International Journal of Advanced Engineering and Technology Research
ISSN: 3106-8677 (Print), ISSN: 3106-8685 (Online) | Vol. 2, No. 1, 2026

Analysis of Pore Structure and Fractal Characteristics of Coal Samples in Pingdingshan Mining Area Based on N_2/CO_2 Adsorption

Borui Li

Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo 454000, China

Abstract: In order to reveal the multi-scale pore structure and fractal characteristics of coal samples in Pingdingshan mining area, typical medium metamorphic coal samples were selected to carry out low-temperature N_2 adsorption and low-temperature CO_2 adsorption experiments. Combined with FHH fractal model and Sierpinski fractal model, the pore volume, specific surface area, pore size distribution and fractal dimension of coal samples were analyzed. The results show that the coal samples in the study area have the characteristics of medium-low ash, low volatile matter and high fixed carbon. The macerals are mainly vitrinite, followed by inertinite. The results of low temperature N_2 adsorption show that the pore volume in the 2-300 nm pores of coal samples is mainly contributed by micropores and mesopores, among which mesopores have more obvious control effect on reservoir space. The specific surface area is mainly controlled by 2-10 nm micropores. The adsorption-desorption isotherm is type IV and superimposed type II. The hysteresis loop reflects the development of composite pore structures such as ink bottle pores, slit pores and fissure pores in the coal body. The results of CO_2 adsorption show that the ultramicropores of coal samples are relatively developed, and the pore size is mainly concentrated in 0.40-0.80 nm, of which about 0.52 nm pores are dominant, which is the main space for gas adsorption and occurrence. The fractal analysis shows that the fractal dimension D_1 of N_2 adsorption is 2.28-2.58, D_2 is 2.55-2.67, and most samples $D_2 > D_1$, indicating that the pore complexity of coal samples is mainly controlled by the heterogeneity of three-dimensional pore network. The fractal dimension Dm of supermicropores for CO_2 adsorption is 2.32-2.38, indicating that the structure of supermicropores is relatively simple and the connectivity is weak. According to the research, the gas occurrence of coal samples in Pingdingshan mining area is mainly controlled by the adsorption space of ultra-micropores, while the gas diffusion and migration are restricted by the complexity of micropore-mesopore pore network.

Keywords: Coalbed methane, coal pore structure, gas adsorption, FHH model, fractal characteristics.

1. Introduction

Coalbed methane is not only an important unconventional natural gas resource, but also a disaster source that needs to be prevented and controlled in the process of coal mine safety mining[1]. As the main carrier of coalbed methane, the pore structure of coal directly affects the process of gas adsorption, desorption, diffusion and seepage. Due to the complex deposition, coalification and tectonic transformation of the coal body, the internal pores have significant multi-scale and heterogeneity, and the pores of different pore size levels play different roles in the occurrence and migration of coalbed methane. Among them, ultra-micropores and micropores mainly control the gas adsorption capacity, while mesopores and macropores affect the gas diffusion channel and seepage capacity. Therefore, clarifying the multi-scale pore structure characteristics of coal is an important basis for understanding the occurrence mechanism of coalbed methane and evaluating the physical properties of coal reservoirs.

At present, the study of coal pore structure has formed a variety of test methods. Low-temperature liquid nitrogen adsorption experiments can effectively characterize the pore volume, specific surface area and pore size distribution of pores above 2 nm, which are often used to reveal the pore structure of micropore-mesopore scale[2,3]. The low temperature CO_2 adsorption experiment has a strong recognition ability for ultramicropores smaller than 2 nm, which can supplement the deficiency of liquid nitrogen adsorption in ultramicropore characterization[4]. He et al.used the low temperature liquid nitrogen adsorption experiment method to systematically study the adsorption pore structure characteristics of anthracite. The results show that the adsorption pores in anthracite are mainly tiny pores, and the pore structure is more complex and shows strong microscopic heterogeneity[5]. Shen Yanjun et al.used low-temperature liquid nitrogen adsorption, mercury intrusion, nuclear magnetic resonance and permeability test methods to point out that the oil-rich coal in Yushenfu mining area is dominated by micro-pores (accounting for more than 70 %), with large specific surface area and pore volume, and has good oil and gas occurrence conditions[6]. The combined application of the two can realize the continuous characterization of nano-scale pore structure of coal, and provide a basis for analyzing the contribution of pores of different scales to gas adsorption and migration.

However, the coal pore system not only shows differences in pore size and pore volume, but also has complex spatial heterogeneity and irregular geometric characteristics. Traditional pore parameters are difficult to fully characterize pore surface roughness, pore network complexity and their influence on gas occurrence behavior. Fractal theory can quantitatively describe the pore structure characteristics of coal from the perspective of geometric complexity [7–9] , The FHH model is often used to analyze the fractal characteristics of pore wall surface and pore structure based on N_2 adsorption data, and the Sierpinski model can be combined with CO_2 adsorption data to characterize the fractal characteristics of ultramicropores. Through the study of low temperature liquid nitrogen adsorption and FHH fractal model, Zhang Shaofeng et al.showed that the fractal dimension of coal body was positively correlated with Langmuir constant a and had little effect on b. The enhancement of fractal characteristics was beneficial to the improvement of gas adsorption capacity[10]. Lu Hongwei et al.analyzed through fractal dimension and adsorption energy theory that the larger the fractal dimension of coal pores, the stronger the heterogeneity of methane adsorption, and the more significant the change of adsorption capacity and energy[11]. Chen Liuyu et al.studied the pore structure parameters of coal samples from typical outburst mines in northern Guizhou based on low temperature liquid nitrogen adsorption experiments, and pointed out that there was a quadratic function increasing relationship between coal adsorption capacity and fractal dimension[12]. Through the comprehensive analysis of pore structure parameters and fractal dimension, the characteristics of coal pore development and its control mechanism on gas adsorption and diffusion process can be further revealed[13].

Pingdingshan mining area is one of the typical coking coal producing areas in China. The occurrence of coalbed methane resources and the prevention and control of gas disasters are closely related to the pore structure of coal[14] . Previous studies have focused on coal quality characteristics, gas occurrence or reservoir physical property evaluation in this area, while comprehensive research on ultra-microporous-microporous-mesoporous multi-scale pore structure and its fractal response characteristics is still relatively insufficient. Based on this, this paper takes typical coal samples in Pingdingshan mining area as the research object, and uses low-temperature N_2 adsorption, low-temperature CO_2 adsorption and fractal models to systematically analyze the pore volume, specific surface area, pore size distribution and fractal dimension characteristics of coal samples. The mechanism of action of pores of different scales in the process of gas adsorption, occurrence and migration is discussed in order to provide reference for CBM reservoir evaluation and gas control in Pingdingshan mining area.

2. Experimental Method and Calculation Model

2.1. Sample Source and Pretreatment

The coal samples in this paper were collected from Shoushan No.1 Mine and No.8 Mine of Pingdingshan Mining Area in Henan Province, and the coal body structure was primary massive structure. The sampling work is carried out in the fresh working face of the mine, and the raw coal block which is not affected by obvious weathering is selected as the research object. After the coal sample was collected, it was immediately wrapped with plastic film and placed in a sealed sample bag to reduce oxidation and water loss, and then transported back to Henan Polytechnic University for pretreatment. During the pretreatment process, the weathering layer and impurities on the surface of the coal sample were removed, and the samples were crushed and sieved to meet the requirements of subsequent experimental tests. The coal samples in the study area are shown in Fig. 1.

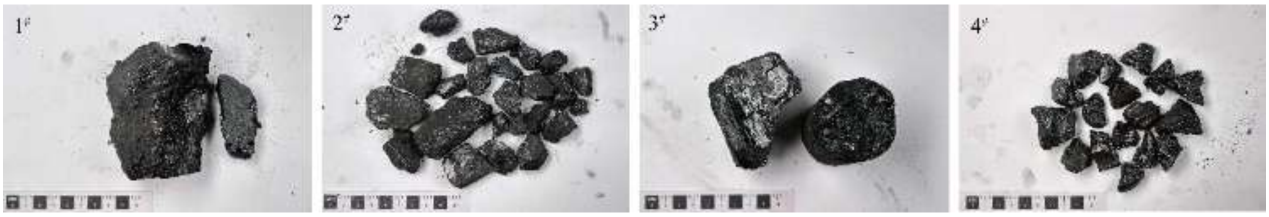

Figure 1. Coal samples in the study area

Table 1. Industrial analysis and maceral characteristics of coal samples in the study area

Coal samples	$R_{o,m}$(%)	Industrial analysis				Coal rock microstructure			
		M_{ad} (%)	A_{ad} (%)	V_{ad} (%)	FC_{ad} (%)	Vitrinite (%)	Inertinite (%)	Exinite (%)	Mineral (%)
PDSSS-21-01	1.24	1.02	15.26	7.02	76.7	52.4	37.1	-	10.5
PDSBK-21-02	1.06	0.7	18.45	7.58	73.28	40.4	30.9	-	28.7
PDSBK-42-03	1.08	1.35	12.78	9.9	75.98	52.1	40.6	-	7.3
PDSBK-42-04	1.20	0.9	9.37	9.44	80.29	55.9	36	-	8.1

As shown in Table 1, the industrial analysis results of experimental coal samples show that the moisture content is 0.70 % -1.35 %, with an average of 0.99 %; the ash content was 9.37 % -18.45 %, with an average of 13.97 %. The volatile content was 7.02 % -9.90 %, with an average of 8.49 %. The fixed carbon was 73.28 % -80.29 %, with an average of 76.56 %. In general, the coal samples have the characteristics of medium and low ash, low volatile matter and high fixed carbon, which is in line with the basic properties of coking coal, fat coal and other medium metamorphic bituminous coal in Pingdingshan mining area. In terms of macroscopic coal rock characteristics, the coal sample is between semi-dark coal and semi-bright coal. The II1 coal seam is dominated by regular fine banded structure, and develops layered, massive and powdered structures. The endogenous fractures are well developed and are partially filled with calcite, pyrite and other minerals. The four 2 coal seam is dominated by powder and block structure, the coal quality is brittle, the stepped fracture is obvious, the linear and strip structure is clear, and the whole presents the typical macroscopic physical characteristics of medium metamorphic bituminous coal. In terms of macerals, vitrinite is mainly formed by gelation of plant lignin and cellulose, which is the dominant component of coal samples in the study area. The vitrinite content of most samples was more than 52 %. Under the microscope, the matrix vitrinite was the main, followed by homogeneous vitrinite and structural vitrinite. The content of inertinite and minerals in the sample $4^{\#}$ is relatively high, and the inertinite is mainly composed of filamentous and semi-fusinite, which reflects the high oxidation degree of the original coal-forming environment and the strong carbonization of the silk. In general, the coal samples in the study area are dominated by vitrinite, followed by inertinite, and the content of exinite is extremely low. The correlation between macerals and coal rank is not obvious.

2.2. Low Temperature Nitrogen Adsorption Experiment

Low-temperature nitrogen adsorption experiments are mainly used to characterize the structural characteristics of pores above 2 nm in coal samples. Before the experiment, the pretreated coal sample was subjected to vacuum degassing treatment to remove water and impurity gases on the surface and pores of the sample. Subsequently, the N_2 adsorption-desorption test was carried out at liquid nitrogen temperature to obtain the adsorption-desorption isotherms of coal samples. Based on the test results, the specific surface area of coal samples was calculated by BET method, and the pore volume and pore size distribution characteristics were analyzed by BJH method, so as to characterize the development of micropore-mesopore-macropore structure of coal samples.

2.3. Carbon Dioxide Adsorption Experiment

Due to the limited ability of low-temperature nitrogen adsorption to characterize ultramicropores with pore size less than 2 nm, this paper further uses CO_2 adsorption experiment to analyze the ultramicropore structure of coal samples. Before the experiment, the coal samples were also degassed to reduce the influence of moisture and residual gas on the test results. Subsequently, the CO_2 isothermal adsorption test was carried out to obtain the variation characteristics of CO_2 adsorption under different pressure conditions. Based on the adsorption experimental data, the DFT model was used to calculate the pore volume, specific surface area and pore size distribution of ultra-micropores in coal samples, which was used to reveal the development characteristics of ultra-micropores in coal and its influence on gas adsorption and occurrence.

2.4. Fractal Model

2.4.1. FHH Fractal Model

The Frenkel-Halsey-Hill (FHH) model is proposed by Pfeifer. It is one of the most widely used fractal models in the analysis of liquid nitrogen adsorption data. It is commonly used to characterize the fractal characteristics of small and medium-scale pores in coal [15], It has the characteristics of simple form and strong applicability. The expression of the FHH fractal model is as follows:

$$\ln V = C + A\ln\left[\ln\left(\frac{P_0}{P}\right)\right] \tag{1}$$

Where V is the volume of adsorbed gas at equilibrium pressure P, cm^3/g; c is the intercept in the relationship between $\ln V/V_0$ and ln (ln (P_0 / P)); a is the slope of the fitting line of lnV and ln (ln (P_0 / P)). P_0 is saturated vapor pressure, MPa.

2.4.2. Sierpinski Fractal Model

CO_2 isothermal adsorption experiments can effectively reflect the ultra-microporous structure characteristics of coal samples. Therefore, CO_2 adsorption data are often used to quantitatively analyze the microporous structure of coal [16]. On this basis, the complexity and heterogeneity of pore structure can be further revealed by fractal theory. Previous studies have shown that the Sierpinski fractal model can well characterize the fractal characteristics of the ultra-microporous structure of coal samples. The model describes the pore structure by establishing the relationship between the fractal volume V and the characteristic scale L, and its basic expression is:

$$V \propto (P - P_f)^{3-D_m} \tag{2}$$

The logarithm of the above formula can be obtained:

$$\ln(V) = c + (3 - D_m)\ln(P - P_f) \tag{3}$$

In the equation: V is the amount of CO_2 adsorption; p is the experimental pressure of CO_2 isothermal adsorption; pf is the threshold pressure point, and the pressure value corresponding to the first adsorption data of isothermal adsorption experiment is usually taken. D_m is the fractal dimension of ultramicropores; c is a constant.

3. Analysis of Pore Structure Characteristics of Coal

3.1. Pore Structure Distribution Characteristics

A large number of studies have shown that pores less than 10 nm are the main adsorption sites for methane in coal. However, the existing pore classification methods (such as HODOT classification and IUPAC classification) are still not clear enough in the division of adsorbed pores below 2 nm and pores about 10 nm. Therefore, this paper refers to the pore size division scheme proposed by Zhang Kun et al [17] to divide the pores in coal into ultra-micropores (<2 nm), micropores (2–10 nm), mesopores (10–100 nm), and macropores (>100 nm)

3.1.1. Micro-mesoporous Adsorption Characteristics

The low temperature liquid nitrogen adsorption experiment can effectively characterize the pore structure characteristics of coal with pore size greater than 2 nm, and the relevant results are shown in figure 2. The results of specific surface area and pore size distribution obtained by BJH method are shown in Table 2. It can be seen from the test results that the total pore volume of BJH in the study area is 0.002-0.006 cm^3/g, with an average of about 0.0035 cm^3/g. Among them, micropores (2-10 nm) pore volume accounted for 23.54 % -41.71 %, mesopores (10-100 nm) accounted for 38.84 % -45.14 %, and macropores (> 100 nm) accounted for 14.12 % -36.41 %. It can be seen that the pore volume of coal samples in the study area is mainly contributed by mesopores, the contribution of micropores is relatively low, and the change of macropores among different samples is obvious. In terms of BET specific surface area, the specific surface area of coal samples ranged from 0.286 to 1.404 m^2 / g, with an average of about 0.632 m^2/g. Among them, the specific surface area of micropores is as high as 73.87 % -85.97 %, the proportion of mesopores is 13.49 % -24.99 %, and the proportion of macropores is only 0.54 % -1.76 %. This indicates that micropores are the main source of specific surface area of coal samples, while mesopores and macropores have limited contribution to specific surface area. In general, the pore volume of coal samples in the study area is mainly controlled by micropores and mesopores, and the contribution of mesopores is more prominent. The specific surface area is significantly controlled by micropores. It shows that pores of different scales have different effects in the coal pore system: mesopores and some macropores mainly affect the pore volume, while micropores mainly determine the surface adsorption capacity of coal.

Table 2. Low temperature liquid nitrogen test results

Sample	BET specific surface area (m^2/g)	BJH Total Pore Volume (cm^3/g)	Porosity ratio (%)			Specific surface area proportion (%)		
			2-10nm	10-100nm	>100nm	2-10nm	10-100nm	>100nm
PDSSS-21-01	1.404	0.006	41.71	38.84	14.12	85.97	13.49	0.54
PDSBK-21-02	0.355	0.003	23.54	40.20	29.82	73.87	24.99	1.14
PDSBK-42-03	0.286	0.002	29.56	39.97	19.82	75.22	23.02	1.76
PDSBK-42-04	0.483	0.003	30.71	45.14	36.41	76.08	23.37	0.54

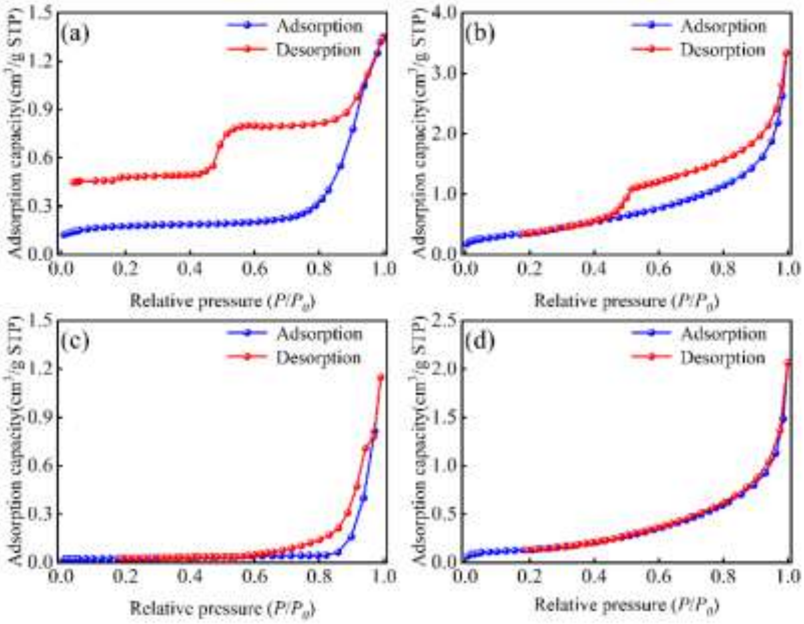

Figure 2. Low temperature N_2 adsorption-desorption isotherms

By comparing the four coal samples, it can be seen that the adsorption capacity of each sample increases gradually with the increase of relative pressure, and the isotherm is generally characterized by type IV, and at the same time, it has certain type II isotherm characteristics. In the low pressure stage ($P / P_0 < 0.1$), the adsorption capacity increases slowly, which mainly corresponds to the monolayer adsorption process of nitrogen molecules on the surface of coal pore wall. This stage is obviously controlled by 2-10 nm micropores. In the medium pressure stage ($0.1 < P / P_0 < 0.9$), the adsorption capacity continued to increase, and the adsorption form gradually changed from monolayer adsorption to multi-layer adsorption. At the same time, capillary condensation began to occur in the mesopores of 10-100 nm. In the high pressure stage ($P / P_0 > 0.9$), the adsorption capacity increased rapidly, indicating that the larger mesopores and macropores (> 100 nm) were further filled. The adsorption-desorption curves of each coal sample showed a hysteresis loop in the medium-high pressure zone, indicating that there was obvious capillary condensation in the pores of the coal body, but the hysteresis loops of different samples were different. The samples (a) and (b) are closer to the H_2-type hysteresis loop, and the desorption branch has a significant turning point near $P / P_0 \approx 0.4$-0.5, indicating that a certain number of ink bottle-like pores may develop in the coal body. In contrast, the hysteresis loops of samples (c) and (d) are narrow and have strong extensibility, showing the characteristics of H_3 type or H_3-H_4 transition type, and the closure is not obvious, reflecting that the pore structure is dominated by slit-like pores and fissure-type pores. In addition, the adsorption-desorption curve in the low pressure section of Fig.2 (a) is not completely closed, which may be related to the change of pore structure caused by the expansion of coal matrix during the adsorption process.

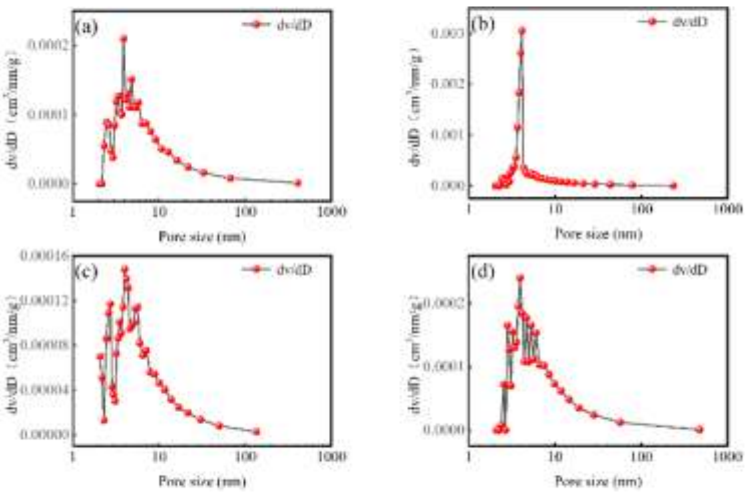

Figure 3. pore size distribution curve of coal sample

The pore size distribution calculated based on the experimental data of low temperature N_2 adsorption is shown in Fig.3. The pore size of each coal sample is mainly concentrated in the range of 2-10 nm, and the dv / dD curve shows a downward trend with the increase of pore size, indicating that the contribution of small pore size pores to pore volume is more prominent, while the contribution of larger pore size pores is relatively limited. The pore size distribution peaks of different coal samples are slightly different. The peaks of samples (a), (b), (c) and (d) are located at 4.79 nm, 3.37 nm, 3.98 nm and 3.96 nm, respectively. In general, the peak values of each coal sample are mainly concentrated in the range of 3-5 nm, indicating that the pore structure of coal samples in the study area is dominated by micropores.

3.1.2. Ultra-microporous Adsorption Characteristics

The aforementioned low-temperature N_2 adsorption experiment is mainly used to characterize the pore structure in the range of 2-300 nm in coal samples, while the ability to identify ultra-micropores with pore size less than 2 nm is limited. Since ultra-micropores are an important space for coal gas adsorption, in order to further clarify the development characteristics of ultra-micropores in coal samples in the study area, this paper uses CO_2 isothermal adsorption experiments for supplementary analysis.

It can be seen from Table 3 that the CO_2 adsorption capacity of coal samples in the study area is 6.146-12.936 cm^3 / g, the total pore volume of DFT is 0.016-0.041 cm^3 / g, the specific surface area is 56.164-130.106 m^2 / g, and the average pore size is about 0.524 nm. There are some differences in CO_2 adsorption capacity, micropore volume and specific surface area among different coal samples, indicating that the development degree of ultramicropores is different, but the ultramicropores of coal samples in the study area are more developed as a whole. As shown in Fig.4, the CO_2 adsorption isotherms of each coal sample are basically the same. As the relative pressure P / P_0 increases, the adsorption capacity increases as a whole, in which the adsorption capacity increases rapidly in the low pressure stage, and the increase in the high pressure stage gradually decreases and tends to be gentle, and there is no obvious hysteresis loop. According to the IUPAC isotherm classification, this type of curve can be classified as type I isotherm, indicating that the coal sample is dominated by microporous adsorption characteristics, and the CO_2 adsorption process is mainly controlled by ultra-microporous filling.

Table 3. Experimental results of low temperature carbon dioxide adsorption

Specimen	CO_2 Adsorption cm^3/g	DFT Total pore volume m^3/g	Pore specific surface area m^2/g	Average hole diameter nm
PDSSS-21-01	11.64507	0.037	117.147	0.524
PDSBK-21-02	6.146	0.016	56.164	0.524
PDSBK-42-03	12.93568	0.041	130.106	0.524
PDSBK-42-04	12.24628	0.040	124.868	0.524

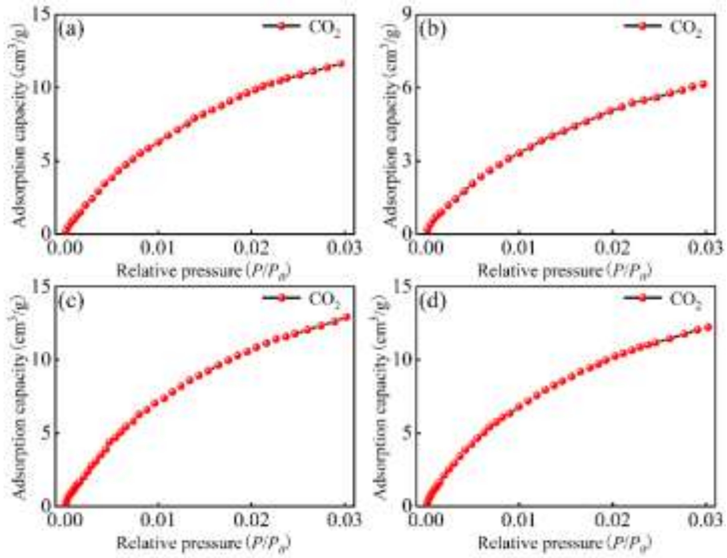

Figure 4. CO_2 adsorption isotherm of coal sample

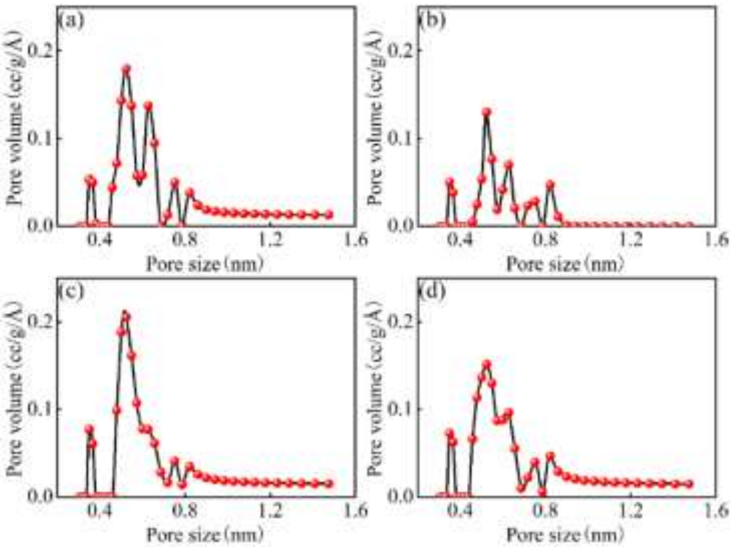

Figure 5. Characteristics of pore size distribution of coal samples

Based on the CO_2 adsorption data, the pore size distribution of the micropores obtained by the DFT model is shown in Figs.5 (a) - (d). The pore size of each coal sample is mainly concentrated in 0.40-0.80 nm, indicating that the ultra-micropores of coal samples in the study area are more developed. The pore size distribution characteristics of different samples are different: sample (a) shows a bimodal distribution, with peaks at about 0.52 nm and 0.63 nm; the sample (b) also has a bimodal distribution, and the peaks are concentrated at about 0.50 nm and 0.82 nm. Sample (c) showed a single peak distribution, and the main peak was located at about 0.52 nm. The sample (d) shows a bimodal distribution with peaks at about 0.52 nm and 0.82 nm. In general, the micropores of coal samples in the study area are mainly distributed in 0.40-0.80 nm, of which about 0.52 nm ultramicropores are the most developed, which is the main pore space for coal gas adsorption.

3.2. Fractal Characteristics of Pore Structure

The above pore volume, specific surface area and pore size distribution parameters can reflect the pore size composition of coal samples, but it is difficult to quantitatively characterize the roughness of pore wall and the heterogeneity of pore network. Therefore, the fractal model is further introduced to characterize the complexity of pore structure of coal samples.

3.2.1. Fractal Characteristics of Nitrogen Adsorption

In the fractal calculation of low temperature liquid nitrogen adsorption, the relationship between fractal dimension D and fitting slope A is affected by the adsorption mechanism. When the adsorption process is considered to be dominated by monolayer adsorption, D = 3A + 3 is often used; if it is considered that the adsorption capacity is mainly controlled by capillary condensation, D = A + 3 is mostly used. Therefore, the choice of calculation formula needs to be judged in combination with the specific adsorption process. When calculating the fractal dimension based on the liquid nitrogen adsorption-desorption isotherm, the desorption branch data are usually selected for analysis, because the adsorption state is relatively stable under the same relative pressure. Substituting the desorption experimental data into the formula (1), establishing the corresponding logarithmic relationship and performing linear fitting, the fractal dimension can be obtained. The fitting result is shown in Figure 6. By piecewise fitting different pressure intervals, two fractal dimensions D_1 and D_2 can be obtained, which characterize the surface morphology and pore spatial structure characteristics of the pore wall, respectively.

Generally speaking, the larger the D_1, the more obvious the fluctuation of the hole wall and the higher the surface roughness; the larger the D_2, the more complex the pore network structure and the stronger the spatial heterogeneity.

According to the classical fractal theory, the fractal dimension of porous media is generally between 2 and 3. By comparing the calculation results, it can be seen that the fractal dimension obtained by D = A + 3 is more in line with the fractal theory. Therefore, this paper finally chooses D = A + 3 as the calculation formula of fractal dimension:

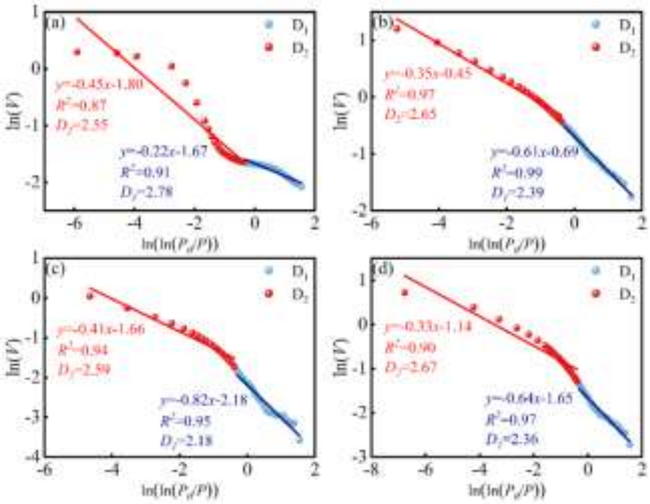

Figure 6. N_2 adsorption fractal dimension fitting curve of coal samples

The results of fractal dimension calculated by liquid nitrogen adsorption-desorption experiment show that the surface fractal dimension D_1 of each coal sample is 2.28-2.58, indicating that the surface roughness of pores is generally at a medium level, and the difference between samples is small, but it still reflects a certain irregularity of pore wall morphology. The fractal dimension D_2 of pore structure is 2.55-2.67, indicating that the pore network of coal samples has strong spatial complexity and heterogeneity. Generally speaking, the larger the D_1, the more obvious the fluctuation of the pore wall, and the more adsorption sites can be provided; the larger the D_2, the more complex the pore size distribution and the stronger the pore space heterogeneity. Most of the samples show $D_2 > D_1$, indicating that the complexity of the pore network is higher than the roughness of the pore wall surface, and the coal pores have obvious multi-scale distribution characteristics. In general, the fractal dimension of each sample is within a reasonable range of 2-3, indicating that the pore system of coal samples has significant fractal characteristics. Among them, D_2 is generally high, indicating that the pore structure is more complex, which can provide abundant pore space for gas adsorption, diffusion and occurrence.

3.2.2. Fractal Characteristics of Carbon Dioxide Adsorption

Through the linear fitting of ln (P-Pf) and ln (V), the ultra-microporous fractal dimension of coal samples can be calculated from the slope of the fitted line. The results are shown in Table 4 and Figure 7:

Table 4. The fractal dimension of ultramicropores is calculated from CO_2 adsorption data.

Specimen	Linear fitting formula	Slope	D_m
PDSSS-21-01	$\ln V=0.68\ln(P-P_f)+4.93$	0.68	2.32
PDSBK-21-02	$\ln V=0.62\ln(P-P_f)+4.03$	0.62	2.38
PDSBK-42-03	$\ln V=0.66\ln(P-P_f)+4.94$	0.66	2.34
PDSBK-42-04	$\ln V=0.64\ln(P-P_f)+4.84$	0.64	2.36

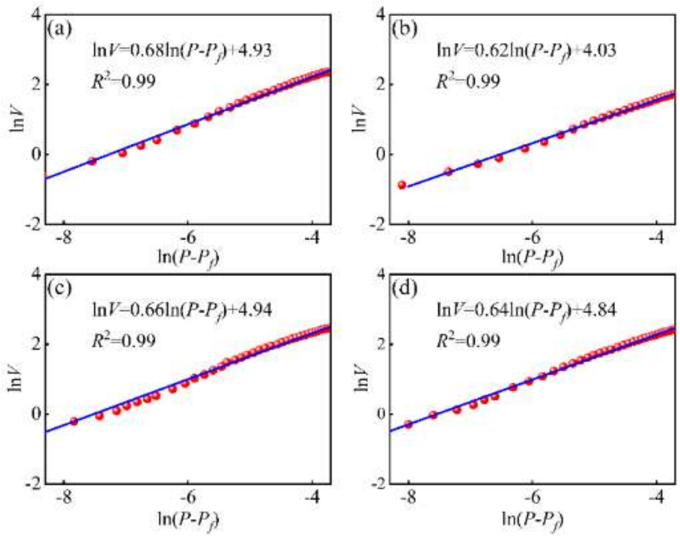

Figure 7. Fitting curve of fractal dimension of ultramicropores in CO_2 adsorption of coal sample

The supermicropore fractal dimension Dm calculated based on CO_2 isothermal adsorption data is 2.32-2.38. The numerical difference of each sample is small, indicating that the ultra-microporous structure of coal samples in the study area has similar fractal characteristics. On the whole, D_m is lower than 2.5, indicating that the complexity of the ultra-microporous structure of the coal body is low, the surface of the pore wall is relatively smooth, and the pore size distribution is relatively simple. In addition, the lower fractal dimension also indicates that the ultra-micropores in the coal body may be dominated by relatively isolated pores, with weak pore connectivity and limited development of ultra-micropore network.

4. Conclusion

(1) The vitrinite reflectance (R_o) of coal samples in the study area is 1.06-1.24 %, which has the characteristics of medium and low ash, low volatile and high fixed carbon, which is in line with the coal properties of metamorphic coking coal in Pingdingshan mining area. The macerals are mainly vitrinite, followed by inertinite, and the content of exinite is extremely low, indicating that the organic composition of coal samples is relatively stable. Coalification promotes the densification of organic matter structure and the preservation of small-scale adsorption pores, while mineral filling and inertinite differences further affect pore morphology and connectivity.

(2) The results of low temperature N_2 adsorption show that the pore volume is mainly contributed by micropores and mesopores in the 2-300 nm pores of coal samples in the study area, and the mesopores control the reservoir space more obviously. The specific surface area is mainly controlled by 2-10 nm micropores. The adsorption-desorption isotherm is type IV and superimposed type II. The hysteresis loop indicates that the composite pore structure such as ink bottle pore, slit pore and fissure pore is developed in the coal body. The peak value of pore size is concentrated in 3-5 nm, indicating that small pore size is an important pore type affecting the adsorption-diffusion behavior of coal.

(3) The results of CO_2 adsorption show that the ultramicropores of coal samples in the study area are relatively developed, and the pore size is mainly concentrated in 0.40-0.80 nm, of which about 0.52 nm pores are dominant, which is the core space for gas adsorption and occurrence. Compared with the micropore-mesopore diffusion channel characterized by N_2 adsorption, the ultramicropores revealed by CO_2 adsorption more directly control the adsorption capacity and gas storage capacity of coal.

(4) Fractal analysis showed that the fractal dimension D_1 of liquid nitrogen adsorption was 2.28-2.58, reflecting the overall medium roughness of the pore wall; D_2 is 2.55-2.67, and most samples $D_2 > D_1$, indicating that the pore complexity mainly comes from the spatial heterogeneity of the three-dimensional pore network, rather than the single pore wall roughness effect. The fractal dimension D_m of supermicropores for CO_2 adsorption is 2.32-2.38, indicating that the structure of supermicropores is relatively simple and the connectivity is weak. In general, the gas occurrence of coal samples is mainly controlled by the adsorption space of ultra-micropores, and the gas diffusion and migration are restricted by the complexity of micropore-mesopore pore network.

References

[1] Zou G, Chau K W. Energy consumption, economic growth and environmental sustainability: Evidence from China [J]. Energy Reports, 2023, 9: 106-116.

[2] Labani M M, Rezaee R, Saeedi A, et al. Evaluation of pore size spectrum of gas shale reservoirs using low pressure nitrogen adsorption, gas expansion and mercury porosimetry: A case study from the Perth and Canning Basins, Western Australia [J]. Journal of Petroleum Science and Engineering, 2013, 112: 7-16.

[3] Qin L, Li S, Zhai C, et al. Changes in the pore structure of lignite after repeated cycles of liquid nitrogen freezing as determined by nitrogen adsorption and mercury intrusion [J]. Fuel, 2020, 267: 117214.

[4] Jia M, Huang W, Li Y. Quantitative characterization of pore structure parameters in coal based on image processing and SEM technology [J]. Energies, 2023, 16(4): 1663.

[5] He Shanshan, Zhao Difei, Liu Jing, et al. Characterization of adsorption pore structure and fractal characteristics of anthracite based on low-temperature nitrogen adsorption [J]. Coal Technology, 2019, 38(1): 66-69.

[6] Shen Yanjun, Wang Xu, Zhao Chunhu, et al. Multi-scale pore structure characteristics of oil-rich coal in Yushenfu mining area [J]. Coalfield Geology and Exploration, 2021, 49(3): 33-41.

[7] Fu Xuehai, Qin Yong, Zhang Wanhong, et al. Coal pore fractal classification and natural classification based on CBM migration [J]. Science Bulletin, 2005(S1): 51-55.

[8] Lang Weiwei, Song Zhimin, Liu Gaofeng, et al. Pore distribution and fractal characteristics of deformed coal based on low temperature liquid nitrogen adsorption experiment [J]. Journal of Henan Institute of Technology (Natural Science Edition), 2015, 27(2): 34-37.

[9] Hao Jinwei, Li Yang. Research on multi-scale fractal characterization and influencing factors of pore structure of tectonic coal [J]. Coal Science and Technology, 2020, 48(8): 164-174.

[10] Zhang Shaofeng, Li Yage, Qin Xinglin. Fractal characteristics of coal reservoir pores in Qinshui Basin and its influence on gas adsorption [J]. Coal Science and Technology, 2019, 47(3): 163-167.

[11] Lu Hongwei, Xu Hongjie, Yang Yichao, et al. Heterogeneity characteristics of pore structure and methane adsorption energy change in coal reservoir [J]. Science Technology and Engineering, 2023, 23(30): 12817-12826.

[12] Chen Liuyu, Li Xijian, Shen Zhonghui, et al. Study on pore structure and fractal characteristics of outburst coal in northern Guizhou [J]. China Safety Science Journal, 2020, 30(2): 66-72.

[13] Yang Y, Jin Y, Song H, et al. Shape and size effects on adsorption performance of methane from pores in coal [J]. Energy, 2025, 318: 134814.

[14] Li Yanhe, Wang Baoyu, Liu Shunxi, et al. Sedimentary environment of coal-bearing strata and its control on coal-measure gas accumulation in Pingdingshan mining area, Henan Province [J]. Journal of Palaeogeography, 2024, 26(6).

[15] An Cheng, Liu Guangdi, Sun Mingliang, et al. Analysis of shale pore structure characteristics based on nitrogen adsorption experiment and fractal FHH model: A case study of Chang 7 Member in Huachi area, Ordos Basin [J]. Petroleum Geology & Experiment, 2023, 45(3): 576-586.

[16] Peng Xin, Jiang Zebiao, Li Bobo, et al. Experimental study on the influence of carbon dioxide fracturing on the fractal characteristics of coal pore surface [J]. Journal of Safety Science and Technology, 2019, 15(2): 111-117.

[17] Zhang Kun, Meng Zhaoping, Jin Yi, et al. Fractal characteristics of pore structure of coal with different coal structure and its research significance [J]. Coal Science and Technology, 2023, 51(10): 198-206.