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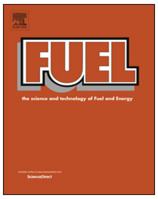

Full Length Article

An imaging and fractal approach towards understanding reservoir scale changes in coal due to bioconversion

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A R T I C L E I N F O

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A B S T R A C T

Microbially enhanced coalbed methane (MECBM) aims to replicate the natural process of microbial methane generation in coal under *in situ* conditions. Considerable work has been reported over the years to optimize the associated microbial geo-chemistry. However, there is very little insight with regards to changes in the physical structure of coal due to bioconversion, and its impact on fluid flow properties. This paper presents the result of an image and fractal-based approach used to evaluate the changes in physical properties of coal. Samples of coal treated over 30, 60 and 120 days respectively were imaged before and after bioconversion. The results revealed that coal bioconversion resulted in swelling of the coal matrix. Cleats narrower than 5 μm reduced in its width post-bioconversion. A 77% drop in the permeability of coal is expected from the obtained results. Bioconversion also resulted in separation of thin layers of coal flakes from the coal surface, serving as a potential source of fines. Fractal analysis of the images revealed a decrease in the fractal dimension post bioconversion, which is in agreement with the previously reported studies, thus corroborating the variations in sorption-trends observed due to bioconversion. Additionally, the methodology to determine the fractal dimension via two-dimensional image processing was modified to improve its accuracy, and remove the dependency of the dimension to the scale of the obtained images. Bioconversion also resulted in formation of new pores/fractures. Shorter treatment duration resulted in nanometer-scale discontinuous pores, which do not contribute to Darcian flow. Longer treatment periods resulted in sub-micron wide continuous pores. Also, few larger fractures (> 5 μm wide) saw an increase in its aperture post-treatment. This opens up new avenues, such as, utilizing artificially induced fracturing techniques to enhance biogenic methane production in future.

1. Introduction

Burning natural gas (methane and higher hydrocarbons) to produce electricity results in half the CO_2 emissions compared to coal-fired power plants [1]. With the scientific community aiming to fuel the earth's energy needs leaving minimum carbon footprint, the use of natural gas is considered an inevitable transition from a coal-to-renewably fueled future. Emissions from burning natural gas also result in lower sulfur, mercury and particulate matter compared to burning coal [2]. Furthermore, recent developments in high-temperature and more efficient natural gas combustion turbines add to the lure of natural gas. While naturally occurring conventional gas deposits are easy to exploit, there needs to be an increase in the resource base to provide a sustainable solution to the world's energy demand. This has resulted in a surge in worldwide interest in unconventional sources of natural gas.

Methane stored in coal seams provides one such avenue to cater to the world's energy need. Since the eighties, methane from coal has been commercially extracted worldwide. Several coal basins, such as, San Juan and Powder River in the United States, have seen tremendous success [3]. Given that coalbed methane (CBM) wells economically produce methane for more than twenty years, there exists at present, a number of depleted reservoirs worldwide. Post gas depletion, the coal *in situ* remains, which could potentially serve as an untapped source of energy.

Significant amount of methane extracted from coal has microbial (biogenic) origin [4–7]. Hydrocarbon production, primarily methane, is a result of microbial breakdown of the organic fraction in coal [8]. Taking cue from the widespread application of microbes in the oil industry as a means to increase the overall recovery, Scott [9] introduced the concept of microbially enhanced coalbed methane (MECBM). MECBM is aimed at replicating the natural process of biogenic methane generation in coal by treating it with suitable microbial consortia and nutrient amendments. Following this, several research studies have provided evidence of the potential of generating methane by treating coal fines with microbial inoculations [4,10–13].

Research in the area of MECBM has accelerated in the past decade

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due to a number of reasons. First, natural gas is a cleaner source of energy. Second, the technology has potential application to unmineable coals and abandoned coal mining operations. Third, vast amounts of coal fines, unusable when combusting coal for electricity production, are stored in slurry ponds worldwide, where microbial gasification provides a suitable solution to utilize this waste. Finally, several areas in mature coalbed methane producing coal basins, like San Juan, are depleted, or nearing depletion, providing the infrastructure required for injection of nutrients and subsequent production of biogenic methane.

Understanding and improving the microbial process to enhance methane production from coal requires extensive research. Over the years, the primary focus of research in MECBM has been from a microbial perspective. It has been recognized that the process of bioconversion is a relatively slow process, with significant methane production under laboratory conditions requiring more than thirty days in most reported studies [10,14]. Given that these studies were conducted on powdered coal, providing additional surface areas for microbes, production rates from *in situ* deposits is expected to be significantly lower and slower. Under such time-dependent production characteristics, it is important to identify the reservoir properties affecting flow and document the changes in these properties. Understanding associated reservoir flow characteristics would enable determining the techno-economic feasibility/pre-feasibility studies of the process.

Coal is characterized as a dual-porosity rock, where micro- and macro- porosity affect flow of fluids through coal [15–18]. Micropores occur as a part of the coal matrix and serve as a storehouse for over 95% of the gas in adsorbed form [19]. The macropore system consists of a network of closely placed natural fractures surrounding matrix blocks, known as the cleat system. The dual porosity structure of coal dictates the gas flow and transport of fluids in the reservoir. In course of CBM production, pumping out water, which saturates the coal, reduces the pore pressure. This reduction results in desorption of methane from the microporous matrix surface, contributing to the first stage of fluid flow in coal. Once desorbed, molecules of methane diffuse across the complex pore geometry of coal in accordance with Fick's second law of diffusion. Methane then reaches the fracture network, that is, the cleat system, where the transport mechanism becomes Darcian, controlled by the permeability, and is dependent on cleat parameters, like the aperture, continuity and spacing. Experimental work conducted on powdered coal to characterize changes in sorption properties as a result of bioconversion was first reported by Pandey et al. in 2016 [20], and more recently by Zhang et al. [21]. It was reported that increase in micro-porous surface area post-conversion results in increased sorption capacity of coal. Bioconversion also resulted in increased diffusion rates for methane and carbon dioxide [20]. Such variations translate to increased microporous surface area available for sorption and altered pore geometry, resulting in increased flow rates (diffusive) at the microscopic scale. The effect of bioconversion on the third transport phenomenon, Darcian flow in cleats, is yet to be reported. It is well accepted that production from coalbed methane reservoirs is a function of the permeability of coal to methane and water. There exists a number of CBM reserves worldwide with significant gas content but are unattractive due to low permeability for commercial extraction of methane. An improved understanding of the Darcian flow and the effect of bioconversion on it is, therefore, critical in order to move forward with commercial application of the technology. This paper aims to elucidate the dynamics of permeability as a result of bioconversion.

Work presented in this paper was conducted on one-inch sized chunks of coal, providing smaller surface areas for the microbes to act on, and a better representation of *in situ* conditions. The coal samples were imaged before and after bioconversion using a scanning electron microscope (SEM). Treatment of coal chunks helped in retaining its overall physical structure, representing cleats and fractures associated with the coal type. High resolution imaging enabled studying the macro-/micro- porous geometries associated with the coal, and thereby documenting changes as a result of bioconversion.

Although two-dimensional SEM images showing the surface of coal provide a reliable and a simple tool to characterize/study physical macroporous properties of coal, characterizing microporous properties bring unavoidable complexities, especially when working with grayscale images of coal. Use of fractal dimensions has proven to be a reliable approach under such conditions. The fractal theory, proposed by Mandelbrot [22], was successful in characterizing some irregular, unsmooth, and non-differentiable objects or shapes in nature. Starting from characterizing complexities associated with neurons in animal and plant morphology, to characterizing particle roughness and pore size distribution in soils, fractals have found application in a number of scenarios. Fractal characterization has also been successfully applied in studying the roughness, pore size distribution and adsorption behavior characterization of porous media, such as, coal and shale [23–26].

Fractals, characterized by their dimension (D), is a study of geometry. There are many fractal dimensions introduced in mathematical and physical literature [22,27,28]. Topological dimension, Hausdorff dimension, box-counting dimension, self-similarity dimension are some of the commonly used fractal dimensions. It should be pointed out that a majority of these dimensions do not provide a definition, but a methodology to determine D, and cannot be used to specifically determine fractal behavior. Definitions of scaling lacunarity and scaling coverage, as put forward by Jin et al. [29] in 2017, make use of mathematically defined topographical parameters, which can be used to characterize a topographically rigorous dimension. Subsequently, several approaches exist towards characterizing fractal nature of porous materials. Techniques of image processing [30,23,31], experimental techniques like BET sorption isotherms [32,33], mercury intrusion porosimetry [34], nuclear magnetic resonance [35,36], ultra-/small-angle X-ray scattering (USAXS/SAXS) [37–39], ultra-/small angle neutron scattering (USANS/SANS) [38,40], and theoretical modelling [26,41] have been widely used to characterize porous material. Of the various methods, use of SEM images to characterize fractal dimensions provides an intuitive technique that is easy to understand and replicate. However, as pointed out by Xia et al. in 2018 [42], there exists two major issues with use of SEM images for fractal characterization: difficulty in obtaining different scales of images, and difficulty in modeling fluid streamlines. The work presented in this paper, adopts and modifies the methodology for fractal characterization of coal using SEM images presented by Liu and Nie [23]. The modified method, where a particular coal sample is imaged and the fractal dimension is determined at multiple levels of magnification, is designed to improve the accuracy of the calculated fractal dimension by removing the scale dependency as pointed out by Xia et al. [42].

For this study, we used the Minkowski-Bouligand dimension or, the box-counting dimension to determine the fractal dimension of the imaged coal samples. The box-counting dimension is a type of space-fractal dimension, where the fractal characterization explores the short-scale behavior by using progressively smaller boxes required to cover an object in a grid. This methodology is opposite to the other commonly used Hausdroff dimension, making it suitable for pore-scale fractal characterization. This box-counting method collects data by analyzing complex patterns by subdividing a dataset or image into smaller pieces and scale. The process observes in detail the changes in geometry with change in scale. Using the box counting method to calculate the fractal dimension of coal from the processed images, the dimension, D, was defined as:

$$D = -\lim_{\delta\to 0}\frac{\ln(N(\delta))}{\ln(\delta)} \quad (1)$$

where, δ is the box size, $N(\delta)$ is the number of boxes needed to completely cover the binary image. The slope of the plots of $\ln(N(\delta))$ vs $\ln(\delta)$ generates the fractal dimension D, which can vary from 1, for a perfectly smooth surface, to 2 for a surface with complex geometry.

The overarching goal of MECBM as a technology is to produce biogenic methane from *in situ* coal. The major goals of the work