an alternative solution that is straightforward and reliable.

In our previous work [32], an efficient method based on DFN was developed for reconstructing representative coal micro-CT images. The method used a voxelisation algorithm to convert continuous DFN geometry into an array of discrete voxels, which aims to avoid the complex and computationally expensive mesh generation for solving NS equations and also to regenerate an image geometry that can be imported to simulation software. However, fracture roughness was not considered and an average fracture aperture was assigned to each cleat. This can cause an overestimation of permeability of coals [13,19,39,32]. The conventional parallel planar DFN models require improvements to be able to describe more realistic fracture geometries. Herein, a novel rough-walled discrete fracture network (RW-DFN) model is proposed in which fractures have stochastic rough surfaces that are based on roughness information extracted from micro-CT data. The developed RW-DFN models are more representative of original micro-CT images in comparison with DFN models in terms of both underlying cleat networks and the permeability estimation. Therefore, the resolution limitation of the original micro-CT images will be eluviated by constructing representative RW-DFN models that are favourable for direct numerical simulation of permeability. Furthermore, RW-DFN models are not restricted by the domain size, so they can be extended in size for upscaling purposes.

2. Roughness analysis

To analyse the fracture surfaces, the surface topography and roughness profiles are generally measured by stylus profilometers [65] or laser profilometers [9,38,35]. But these line-of-sight techniques are either destructive or fail to examine the internal surface roughness of 3D structures. Thus, micro-CT scanning is more advantageous to acquire high-resolution volumetric data of an internal fracture network without damaging the specimen physically [14], which allows for a more thorough analysis of the surface topology. In our work, a helical scanning micro-CT instrument developed at the Australian National University [63] is used to generate a 3D high-resolution spatial representation of coal. Therefore, the internal fracture tomography of the specimen is obtained without touching the surface and line-to-line scanning, which is required by profilometers to give surface profiles. The micro-CT image acquisition and processing are described by Ramandi et al. [59].

2.1. Fracture surface extraction

2.1.1. Cleat classification

Since face and butt cleats have different attributes and statistical properties [39], we categorise segmented micro-CT images into face cleat and butt cleat images (Fig. 1). Firstly, the image is rotated such that the majority of the cleats are placed either horizontally or vertically. Then cleats of the segmented micro-CT image are skeletonised with a thinning algorithm [40] to give one-voxel wide cleats. Each fracture-identified voxel on a 2D slice is tagged with 8 neighbours that are used to determine the direction in which the tagged voxel extends. As a result, skeletonised cleats are partitioned into horizontally and vertically-oriented groups [32]. However, these partitioned cleats are one-voxel wide, which cannot be used for aperture and roughness measurements. To preserve the aperture heterogeneity, we overlay the two groups of skeletonised cleats onto the original image respectively, which are then utilised to locate the medial axes of face and butt cleats. Therefore cleats in the original image whose medial axes overlap with each partitioned cleat group are kept to provide two separate cleat families with aperture variation.

2.1.2. Fracture labelling and surface extraction

To study fracture surfaces individually, fractures must be labelled. Individual cleats have already been isolated during the cleat classification step; therefore, cleats can be identified and labelled by finding connected components. Fracture labelling is realised by applying a flood-fill algorithm [27], which searches for all voxels that are connected to the starting investigation voxel and then assigns them with a particular value. Consequently, voxels represent a single fracture are identified and labelled with a unique value.

For each fracture, there are two opposite rough walls to be analysed. In the previous step of cleat classification, we spin the image such that the majority of the face cleats are placed horizontally and orthogonal butt cleats are vertically oriented. Thus, two wall surfaces of one single fracture are extracted by finding the minimum and maximum coordinates in X- and Y-directions for butt and face