Progress in Research of Characterization Methods for Pore and Fissure Structures in Coal

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***Abstract*—The pore and fissure of coal directly affect the occurrence and seepage of gas. Therefore, it coal seam methane should be developed for utilization and gas control. In this study, characterization methods for coal fractures are introduced on the basis of extensive literature research. They are usually divided into observation and physical test methods, and their principle and research status of each method are reviewed in detail. The application of CT three-dimensional reconstruction and fractal dimension in the physical progress of digital rock is also presented.**

Keywords—coal, pore and fissure, characterization method, three-dimensional reconstruction

I. INTRODUCTION

Coal is a complex porous medium with remarkable stratification characteristics. Its pore and fissure structures influence porosity, permeability, and other parameters. Many macroscopic physicochemical parameters, such as density and coal strength, are related to the structure of coal hole fractures.

The pore structure of coal is mainly examined on the basis of pore size, distribution, porosity, and permeability information in pore fracture parameters to characterize pore fracture structures. Numerous methods have been applied to characterize fracture structures in coal pores [1]. For instance, density calculation can yield porosity. Traditional nitrogen adsorption and mercury injection can be used to determine the pore size, pore volume, and specific surface area of coal, but the fracture structure of coal pores is destroyed during experiments. Other characterization methods of pore fracture require the use of high-resolution equipment, such as micro-CT and scanning electron microscopy (SEM), and these methods not only reveal the fracture structure of coal but also allow the analysis of coal structure from a three-dimensional surface through the three-dimensional reconstruction of pore fracture models. Fractal dimension can be further utilized to quantitatively analyze the complexity of the pore structure of coal pores, and this parameter has a non-negligible effect on studies on the pore fracture structure of coal. These characterization methods have greatly promoted research on the pore structure of coal pores and contributed to the development and utilization of coal seam methane (CBM).

II. RESEARCH METHODS OF COAL FRACTURE STRUCTURE

A. Observation description method

Description methods mainly include macroscopic description and optical microscopic description. In the macroscopic description of the fracture structure of the coal pores, the primary and representative samples of coal fracture should be selected, fracture types, coal types, and other types should be described, various parameters, such as crack size, direction, inclination, and dip angle should be measured, described, and recorded, and fissure filling minerals, degree, connectivity, and other properties should be documented as statistical results of macroscopic cracks[2].

The optical microscopic description of the pore structure of coal rock is based on optical microscopy that considers the different reflection and absorption capacities of various sample components to incident light and the difference between the human sensory system and the transformation of the electrical signal to obtain the fracture structure of a sample for analysis [3].

B. Physical test method

(1) Density calculation. Density calculation is a common method to calculate porosity. Porosity is the ratio of pore volume to total volume, and porosity is essential for research on coal permeability, gas adsorption, and other parameters [4].

The total porosity of coal   is expressed as follows(1):

$$\phi = \frac{\rho_d - \rho_{p,d}}{\rho_d} \quad (1)$$

where ρ_d is the true density of dry coal, and $\rho_{p,d}$ is the apparent density of dry coal (g/cm^3).

(2) Nitrogen adsorption method. In this method, the amount of nitrogen adsorbed by dry degassed powders in liquid nitrogen is measured at different pressures, and

adsorption and desorption iso therms are drawn for analysis [5]. Zhao Zhigen et al. [6] studied the microporosity characteristics of coal through low-temperature nitrogen adsorption and obtained a minimum pore size of 0.6 nm. Yang Feng et al. [7] investigated the pore structure of shale through nitrogen adsorption experiments to obtain pore information, such as pore size distribution and pore volume.

(3) Mercury injection method. This method is usually divided into conventional mercury injection method and constant velocity mercury injection method. This method is applied to analyze and characterize the pore structure of porous media. It has been widely used because of its advantages of simple principle, short test period, and wide measurement of a broad range of pore size [8]. Conventional mercury injection and constant velocity mercury injection methods assume that a porous medium is composed of capillary bundles, throats, and differently sized pores. Conventional mercury injection method can be applied to determine the pore volume corresponding to the pore size, and statistically analysis of the amount of mercury in holes at different external pressures can reveal the pore size distribution [9]. In constant velocity mercury injection method, mercury is pressed into the pore of a rock at a low constant speed. The advantage of the constant velocity mercury injection method is that it can distinguish the pore and throat from conventional method and statistics the distribution of its quantity. Zwietering et al. [10] pioneered the use of mercury injection method to study the pore structure of coal. The following researchers used this technology to study coal and rock mass. Yuan and Swanson [11] used the constant velocity mercury injection method to successfully distinguish pores and throats. Zhang Tao et al. [12] applied mercury injection method to examine the pore characteristics of different pore sizes and contact angles of shale. Zhao Huawei et al. [13] further demonstrated the applicability of constant velocity mercury injection method to the characterization of pore fractures.

(4) SEM. In this method, pore types, pore fracture development, and coal and rock composition can be directly understood. This method has been utilized to analyze the pore structure of coal from different angles. Zou Junpeng et al. [14] used a scanning electron microscope to examine the development of the fracture structure of a coal sample hole and estimated the content of the mineral composition and the fracture volume fraction.

(5) Focused ion beam (FIB)/SEM. FIB/SEM is used to scan the sample surface with FIB. Surface atoms sputter because of the impact of the ion beam. After the ion beam is scanned on the basis of a specified pattern, the desired pattern can be depicted [15]. The advantage of FIB over SEM is that the former can simultaneously perform nanofabrication on surfaces and surface imaging. FIBs have been used in materials science and biology. S. Giffin et al. [16] utilized this technique to examine the structure and distribution of meso-macropores in coal samples.

(6) Small-angle X-ray scattering (SAXS). SAXS is an advanced method of physical structure analysis. It involves a coherent scattering effect produced by changes in electron density within a certain range to obtain the shape and size of a scatterer. This method is suitable for studies on the pore structure of a porous medium material [17]. The pore structure of coal has been investigated through SAXS. Applying SAXS, Wang Bowen et al. [18] analyzed the parameters of the SAXS curve and the specific surface area of pores of coal samples before and after deashing and quantitatively characterized the effect of ash on pore structure. Radlinski et al. [19] demonstrated the validity and superiority of SAXS and small angle neutron scattering (SANS) for the characterization of the pore structure of coal rock.

(7) Transmission electron microscopy (TEM). This technique involves the conversion of a high-energy electron beam into a beam with large brightness and a small beam spot via a condenser lens. The final screen image is formed by optically processing the scattered electrons that have passed through the sample. With its high resolution, it can be used to examine the ultramicropores of coal [20]. This method has been applied to study the microstructure of coal and achieve certain results. Zhang Xiaodong et al. [21] analyzed the arrangement of the macromolecular skeleton structure of Longkou lignite and the modified characteristics of microcrystalline structure parameters before and after extraction through XRD and HRTEM. Castro-Marcan et al. [22] used TEM in combination with various experimental methods to assess the microscopic pore structure of coal and established a molecular structure model of coal.

(8) Nuclear magnetic resonance (NMR). In this technology, the relaxation time of NMR T2 is measured, and various parameters, such as the distribution of different pore sizes and connectivity in pore structure, are obtained [23]. The method can detect coal porous media without damage and exhibit numerous advantages, including simple experimental process and low experimental cost; this method can also be used to quantitatively describe the pore volume distribution of porous media and analyze the characteristics of pore structures and the interaction of a solid–liquid interface[24].

NMR has been applied to study the structure of coal seam fracture. Yao and Liu et al. [25] demonstrated the feasibility and effectiveness of using a NMR relaxation spectrum to examine the meso-macroporous structure of coal. Xie Songbin [26] used low-temperature liquid nitrogen adsorption-desorption and low-field NMR to determine the pore size distribution of coal. The feasibility of NMR to characterize the small pore size distribution of coal has been further demonstrated by low-temperature liquid nitrogen method.

(9) Computerized tomography (CT) involves X-rays to reduce the attenuation ability of different density materials. In CT images, the greater the material density of an image is, the higher the brightness on the image will be. Therefore, high-density minerals are white, and black pores and fissures are the smallest [27].

CT scanning technology has been widely used to characterize coal pore fracture structures because of its nondestructive and fine features. Van et al. [28] studied the distribution of pore fissures by using CT techniques. Yao et al. [29] demonstrated the validity and feasibility of the CT characterization of fracture structures in coal seams. Song Xiaoxia et al. [30] characterized the seepage pores of structural coal through CT.

This method can effectively characterize pore fracture structures (Fig. 1). Therefore, these methods are classified and summarized on the basis of the magnitude and analysis method of pore size.

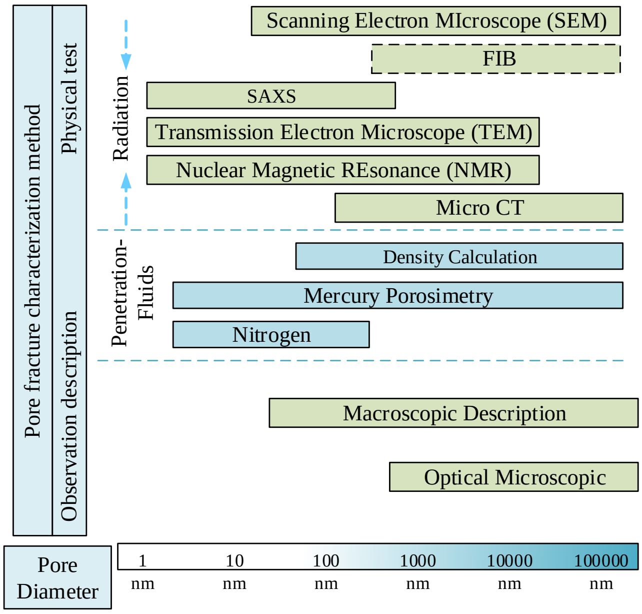

Fig. 1 Schematic of methods used to estimate porosity and pore size distribution.

III. PHYSICAL PROGRESS AND FRACTAL CHARACTERIZATION OF DIGITAL ROCKS

A. Three-dimensional Reconstruction of Coal Fissure Structure

Although the physical properties of coal can be obtained through laboratory physical experiments, numerous methods have been successfully used to examine and characterize the pore and crack structure of a coal body. With the development of science and technology, some methods have shown limitations. For example, nitrogen adsorption and mercury injection method cause damage to the structure of coal, and SEM and other methods can analyze a certain section only.

Digital Rock Physics (DRP) is a new field that involves an organic combination of advanced 3D imaging equipment, image processors, high-performance computers, and advanced computing methods. It has the advantages of high efficiency and relatively low cost. Its basic principle is imaging plus calculation. CT three-dimensional reconstruction is a key technology that can be used for the accurate and nondestructive three-dimensional characterization of fractures in coal bodies and for the clear observation of pore fracture structures [31-32].

In CT three-dimensional reconstruction, scanned images are stacked in a certain sequence. To reconstruct the fracture structures of coal pores, we should extract fracture structures from images. First, a CT image should be segmented on the basis of a given threshold to obtain a binarized image of a pore fissure structure. Second, a three-dimensional reconstruction procedure is applied to reconstruct the pore fissure structure. A complete flowchart of CT three-dimensional reconstruction is presented in Fig. 2, and CT images are combined with fractal theory to quantitatively analyze the complexity of pores in coal. The distribution of differently sized pores can be observed in the pore structure of the reconstructed hole, and the pore structure of the internal pores of the coal body can be intuitively understood. Different colors represent various pore sizes. CT three-dimensional reconstruction technology has also been utilized to characterize coal. Simons et al. [33] used CT reconstruction technology combined with image analysis technology to quantitatively characterize the coal structure. Wang Gang et al. [34-35] conducted the three-dimensional reconstruction of coal samples, simulated the seepage flow of CBM, and proposed an empirical formula for the non-Darcy seepage of CBM flow.

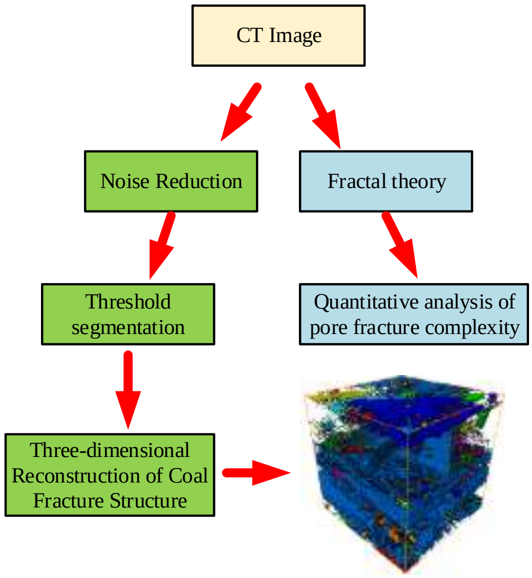

Fig. 2 CT three-dimensional reconstruction process

B. Fractal Characterization of the Structure of a Coal Body Fracture

In 1967, Mandelbrot proposed the concept of fractal that has been widely used in scientific research and engineering practices because of its advantages of quantitative representation of the complexity of materials. Previous studies demonstrated that the distribution of porous media satisfies self-similarity and fractal rule [36-37]. Traditional Euclidean geometry is not easily described because the pore structure of coal is complex. Fractal dimension, as a characteristic parameter of fractal geometry, can quantitatively characterize the complexity of the pore structure of a coal body.

Considering the differences in objects, we should use various methods to calculate fractal dimension. General methods are summarized into three categories: box dimension, fractal Brownian motion, and area measurement. Box dimension method algorithm is widely used to examine pore fracture structures because it is relatively simple, and its physical meaning is relatively intuitive [38]. In this algorithm, a binarized image is considered as a set F of R2 space, and the minimum number of subsets that can cover F is set as $N_\delta(F)$, where δ is the maximum diameter in $N_\delta(F)$, and the box dimension is defined as Equation (2) [39].

$$D=\lim_{\delta\to 0}\frac{lgN_\delta(F)}{-lg\delta} \tag{2}$$

The fractal dimension of an image is calculated by dividing an M × M pixel binarized image into a grid with a side length σ_k, and the number of meshes $N_{\sigma k}$ required to cover the black pixels representing the pores in the image is counted. When $\sigma_k\to 0$, $lgN_{\sigma k}/lg(1/\sigma_k)\to D$. Therefore, the least squares method is used to linearly fit the data points ($-\lg\sigma_k$, $\lg N\sigma_k$) and find the linear equation(3)[38].

$$lgN_{\sigma_k} = a \cdot (-lg\sigma_k) + lgA_0 \tag{3}$$

In the formula, the slope a is the fractal dimension D; and A_0 is the initial value of the distribution of the number of pores.

In the two-dimensional plane state, the range of D is between 1 and 2, and the complexity of pore fractures is further exacerbated as D increases. A small D corresponds to a uniform pore structure. A high lgA_0 is equivalent to a large proportion of macropores in the corresponding coal .

IV. Conclusion

(1) Current technology has achieved a high characterization level for fracture structures in coal . Mercury injection method, nitrogen adsorption method, and other methods can be used to obtain various pore-related data, such as pore size distribution, pore volume, and specific surface area. Scanning electron microscopy, transmission microscopy, and other techniques can be utilized for the nondestructive characterization of pore fracture structures from a two-dimensional perspective. Small-angle X-ray scattering and nuclear magnetic resonance can be applied to quantitatively characterize pore volume distribution and pore fracture characteristics. CT technology combined with image processing software and three-dimensional reconstruction program can be employed to analyze pore fissure structures from two- and three-dimensional perspectives.

(2) Coal pore fracture three-dimensional reconstruction technology can be utilized to show the fracture structure of coal pores and calculate the microscopic parameters of pore fractures. Fractal dimension is another quantitative characterization parameter of the complexity of pore fracture structures based on three-dimensional reconstruction. With the continuous development of computer and CT technology, digital coal models will be developed in the future and will have a far-reaching impact on future research on coal body fissures.

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