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Review Article

Cleat-scale characterisation of coal: An overview

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ABSTRACT

This paper reviews recent developments on the cleat-scale characterisation of coal. Novel micro-CT imaging and image calibration methods are described. The application of micro-CT imaging for studying diffusion processes in ultralow permeability media is shown. The extraction of statistical information from micro-CT images to reconstruct cleats are demonstrated. The developments of microfluidic methods for understanding complex displacement mechanisms in coal seams and variation of coal contact angles are described. We explain numerical methods for prediction of petrophysical properties from micro-CT images and discuss limitations when dealing with coal. The paper concludes by addressing the challenges for microscale coal characterisation.

Contents

1. Introduction

Coal seam gas (CSG), which is also commonly known as coalbed methane (CBM), is the natural gas trapped in unconventional

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coalbeds. It had been causing outbursts and explosions during coal mining processes for over a century. The gas in coal seams was vented by airways to eliminate hazards until it began to be of economic interest in the 1970s' oil crisis in the USA (Flores, 1998). Nowadays, CSG has been commercially extracted in many countries, mainly Australia, Canada, China, India, Poland and USA (Gunter et al., 1997; Kotarba, 2001; Narasimhan et al., 1998; Shengchu et al., 2009; Towler et al., 2016). Recently, there have been investments in CSG recovery in other countries including Indonesia and Russia. CSG reservoirs have also been considered to be used for sequestering carbon dioxide (Gale and Freund, 2001; Tsotsis et al., 2004; Wei et al., 2010).

Several factors make displacements in coalbeds different to conventional hydrocarbon reservoirs. These differences are associated with specific physical mechanisms occurring during methane recovery as well as the formation of the CSG reservoirs. (i) In a conventional reservoir, hydrocarbons are mostly generated in shales or limestones, also known as source rocks, and migrate to shallower depths where it is trapped by a cap rock (Cossé, 1993). However, in CSG reservoirs, coal acts as both source and reservoir rock such that the gas initially formed during the coalification processes is stored there (Clarkson and Bustin, 1999; Seidle, 2011). (ii) Coal as a reservoir rock is of low porosity (0.5–2.5%) (Gash et al., 1992; Laubach et al., 1998) with a wide range of permeability (0.1–100 mD). (iii) Another difference is related to the presence of gas in conventional reservoirs where it exists mostly in free state, i.e. the gas is free to move in the pore spaces. For CSG reservoirs, 98% of gas is stored in the coal matrix and is released by sorption mechanisms during dewatering and production processes (Gray, 1987; Meng et al., 2014). This introduces new physics into the production mechanisms from these resources. (iv) The production profiles in conventional gas reservoirs are also different in comparison with CSG reservoirs. The initial production from a conventional gas reservoir consists of mostly gas with negligible amount of water. As the production continues, the fraction of water produced increases while the gas production decreases. However, in CSG reservoirs, production is initiated by dewatering, which releases the gas adsorbed to coal surfaces. This makes the production profile different to that of a conventional reservoir (Moore, 2012). (v) The pore space morphological properties are also unique in coal such that, at the pore scale, an orthogonal fracture system provides pathways for fluid flow. The coal fracture system is known as “cleats”, which commonly occur in two main sets of sub-parallel fractures; face cleats and butt cleats. 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 (Gao et al., 2014; Scholtès et al., 2011). This is in contrast to conventional sandstone gas reservoirs where the pore space is a granular medium formed through processes including sedimentation, compaction, and diagenesis. The unique pore space geometry of coal with cleat apertures less than 0.1 mm (Laubach et al., 1998) as well as the brittle textures of coal cause difficulties in the use of traditional laboratory measurements on coal cores. (vi) Coal permeability varies dramatically during reservoir production as coal is highly deformable and the cleat system deforms due to change of reservoir pressure and sorption mechanisms (Pan and Connell, 2012).

Over the last two decades, pore-scale imaging and modelling has received increasing attention for the understanding of displacement phenomena in reservoir rocks (Blunt, 2001; Blunt et al., 2013). It has offered oil and gas industries novel solutions for prediction of petrophysical properties of rocks that are difficult or in some cases impossible to obtain through applying conventional laboratory routines. Pore-scale modelling of rocks has also provided several new research opportunities to answer many questions on flow, transport, and reaction in porous media (Armstrong et al., 2016; Bijeljic and Blunt, 2006; Bijeljic et al., 2011; Joekar-Niasar and Hassanizadeh, 2012; Liu and Mostaghimi, 2017; Mostaghimi et al., 2012, 2016b; Tansey and Balhoff, 2016). In this paper, we review some recent developments of pore-scale imaging and modelling in the CSG context and demonstrate the unconventional challenges that are faced. Even though, many of the methods discussed are now a standard tool for managing and analysing conventional hydrocarbon reservoirs, they have not been fully translated to unconventional resources and in particular for the CSG industry. Due to the specific pore structure of coal cores as well as different multiphysics occurring during gas production, new challenges are to be faced for the micro-scale characterisation of coals. This paper is not intended to review all of the different applications of pore-scale imaging and modelling of coal. It is mainly focused on a few comprehensive applications of pore-scale analysis in coalbeds of interest to the authors. These include wet and dry imaging, image calibration, statistical analysis of cleat systems, diffusion modelling, coal wettability and microfluidics that have been developed mostly over the last few years. Fig. 1 illustrates the organisation of this paper.

2. Micro-CT imaging

2.1. X-ray imaging and processing

X-ray micro-computed tomography (micro-CT) is a non-

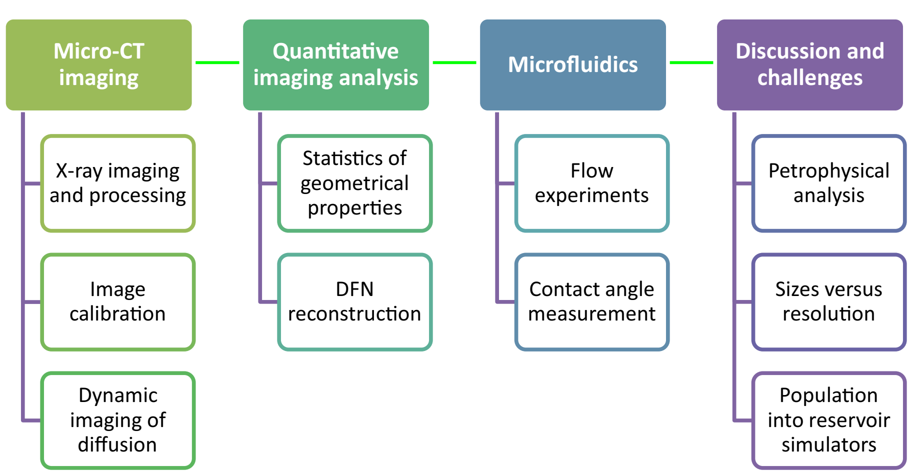

Fig. 1. An overview of the contents provided in this paper.