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Full Length Article

Digital coal: Generation of fractured cores with microscale features

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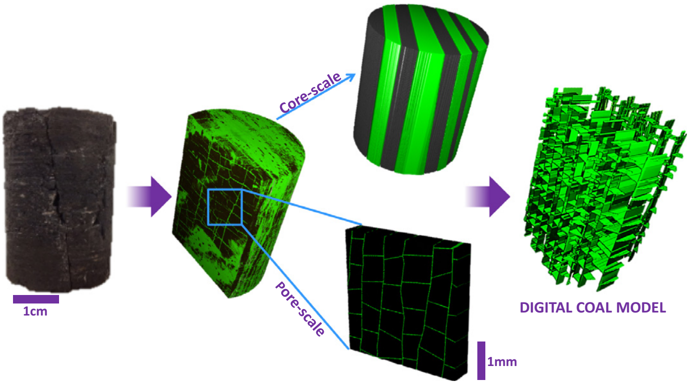
HIGHLIGHTS

- The band information of coal is numerically extracted from micro-CT data.
- A 'digital coal' model is developed to characterise coal multiscale heterogeneity.
- Pore-scale features of cleats are integrated into core-scale digital coal model.
- Petrophysical properties of original micro-CT images are preserved by numerical models.

GRAPHICAL ABSTRACT



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ABSTRACT

Coal is highly heterogeneous at multiple scales, such that the characterisation of coal lags behind that of conventional reservoir rocks. This paper demonstrates the capability of a digital coal model that can be used to characterise the multiscale structure of coal as well as its petrophysical properties at the core scale (cm). X-ray micro-computed tomography (micro-CT) is applied to obtain the internal cleat structure of a heterogeneous fractured coal sample, based on which statistics of coal lithotype distributions and cleat geometrical properties are extracted. Digital coal models are constructed stochastically according to the measured statistics. Resulting models preserve the core scale (cm) heterogeneity and pore scale (μm to mm) cleat properties of the imaged coal sample. Furthermore, petrophysical evaluation is performed based on the stochastic digital coal models. We find that the generated digital coal models can provide permeability estimation with errors of 26.7% in comparison to that of the original micro-CT data. Since the presented model is able to preserve the multiscale heterogeneities as well as petrophysical properties of coal, our work provides an alternative to segmented micro-CT images. Therefore, we can avoid the challenges that are inherent to micro-CT images, such as segmentation errors, size and resolution limitations. The digital coal model can also be a tool of linking the rock microstructure to petrophysical properties at the core scale, such that we can predict the permeability of coal based on its geometrical measures rather than expensive laboratory experiments.

1. Introduction

Coalbed methane (CBM), also known as coal seam gas (CSG), is an important source of natural gas rapidly emerging around the world [1]. Compared with conventional gas reservoirs, coal is so permeated with methane that it can contain up to seven times more methane than that of an equivalent size sandstone gas reservoir [2]. To efficiently recover this abundant energy, a detailed understanding of the fundamental properties of coal is required. However, coal is notoriously difficult to characterise due to the complex structure and extreme heterogeneity at multiple length

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scales [3]. Therefore, a more comprehensive characterisation method is necessary to characterise the multiscale heterogeneities of coal.

X-ray micro-computed tomography (micro-CT), as a non-destructive imaging technology, can provide the internal structures of reservoir rocks in 3D with resolution down to micrometres. It has been used for a range of rocks such as sandstones [4,5], carbonates [6,7], shales [8,9] and coal [10,11]. Micro-CT imaging has been applied for a wide variety of purposes, including the micromorphology analysis [12,13], prediction of permeability and relative permeability [5,6,14,15] and reactive transport [7,16,17]. For a review on the application of micro-CT imaging for reservoir rock characterisation, we refer to Blunt et al. [18] and Bultreys et al. [19]. As coal is strongly heterogeneous at microscopic scale [3], micro-CT imaging is widely utilised to obtain the microstructure of coal samples for various analyses: gas sorption process [20,21], coal swelling [22,23] and cleat geometrical properties [11,24,25]. Mostaghimi et al. [26] has reviewed recent developments in micro-scale characterisation of coal.

Methane production is mainly controlled by coal permeability [27,28], which is governed by the geometrical properties of the cleat network, including orientation, length, spacing and aperture size [26,29,30]. To obtain the geometrical statistics at the core scale, a quantitative image analysis method based on the segmented micro-CT images is developed. The orientation measurement is based on calculating the largest eigenvector of the structure tensors [31,32]. Lengths are determined by the number of voxels of skeletonised cleats. However, cleats intersecting with each other must be separated prior to these measurements, which requires manual editing and is less efficient for hundreds or thousands of cleats [24,33]. Jing et al. [11] have developed an automatic cleat-grouping algorithm to distinguish between face and butt cleats for subsequent image analysis, so that attributes of different cleat families can be analysed separately. In addition, aperture sizes are measured by placing 3D spheres inside cleats. The diameter of the sphere that fits inside is regarded as the aperture of the corresponding fracture [34]. Apart from that, cleat apertures can be measured from the CT number profiles that traverse a cleat [24,35–37], where an obvious dip of the grey-scale profile indicates a cleat. Two parameters such as peak height (PH) and missing attenuation (MA) [38] of the profile are defined to calibrate with corresponding cleat apertures, thus apertures can be estimated according to the calibration curve. Statistics measured from micro-CT data have been used for generating discrete fracture network models (DFN) [11,25,33,39]. DFN models, consisting of discrete planes whose geometrical properties are statistically distributed, have been widely applied to characterise the cleat system since this method explicitly accounts for fracture geometrical properties [40–45]. Recently, Jing et al. [11] have developed a novel DFN model that is comprised of two orthogonal sets of sub-parallel cleats: face cleats and butt cleats. The DFN algorithm mimics the cleat formation process, where face cleats form first and are extensive while butt cleats are generated later and terminate at face cleats, creating "T-junction" connections. This approach mimics the regular and extensive cleat patterns commonly occur in bituminous coal while subbituminous coal have poorly-developed cleats [46] and thus, an alternative approach may be necessary. However, this work focuses on bituminous coal only since these are the coals of interest from a production point of view.

The well-organised cleat network pattern studied above mostly occurs in "bright bands" that are rich in vitrain material, which is brittle [47]. Bright bands have a bright lustre and are permeated with fractures at right angles [48]. However, coal is highly heterogeneous, comprising of multiple lithotypes [47,49]. Apart from bright bands, coal that is composed of durian is called "dull bands", where durian is a grey to black material with a dull lustre [48]. Most coal appear to be banded because of the alternating bright and dull bands [50,51] that originate from different plant materials [47,49]. Unlike bright bands, dull bands have significantly different cleat properties: (1) dull bands do not have a systematic cleat network and thus, face and butt cleats are hardly recognised [50,52]; (2) cleats of dull bands, named "dull cleats", are poorly developed, appearing to be short, discontinuous and unidirectional [50]; (3) dull cleats have larger spacing than bright cleats [27,53–55]. Dull cleats are rarely observed in coal samples not only because they are generally rare, but also because the spacing of dull cleats is often larger than standard core samples [56]. As evident from these studies, different coal bands have unique cleat properties and thus, the characterisation of coal bands is of paramount importance.

The main aim of this work is to develop a digital coal model that is able to preserve pore-scale cleat geometrical properties as well as core-scale lithotype information of coal. The micro-scale features of coal cleats are integrated to a core-scale model. We further evaluate the developed digital coal models in terms of petrophysical properties to investigate if they can characterise the flow properties of original micro-CT images. Digital coal models can be an alternative to the collection of micro-CT data and we can avoid challenges that are inherent to micro-CT images, such as segmentation errors, size and resolution limitations. Besides, the digital coal model can be used to link the microstructure of rocks to petrophysical properties at the core scale, such that we can predict the permeability of coal based on its geometrical properties that are observed directly from micro-CT images without laboratory experiments.

2. Material and method

2.1. Sample information

A bituminous coal sample (D = 24 mm, L = 28.5 mm) is collected from the Moura coal mine of Bowen basin, Australia. Its detailed specifications, including proximate and ultimate analyses are provided by Ramandi et al. [57]. Alternating bright and dull lithotypes with approximately similar proportions can be seen in Fig. 1. A high-resolution, large-field, helical micro-CT scanning instrument is used to evaluate the three-dimensional pore-scale structure of the sample. X-rays are emitted from a micro-focus source to probe the sample, and a detector is used to record a series of X-ray transmission radiographs at different viewing angles [58]. Then, collected data are processed with a reconstruction algorithm [59] to provide a 3D micro-CT image that has a 16-bit grey-scale map represented by an array of voxels. Image segmentation is then applied

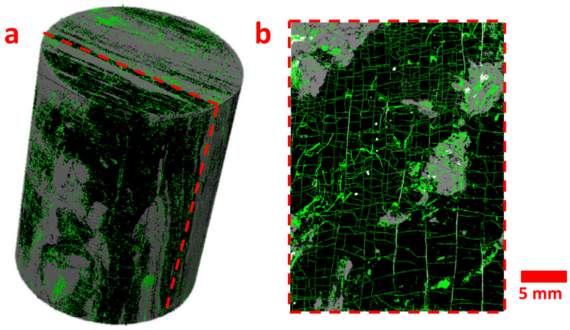

Fig. 1. (a) The coal sample with alternating bright (shown in black) and dull bands (shown in grey); (b) A cross section from the bright band (indicated by the dashed line) where the cleat network (shown in green) with "T-junctions" is well-developed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)