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Resistivity response to the porosity and permeability of low rank coal

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ABSTRACT

Laojunmiao coal samples from the eastern Junggar basin were studied to understand the relationship between coal resistivity and the physical parameters of coal reservoirs under high temperatures and pressures. Specifically, we analysed the relationship of coal resistivity to porosity and permeability via heating and pressurization experiments. The results indicated that coal resistivity decreases exponentially with increasing pressure. Increasing the temperature decreases the resistivity. The sensitivity of coal resistivity to the confining pressure is worse when the temperature is higher. The resistivity of dry coal samples was linearly related to ϕ^m. Increasing the temperature decreased the cementation exponent (m). Increasing the confining pressure exponentially decreases the porosity. Decreasing the pressure increases the resistivity and porosity for a constant temperature. Increasing the temperature yields a quadratic relationship between the resistivity and permeability for a constant confining pressure. Based on the Archie formula, we obtained the coupling relationship between coal resistivity and permeability for Laojunmiao coal samples at different temperatures and confining pressures.

1. Introduction

Porosity and permeability are important parameters for coal, which is important to CBM exploration and development [1]. Traditionally, increasing the buried depth increases the formation pressure and decreases the coal permeability, which is not considered conducive to deep CBM resource exploitation [2–4]. However, there is no lack of successful examples for exploiting deep CBM resources around the world [5,6]. Directly testing the porosity and permeability of coal under high temperatures and pressures is difficult. The response of resistivity to porosity and permeability indirectly predicts the porosity and permeability of deep coal seams. There have been numerous studies on the relationship between resistivity and petrophysics, both at home and abroad. Zhou [7] entered the permeability into the Archie formula and illustrated that the resistivity correlated well with the porosity and permeability, which are not influenced by the depositional environment and pore structure. Huang et al., Sun et al., and Ma et al. [8–10] deduced the relationship between the rock permeability and resistivity based on the Archie and Carman–Kozeny formulas and tested the petrophysical parameters to verify the feasibility for calculating the rock permeability from the resistivity via multi-parameter core scanners. Chen [11] determined the resistivity of competent sandstone with different water saturations via electricity experiments. Thus, the pore structure parameter can be computed. Foreign scholars [12–15] also obtained empirical formulas for the permeability and resistivity, which can successfully predict and evaluate aquifer permeability. However, this research was confined to sandstone, shale and carbonates, which are not argilliferous. Studies on the relationship between coal reservoir physical properties and resistivity under high temperatures and pressures is still limited [16].

Several factors influence coal resistivity, such as temperature, pressure, formation water salinity, wettability, porosity, pore sinuosity, pore-throat ratio, and metamorphic grade [17–25]. Previous studies focused on effects the static and dynamic factors of outburst and non-outburst coals had on resistivity [26–31]. However, the formation pressure is not the entire case. The triaxial confining pressure also must be considered. Therefore, coal seam resistivity has important reference values for understanding its physical conditions under high temperatures and pressures. The research described in this paper studied a dry coal sample to analyse the relationship of coal resistivity to porosity and permeability at high temperatures and pressures while excluding the impact of the coal seam structure, water saturation, formation water salinity and many other factors.

2. Coal samples and geological background

The coal samples used for these experiments were collected from Wucaiwan in the eastern Junggar basin of the Xinjiang Uygur

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Autonomous Region. The coal samples were jet coal from the Xishanyao formation, middle Jurassic period. The Xishanyao formation was formed in the delta of Retreat Lake. Delta plain distributary channels and flood plain swamps develop vertically, and are characterized by thick coal seams, and are controlled by the "three concave and two convex" tectonic pattern [32,33]. Large raw coal blocks were collected from fresh working faces in the coal mines while ensuring that the sides were longer than 200 mm. To prevent oxidation, all coal blocks were immediately packaged in black plastic bags and taken back to the Key Lab of CBM Resources and Dynamic Accumulation Process, Ministry of Education of China. The collected raw coal blocks were drilled into cylindrical coal samples for coal porosity, permeability and resistivity tests along the bedding surface. The coal samples were 25 mm in diameter and 50 mm high or 50 mm in diameter and 40 mm high. The columnar coal samples were air-dried and sealed in polyethylene film wrap for storage [34]. Meanwhile, the coal column end cut offs were collected and divided into three parts. One part was crushed and ground to below 20 mesh (particle size below 0.83 mm) for the analysis of coal macerals and maximum vitrinite reflectance in oil. One part was crushed and ground to less than 80 mesh (particle size below 0.18 mm) for proximate analyses as shown in Table 1. The final part was broken into particles greater than 2 mm in size for mercury-injection experiments. The mercury-injection experiments used an AutoporeIV9510 porosity-measuring instrument made in the U.S.A. The mercury-injection pressure ranged from 0 to 414 MPa. The measurable pore diameter was above 3 nm. The mercury-injection and mercury-ejection curves, porosity, pore volume, pore structure and specific surface area were obtained (Table 2).

Primary porosity is the main pore type in low-rank coal and accounts for 63.37% of the pore volume for macroporous and mesoporous Laojunmiao coal samples. The mercury intrusion porosity is 17.91%, and the median pore diameter is 426 nm. Song [35] believed pores with diameters above 100 nm provide diffusion-seepage-migration channels for CBM and determined the difficulty for fluid seepage in coal reservoirs.

3. Experimental methods

The Xishanyao and Badaowan formations are 900–3300 m and 600–2900 m deep, respectively. Based on the average effective stress gradient for the Junggar basin (1.025 MPa/100 m), the effective coal seam stress can be estimated as 30.75 MPa when 3000 m deep. The modern average geothermal gradient in the Junggar basin is 2.55 °C/100 m. Subtracting the thermostatic temperature (15 °C) [36–38] indicates that the coal seam temperature is 66 °C when the depth is 2000 m and 91.5 °C when the depth is 3000 m.

The effective stress is the difference between the confining and fluid pressures. Because the nitrogen gas fluid pressure is below 0.5 MPa and decreased during testing, the effective stress cannot be accurately obtained. We focused on relating the confining pressure to the resistivity, porosity and permeability. According to the buried coal seam depth and geothermal gradient, we used 30 °C, 50 °C and 70 °C as the experimental temperatures. The test medium was 99.999% pure nitrogen. For each temperature, we designated 12 confining pressure points (2 MPa, 3.5 MPa, 5 MPa, 8 MPa, 11 MPa, 15 MPa, 19 MPa, 23 MPa, 27 MPa, 31 MPa, 35 MPa and 40 MPa). The experimental device is a GWFY-01 high-temperature and confining-pressure tester made by Shandong Shiyi Science and Technology Co., Ltd. of U.P.C. We designed 30 °C, 50 °C and 70 °C as the experimental resistivity temperatures. For each temperature, we designated 6 confining pressure points (5 MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa). A comprehensive automatic measuring device made in Haian Shiyi Science and Technology Co., Ltd. was used to measure the coal rock acoustic parameters.

Table 2
Pore volume distribution for the coal sample.

Producing area	Pore volume (10^{-4} cm^3/g)					Ratio of the pore volume (%)			
	V_1	V_2	V_3	V_4	V_t	V_1/V_t	V_2/V_t	V_3/V_t	V_4/V_t
Laojunmiao mine	274	385	327	54	1040	26.35	37.02	31.44	5.19

Note: V, V_1, V_2, V_3, V_4, and V_t represent the pore, macropore ($\phi > 1000$ nm), mesopore ($1000\text{ nm} > \phi > 100$ nm), transition pore ($100\text{ nm} > \phi > 10$ nm), micropore ($10\text{ nm} > \phi > 7.2$ nm) and total pore volumes, respectively.

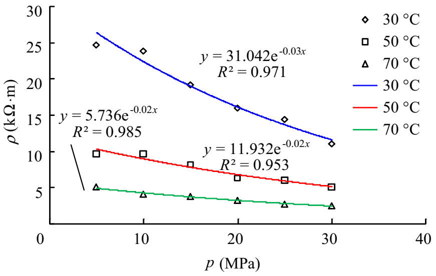

Fig. 1. Relationship between resistivity and pressure.

4. Results and discussion

4.1. Resistivity experiments at high temperatures and an overburden pressure

The fitted relationship between the resistivity and confining pressure is as follows:

$$\text{When } 30\,^{\circ}\text{C},\ \rho = 31.042\mathrm{e}^{-0.03p},\ R^2 = 0.971 \tag{1}$$

$$\text{When } 50\,^{\circ}\text{C},\ \rho = 11.932\mathrm{e}^{-0.02p},\ R^2 = 0.971 \tag{2}$$

$$\text{When } 70\,^{\circ}\text{C},\ \rho = 5.736\mathrm{e}^{-0.02p},\ R^2 = 0.971 \tag{3}$$

where ρ is the resistivity ($10^3\ \Omega$ m); p is confining pressure (MPa).

Coal generally is, or is similar to, a semiconductor. An electric current occurs under an applied voltage [28]. Therefore, low rank coal can be treated as a dielectric with two types of electrical

Table 1
Basic properties of the coal samples.

Producing area	Position	$R_{o,max}$[a] (%)	Proximate analysis (%)			Coal macerals (%)			
			V_{daf}[b]	M_{ad}[b]	A_{ad}[b]	V[c]	I[c]	E[c]	M[c]
Laojunmiao mine	J_{2x}	0.62	29.99	9.43	2.98	32.43	61.56	1.2	4.8

Note: M is the percent volume for minerals in the dry basis.
[a] Mean maximum vitrinite reflectance in oil.
[b] V_{daf}, M_{ad}, and A_{ad} represent the volatile yield of the dry ash-free basis, moisture content of the air-dried basis and ash yield of the dry ash-free basis, respectively.
[c] V, I, and E represent the percent volume for vitrinite, inertinite and liptinite in the coal maceral, respectively.