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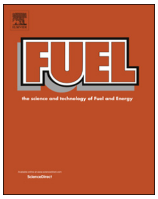

Full Length Article

# High-pressure X-ray imaging to interpret coal permeability

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ABSTRACT

Coal seam gas (CSG) is an unconventional resource drawing attention globally and is considered to play a crucial role in the future natural gas market. In CSG reservoirs, the characterisation of fracture aperture sizes is critical since coal permeability and wellbore performance are highly dependent on this parameter. To optimise gas recovery and predict gas production rate, it is important to analyse reservoir properties at *in situ* conditions. By using a high-pressure flow cell and X-ray microcomputed tomography (micro-CT) imaging, we visualise how the internal structure of coal changes under prevailing reservoir conditions. Important differences in the size of fractures can be seen from images of the coal sample obtained at different pressure. As anticipated, aperture size was found to decrease with increasing confining stress from atmospheric to reservoir pressures and it was more sensitive to the change of initial pressure. Similar conclusions were drawn for both gas and Klinkenberg-corrected permeability using helium and methane gases. In the permeability experiments, methane gas is used to mimick *in situ* conditions whereas helium is used for comparison as a non-adsorbing gas. There was less change in fracture aperture size if the ends of a coal cleat are sealed by minerals. We successfully applied micro-CT imaging on coal samples under high confining stress. The coal sample studied has a relatively large diameter compared to the common core sizes used for high-pressure imaging. Overall, this paper demonstrates a quantitative analysis of coal permeability at reservoir conditions, which provides a better understanding of deformation and further insights into enhanced CSG exploration and development techniques.

## 1. Introduction

Coalbed methane (CBM), also known as coal seam gas (CSG), refers to natural gas adsorbed to the internal coal surface. It has been associated with safety problems including outbursts and explosions for more than 100 years before being considered as a recoverable source of energy [1]. As natural gas starts to gradually replace oil and coal for electricity generation, CSG is being widely recognised as an important energy resource worldwide [2]. The future of CSG is promising as the world is in need of cleaner energy [3].

The ease at which hydrocarbons can be recovered from conventional oil and gas reservoirs is largely affected by the reservoir permeability and porosity, which is also true for CSG reservoirs. A coal seam is a dual-porosity structure with the majority of porosity coming from the almost impermeable matrix and fractures called cleats that contribute to coal permeability [4–6]. Coal cleat aperture size, that is the width of the coal fracture, is an important cleat property that impacts reservoir permeability and gas recovery [7,8]. Fracture aperture size is stress-dependent and therefore challenging to characterise during the production phase where the reservoir pressure is continuously changing [9]. Thus, the relationship between aperture size and confining stress is a point of interest for petroleum engineers and should be thoroughly understood [7].

The aperture size of coal cleats has been reported in many papers [7,10–15]. However, limited studies have been conducted on the effect of confining stress on aperture size. Huy et al. [14] reported aperture sizes at confining stress up to 2 MPa ($\approx$290 psi) and concluded that the width of fractures does not depend on confining stress at this low-pressure range.

Naturally, as confining stress increases, aperture sizes are expected to decrease [16]. Therefore, it is crucial to study how *in situ* pressure affects fracture openings [9,16]. Cleat aperture sizes are often less than 0.1 mm at surface conditions indicating that it is even more difficult to be measured at *in situ* conditions [9]. Therefore, X-ray micro-computed tomography (micro-CT) imaging technique, which can generate images with resolution down to 1 μm [17,18], has been considered as a suitable method to assess coal cleat aperture sizes.

Micro-CT imaging has been widely used for rock characterisation [19–21] and petrophysical analyses [22,23]. During the past twenty years, it has been applied to study coal from different aspects. Yao et al. [8], Van Geet and Swennen [12], Verhelst et al. [24], Simons et al. [25] studied the density of different components of coal and how to

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distinguish between them. Karacan and Okandan [7] analysed the adsorption and transport properties of different coals. Pyrak-Nolte et al. [11], Mazumder et al. [13], Wolf et al. [26], Cai et al. [27], Jing et al. [28], Jing et al. [29,30], Jing et al. [31] provided analyses on coal fracture direction, spacing, aperture size and roughness. Jing et al. [32] also developed a digital coal model based on analyses of coal microstructure. Vega et al. [33], Zhang et al. [34] studied coal pore structure including the estimation of porosity and its distribution. Ramandi et al. [35] proposed a technique for studying coal porosity and permeability as well as these properties in different coal lithotypes. Mostaghimi et al. [36] introduced the method of using micro-CT imaging to obtain coal cleats network for further microfluidic flow experiments to study the effect of coal topology on fluid flow through coal. Gerami et al. [37] then applied this method to obtain more insights into the relative permeability of coal. Zhang et al. [38] focused on using micro-CT imaging to study the effect of swelling on rock structure. These studies have provided insights on the understanding of coal petrophysics and demonstrated the effectiveness of micro-CT imaging for coal analyses. In this study, we use a high-pressure aluminium coreholder for micro-CT imaging of coal samples at reservoir conditions to study fracture aperture sizes.

Many methods have been proposed to measure fracture aperture size from micro-CT images. Three of the popular methods are peak height (PH) [39], full-width-half-maximum (FWHM) [12] and missing CT attenuation (MA) [40–42]. Among these methods, the FWHM method fails when the fracture is too thin and the PH method is not applicable for wide fractures [41]. The theory behind the missing attenuation method is that in micro-CT images, the CT number for fractures or pore space is lower than that of rock matrix because of the difference in density. However, due to partial volume effects [43], the CT number in the voxels near fractures is also decreased, which means that no clear and precise boundary between the two different components can be observed. This causes inaccurate prediction of fracture aperture size from micro-CT images. To circumvent this effect, the MA method assumes that during the scanning process, the amount of X-ray attenuation remains constant, which means that the total amount of attenuation caused by the presence of a fracture is equal to the integration of any attenuation in the nearby voxels. The fracture size can then be estimated by establishing a relationship between itself and the total attenuation amount [40]. The MA method is proven to provide the most accurate result [44]. However, significant effort is required to calibrate the method [44]. Ramandi et al. [45] correlated the true aperture size obtained from SEM images with the midpoint greyscale value of the fracture in micro-CT images [46]. However, common problems with the method are: (i) possible damage to the rock as SEM is considered as a destructive method and (ii) significant amount of calibration required. In this paper, we use the calibration-free missing CT attenuation (CFMA) method to conduct aperture size measurements. This method was proposed by Huo et al. [47] based on the MA method and has been proven to provide accurate results when applied to heterogeneous rocks by data matching with conventional measurement methods. According to Huo et al. [47], the error is expected to be one-twentieth of the voxel size.

The flow of gas through coal is highly dependent on the aperture size of coal [48]. A thorough understanding of fracture behaviour under reservoir conditions, i.e. when fractures are subject to high effective stress, is required for reliable gas flow simulation. However, it is challenging because coal cleat aperture sizes range from only a few to tens of micrometres. Therefore, limited studies have been performed on the aperture size of coal cleats under confining stress. Furthermore, the fact that coal may easily break or crumble during coring encourages researchers to conduct experiments on the as-received samples from initial coring. This paper aims to investigate coal aperture sizes under reservoir pressure conditions by applying micro-CT scanning at confining stress on an 80 mm diameter coal sample. A permeability test is conducted and related to the obtained micro-CT images and calculated aperture sizes for comparison.

## 2. Materials and methods

The coal sample is cut to a length of 83 cm and placed in an aluminium high-pressure coreholder for scanning. The sample is then scanned at two different confining stresses. The high-pressure micro-CT images are then compared with the original scan at ambient pressure for comparison of cleat aperture size using the CFMA method presented by Huo et al. [47].

### 2.1. Sample

The sample is a dull coal with minor bright bands with a diameter of 76 mm. The core is imaged at as-received condition under ambient pressure using the micro-CT scanner. No further coring is done on the sample to avoid damaging of the sample by inducing more fractures. The sample is then wrapped with heat shrink wrap to protect it from cracking during the cutting process. The sample is cut using a Gemini Apollo Ring Saw to a length of 83 mm in order to fit in the high-pressure coreholder.

### 2.2. High-pressure micro-CT imaging

During the imaging process, the X-ray beam emitted from the source passes through the coreholder, which holds the rock sample and moves along a circular trajectory. A two-dimensional 43 × 43 cm 139 μm-pixel amorphous silicone detector collects the remaining X-ray at different viewing angles and records the radiographs based on the measured attenuated amount [49]. The sample is scanned at a voltage of 120 kV and a current ranging from 160 to 250 μA with an exposure time of 1.5 s. The radiographs are reconstructed by using an inversion formula-based algorithm developed by Katsevich [50] in order to generate three-dimensional images of the internal structure [51].

To conduct micro-CT scanning under high confining stress, an 80-mm aluminium coreholder is used. Since coal is brittle and has a high chance of breaking when drilling subsamples, this coreholder is designed to hold rock samples directly from the borehole to avoid any possible damage to the rock during further coring. Fig. 1 provides a schematic of the coreholder. The top plug, bottom plug and outer high-strength Viton sleeve together hold the coal sample in place and make a seal to contain the confining fluid. A thin layer of vacuum grease is then applied at the seams between plugs and sleeve to form a tight seal. The spigot at the bottom is designed for installation on the micro-CT imaging stage.

The setup for permeability measurement (Fig. 2) consists of the coreholder, hydraulic hand pump for applying confining stress, pressure transducers for monitoring confining and inlet pressure, and valves for maintaining pressure when disconnecting the pump from the flow cell. We use the hydraulic hand pump to inject the confining fluid, in our case water, into the cell through the inlet port and adjust the confining stress to reach desired values. During this process, the Viton sleeve and the top plug will be forced against the coal sample and exert hydrostatic stress on the sample. We study the coal sample under two confining stresses of 1000 and 500 psi to mimic the initial reservoir condition and a condition during the production stage, respectively. We first increase the confining stress to 1000 psi and monitor the pressure for at least 12 h to ensure it is stabilised and ready to be scanned. The pressure cell is then imaged by connecting the bottom spigot to the micro-CT stage. The pressure was then adjusted to 500 psi for another scan.

The sample is scanned at three different conditions: at ambient pressure, with a confining stress of 500 psi and with a confining stress of 1000 psi. The effective stress is defined as the difference between confining stress and pore pressure. Since we do not inject high-pressure gas into the pore space, the confining stress can be an estimate of