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Fractal dimensions of low rank coal subjected to liquid nitrogen freeze-thaw based on nuclear magnetic resonance applied for coalbed methane recovery

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ABSTRACT

The aims of this research are to quantitatively evaluate the complexity of the pore structure in coal frozen with liquid nitrogen (LN_2) and then study the influence of the modified pore system on coalbed methane (CBM) extraction. To do this, nuclear magnetic resonance (NMR) and fractal dimension theory were used to determine the properties of the coal's pore system after samples of low rank coal had been frozen and then thawed. The fractal dimensions of pores in frozen-thawed coal samples were divided into five types according to pore size and the state of the fluid in the coal pores. The results showed that the fractal dimension D_A of adsorption pores was less than two, indicating that these pores did not exhibit fractal characteristics. The fractal dimensions D_{ir} and D_T representing closed pores and total pores presented low fitting precision, so the closed pores showed insignificant fractal characteristics. However, the fractal dimensions D_F and D_S representing open pores and seepage pores had high fitting precision, suggesting that open and gas seepage pores exhibited a favorable fractal characteristic. Correlation analysis revealed that D_F and Ds were negatively correlated with LN_2 freezing time and the number of freeze-thaw cycles. After being frozen and thawed, coal porosity and permeability showed a strong negative correlation with fractal dimension and this relationship allowed predictive models for permeability and fractal dimensions (D_F and D_S) to be constructed. The models showed that the smaller the fractal dimension, the more uniformly the pores were distributed and the higher their degree of connection. These properties favor the production of CBM. This study also showed that compared with single LN_2 freezing events, repeated cyclic freezing with LN_2 followed by thawing is more favorable for CBM production.

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1. Introduction

Coalbed methane (CBM), a gas common in coal seams, is produced during the development of some coal deposits [1]. In the course of coal production, the existence of CBM can lead to serious accidents such as gas outburst and explosion [2,3]. In addition, as a strong greenhouse gas, CBM exhibits a greenhouse effect with a magnitude 21 times that of CO_2 [4]. However, as a source of relatively clean energy, CBM can help to relieve world's energy shortages because, worldwide, CMB reserves are abundant [1,5]. For these reasons, it is both necessary and advantageous to extract CBM before the coal is mined.

Generally, CBM is adsorbed onto microcellular structures of coal and is difficult to extract directly because coal reservoirs have low-permeability [6–8]. Several different hydraulic measures have been used widely to increase the permeability of coal seams including hydraulic fracturing and hydraulic cutting [9,10]. Using water as a medium for fracturing and increasing permeability, the above measures promote the development of fractures and change the physical and mechanical properties of the coal. However, these hydraulic permeability enhancement techniques consume large amounts of water and can pollute water resources [11,12]. Moreover, in coal seams with pre-existing fractures, hydraulic fracturing media can quickly leak along the fractures so that effective fracturing pressures cannot be produced. Thus, developing new fracturing methods to solve the aforementioned problems has the potential to be very valuable.

In order to reduce the deficiencies of existing permeability enhancement techniques and reduce the environmental degradation that can be associate with hydraulic fracturing, anhydrous fracturing technologies such as using liquid nitrogen or liquid carbon dioxide as fracturing fluids have gradually attracted more attention [13–17]. Compared with fracturing using gaseous N_2, fracturing with liquid nitrogen (LN_2) has many advantages because of LN_2's low temperature (−196 °C), huge latent heat of vaporization, and the fact that LN_2 expands to 696 times

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its liquid volume upon vaporization. The low-temperature LN_2 causes a frost heaving force of 207 MPa at the tips of fractures when the water in the fractures freezes and the volume of the water expands by 9%; the ice cannot flow along the fractures [18,19]. This frost heaving combines with the high pressures produced by LN_2 vaporization and the damage the low temperature LN_2 causes to the structure of the coal itself. Theory suggests that abundant fracture networks can be formed in coal using this technique.

Quantitatively evaluating the pore structures in frozen-thawed coal is important for the study of CBM seepage and migration. Fractal geometry was initially founded by Mandelbrot [20]. Fractal dimension is proposed to measure how efficiently a complex structure occupies a space as it measures the irregularity of the complex structure. In recent years, fractal dimension theory, which has developed rapidly, has been used widely in many fields including the natural science [21–26]. Numerous researchers depict the microscopic anisotropy of coal through fractal dimension theory, and its use is testimony that fractal dimension theory is an effective method for evaluating pore structures in coal [27,28].

As for describing the fractal dimension of coal surfaces, CT and SEM images of coal generally undergo digital processing and then fractal dimensions can be calculated using several methods including correlation, similarity, capacity, and box dimensions [29–32]. With regard to the determining the fractal dimension of pores in coal, the dimensions are generally calculated by applying different techniques including the nitrogen adsorption and mercury intrusion methods [33–36]. However, these methods have disadvantages in that they damage the samples and they are very time consuming. Low-field nuclear magnetic resonance (NMR), a speedy, nondestructive test, has been proven by numerous researchers to be superior for characterizing the fractal dimension of coal pores [27,37–39].

There are no relevant studies on the fractal dimension of pores in coal after freeze-thaw treatment of the coal with LN_2. In this study of coal fracturing by freeze-thaw using LN_2, the fractal dimensions were evaluated using NMR fractal dimension theory. In addition, the influence of freeze-thaw variables on fractal dimensions was evaluated to study the correlation of fractal dimension with a number of parameters like changes in coal permeability during freeze-thaw cycles.

2. Samples and experimental procedures

2.1. Coal core samples

The coal samples used for the experiments were lignite taken from the Shengli coalfield in Inner Mongolia, China. In order to ensure uniformity, all of the coal samples were drilled from the same block of coal, as shown in Fig. 1. The samples were 25 mm diameter cylinders cut to 50 mm lengths. Analytical tests (proximate analyses) were conducted according to the GB/T 212-2008 analysis standard for coal in China. The maximum vitrinite reflectance, $R_{o,max}$, for the coal samples was 0.331%. The coal samples chosen for the experiments had the same physical properties as determined by several measurements including density and acoustic wave transmission. By applying this comprehensive sample screening procedure, the freezing-thaw specimens are quite similar in terms of mechanical property and structure. The uncertainty of the testing results is minimized due to the sample screening

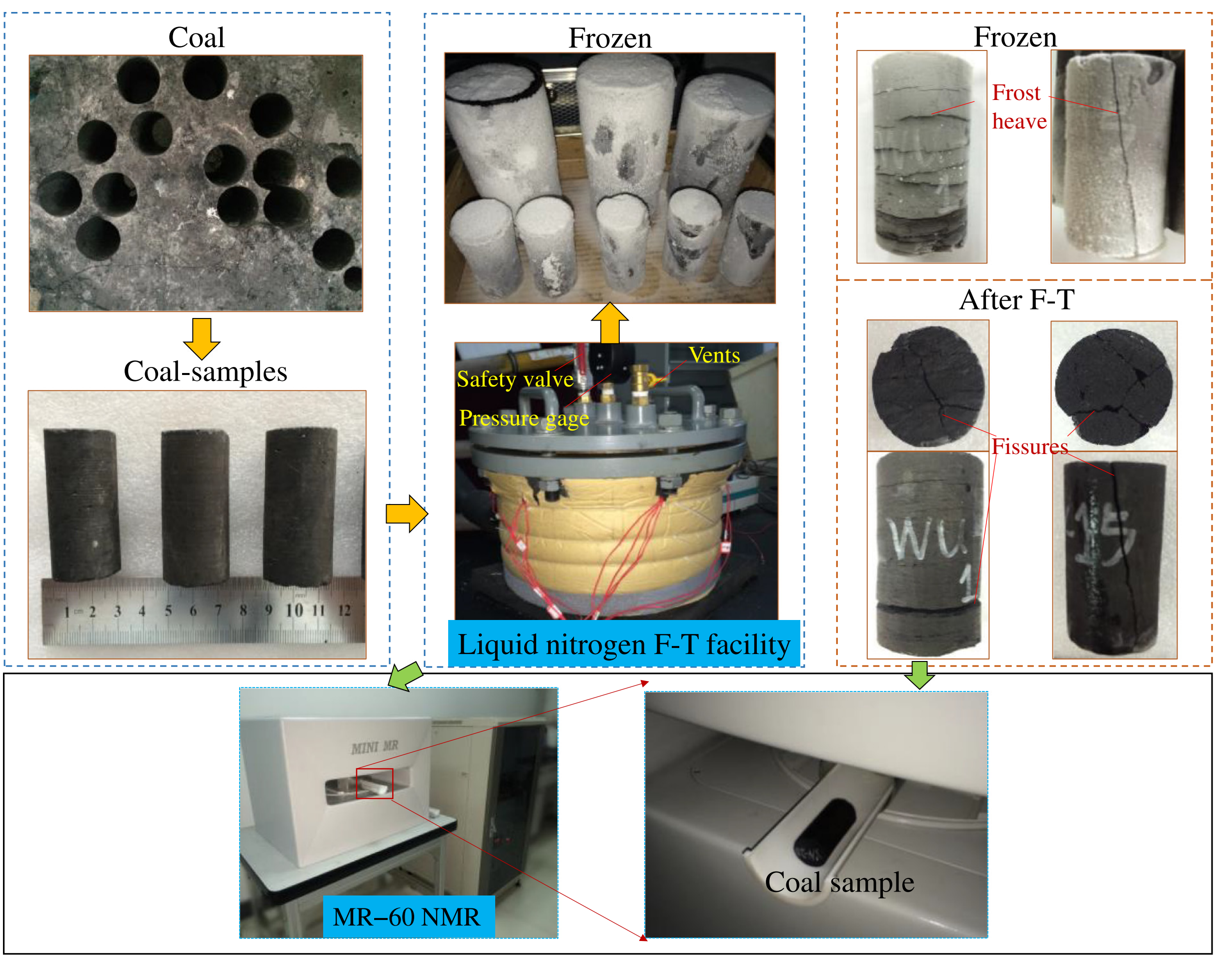

Fig. 1. Sample preparation and experimental procedures.

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