# MICRO-CT IMAGING AND MICROFLUIDICS FOR UNDERSTANDING FLOW IN COAL SEAM RESERVOIRS

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## ABSTRACT
We investigate transport through fractured coal samples using microfluidic experiment. Firstly, micro-CT imaging at dry and wet conditions are performed to identify sub-resolution natural fractures in coal (cleats). Scanning Electron Microscopy (SEM) is also performed to image cleats at resolution of 100 nm. A novel image segmentation method is developed to segment the micro-CT image and measure the fracture apertures based on SEM data. We fabricate micro-models based on observed geometrical features on the segmented coal images. Microfluidic facility and high speed video microscopy are used to capture displacement of gas by brine on the fabricated model. This is a first step for understanding and analysis of high-viscosity ratio displacement in complex coal cleat systems and to optimize gas recovery from coal beds.

## INTRODUCTION
Coal seam methane is a form of natural gas stored in coal beds and is one of the most important unconventional resources of energy. The flow and transport in coal beds occurs in a well-developed system of natural fractures that are also known as cleats. The cleat systems in coals have been the subject of intensive studies in recent years. The techniques used range from two-dimensional visual observations of coal outcrops and mine sites, high magnification and scanning electron microscopy (SEM) studies of rock fragments [3, 7, 8] to three-dimensional studies using X-ray micro-computed tomography (micro-CT) imaging with resolutions down to approximately a micron [2, 5, 9]. These studies show that the natural cleat system in coals spans all length scales from meters to hundreds of meters for exogenous fractures resulting from tectonic activity down to micro and nano-meters for endogenous micro and sub-micro fissures formed during coalification.

Although cleat orientation, density, aperture, height, length and connectivity are suggested to be important to the development of permeability none of the existing studies attempt to relate these features to flow properties of coal [1, 4]. This is a major shortcoming in the current understanding of the production characteristics of coal seam gas and in the ability of the industry to assess the value of laboratory measured core data.

In this paper, we discuss a workflow where coal samples are imaged twice, i.e. without and with an X-ray attenuating fluid present in pore spaces. This will allow for visualisation of micro-cleats under the resolution of the micro-CT scanner. Following this, a novel image segmentation method is developed that employs data from SEM to find the cleat aperture on the micro-CT image. We fabricate micro-models based on observed geometrical features in the coal images and study transport phenomena at micrometer scales using microfluidic technology. This will assist in understating transport phenomena in coals and optimising recovery from coal seam gas reservoirs.

# MATERIALS AND METHODS

## Imaging

The coal sample is a volatile bituminous coal from Queensland, Australia. Micro-CT imaging was performed using a high-resolution, large-field, helical scanning instrument at Australian National University. The sample was saturated with 1.5 molar Sodium Iodide (NaI) brine to increase the X-ray attenuation of the coal fractures. The sample was a full size core plug, i.e. 25 mm diameter and 35 mm length, imaged at a resolution of 16.5 micrometers. The collected images were segmented using a watershed-based segmentation technique. After micro-CT imaging the sample was cut, parallel to butt cleats, and polished for the SEM imaging. SEM images were registered to the micro-CT data using the method developed by Latham et al. [6].

## Flow Simulations

We calculate permeability and find the pressure and velocity profiles of coals on images obtained from micro-CT imaging. After image segmentation, the pore space is used as a computational domain to solve for Stokes flow. The governing equations for flow at the pore scale are:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$\mu \nabla^2 \mathbf{v} = \nabla P \tag{2}$$

where **v** is the velocity vector, $P$ is pressure and $\mu$ is viscosity of the fluid flowing in the porous medium. The equations are discretized using the finite difference method. The main numerical challenge in solving the Stokes equation – Eq. (2) – is the weak coupling of the pressure and velocity fields. For decoupling pressure and velocities, the Semi Implicit Method for Pressure Linked Equations (SIMPLE) is used.

## Experimental Setup

To perform the microfluidic experiment, a CAD (Computer-Aided Design) model based on the observed coal features is designed. A micro-model is fabricated using Polydimethylsiloxane (PDMS) based on the CAD design using softlithography technique. Then 1/16” PTFE tubes are connected to the flow inlet and outlets and a syringe pump with the accuracy of 0.35% and step resolution of 0.046 microns is used for flow injection. The injection rate is 1 μl/min. To visualise the flow pattern inside the microfluidic channels, an inverted microscope with equipped high-speed and CCD camera (Oympus IX81 and DP80) with 1360×1024 pixels resolution is used.

## RESULTS

Figure 1 shows the workflow used in this study for creating the micro-models and running the experiments. Figure 1(A) shows the grey scale image obtained from micro-CT imaging of the coal sample. The image has the resolution of 16 microns and imaging has been performed at wet and dry conditions. The grey scale image is obetained by subtracting the dry image from the wet image. This will enable us to visualise features smaller than the scanner resolution [5].

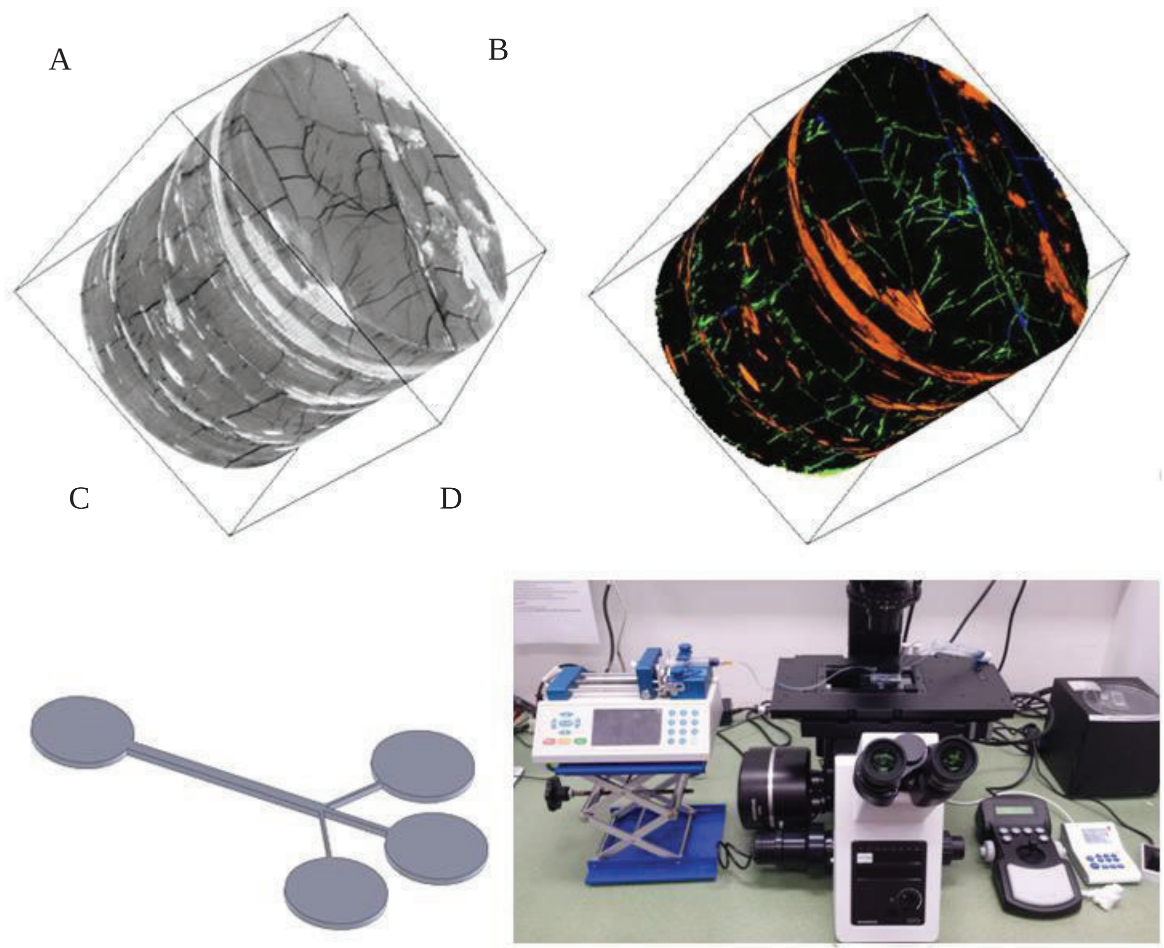


**Figure 1:** Workflow for the fabrication of micromodels based real cleat geometries. Micro-CT images of coal at wet and dry conditions are used to obtain a grey scale image (A). The image will be segmented (B) and the cleat system features will be visualised to be fabricated (C). The fabricated micro-model is used for microfluidic flow experiments using advanced microscopy tools (D).

The segmentation of coal images is of high importance due to existence of very narrow connectivities in coal samples. Figure 2 shows results of flow simulation over a region of interest (ROI) on the coal image. As can be seen from the velocity profile, there is a single voxel connecting the cleat system. Therefore, losing a single voxel in segmentation may lead to losing the connectivity.

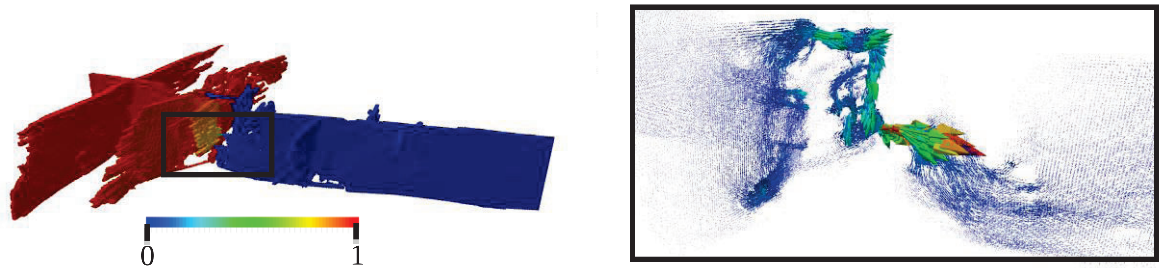


**Figure 2:** Single-phase flow simulation on extracted fracture geometry (Left: normalized pressure profile, Right: normalized velocity vectors in the black rectangle).

To segment the grey scale image, we use data from SEM imaging performed at a resolution of 100 nm and relate the grey scale micro-CT values to the measured aperture for the cleat system on the SEM image. Figure 3 shows a single cleat as observed in micro-CT and SEM imaging. The aperture of the cleat has been measured on SEM image and is related to the grey scale value. Repeating this process for different apertures will result in a curve that shows the corresponding aperture size for each grey scale value on the micro-CT image (Figure 3). The curve is used for image segmenation and the grey scale image is segmented into four different phases: (1) resolved fractures, (2) sub-resolution porous regions, (3) minerals, and (4) solid regions.

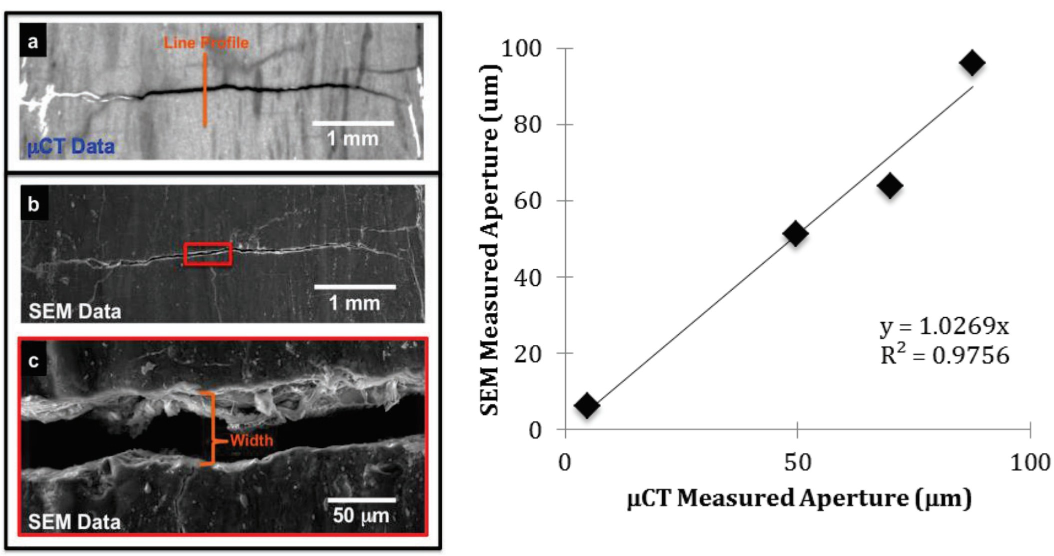


**Figure 3:** Registered micro-CT and SEM data for measurement of coal fracture apertures.

After segmentation, the resolved cleat system can be visualised and we generate CAD models based on the observed features in the cleat system. In this paper, we focus on a small region of interest where a junction of four fractures is observed (Figure 4). A micromodel is fabricated with similar topology and fracture aperture. Brine is injected from the widest fracture to the junction at the rate of 1 μl/min and the displacement of air is captured using the high speed camera. Figure 4 shows the movement of interface between fluids accurately with a contact angle of almost 90°. In our future works, we will use plasma treatment to change the wettability of surfaces and study the effect of wettability on gas recovery in coal seam reservoirs at micrometer scale. In addition, we will extract several unique features observed on segmeneted coal images and fabricate micro-models based on them. Then, displacement at each of these micromodels will be captured and investigated. This provides a comprehensive framework for investgating flow characteristics of coals and validation data for numerical computations.

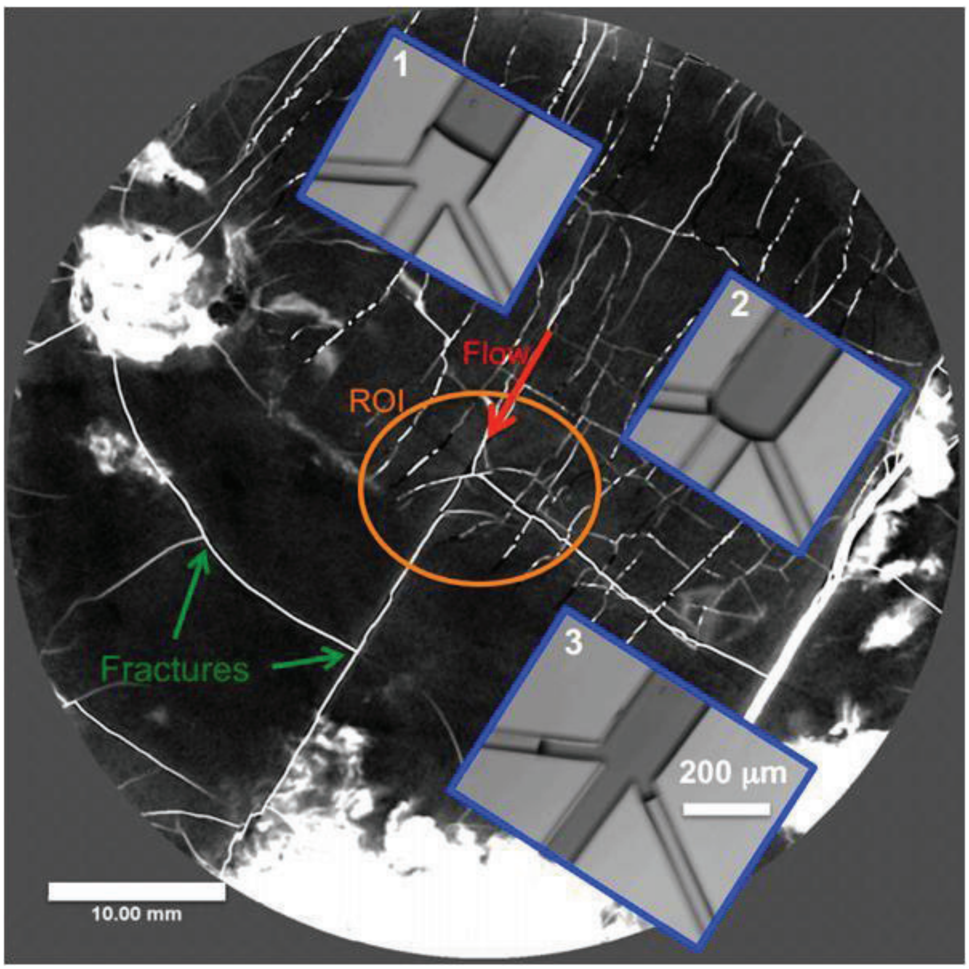


**Figure 4:** A 2D slice of the micro-CT image of coal where a region of interest (ROI) is chosen to be fabricated. The displacement of air by water at three stages is shown on the fabricated model representing a junction of coal cleat system. The dimension and the shape of the fabricated micromodel is chosen based on measurement of the fracture aperture size of the micro-CT image.

## CONCLUSION AND FUTURE WORK

A novel workflow for investigating the effect of cleat topology and geometry on fluid flow in coals is discussed. Coal is imaged at dry and wet conditions. This allows for visualisation of sub-resolution cleats in the image. An original segmentation method is used to extract the cleat network from the micro-CT data. Numerical simulation of flow shows that the cleat systems have very narrow connection that needs to be honoured in the segmentation. A unique feature of the cleat system is fabricated for microfluidic flow experiments. Preliminary flow experiments are performed to capture the interface between brine and air and to understand transport at cleat junctions. In future, we will conduct several experiments on a range of observed topological features in coals. This data presented herein is the first stage of an ongoing research effort to better understand flow in coal seam gas reservoirs.

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