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Study on Dynamic Response Characteristics of Electrical Resistivity of Gas Bearing Coal in Spontaneous Imbibition Process

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Abstract

The capillary force driving the water penetration process in the coal pore network is the key factor affecting the effect of coal seam water injection. The resistivity method can be used to determine the migration characteristics of water in coal. In order to study the relationship between the resistivity of gas-bearing coal and the migration of water in the process of imbibition, the self-generated imbibition tests of coal under different external water conditions were carried out by using the self-developed gas-bearing coal imbibition experimental platform and the dynamic response characteristics of coal resistivity with external water were obtained. The results show that the water injected into the coal body migrates from bottom to top under the driving of capillary force, and the resistivity of the wetted coal body shows a sudden decline, slow decline, and gradually stable stage change. Through the slice drying method, it is found that the moisture in the coal body is almost uniform after imbibition, and the resistivity method can be used to accurately and quantitatively characterize the moisture content of the coal body. In the axial direction, as water infiltrates layer by layer, the sudden change time of resistivity is delayed with the deepening of the layer. The resistivity of each layer first drops sharply then slows down and tends to stabilize. The stable value of resistivity increases gradually with the depth of the layer. In the radial direction, within the same plane, water first migrates to the centre of the coal body and then begins to spread outwards. The average mutation time and stable value of coal resistivity during spontaneous imbibition decrease with increasing water content. When the water content reaches 10%, the stable value of resistivity tends to be constant, and the relationship between the stable value of coal resistivity and water content conforms to an exponential function.

Keywords: gassy coal; coal seam water injection; moisture; resistivity; spontaneous imbibition

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1. Introduction

Coal is the primary source of energy consumption in China and occupies an irreplaceable strategic position in the national economy. The national energy development strategy highlights that the proportion of coal energy consumption in China is expected to remain above 50% in the coming decades [1–4]. With the gradual depletion of shallow minable resources, China has entered the deep mining stage ahead of schedule, and the vertical depth of some mines has reached more than 1000 m, which means that coal mining will face more challenges, including more frequent coal and gas outburst events and greater outburst intensity [5–7].

Coal seam water injection is the most effective dust prevention measure in coal mines. By injecting pressurized water into the coal body, the coal seam can be thoroughly wetted, and the dust generation can be significantly reduced [8–11]. With the in-depth study of coal seam water injection, scholars found that coal seam water injection can promote gas desorption and reduce the gas content of coal seam. The gain effect of coal seam water injection on gas desorption characteristics is primarily manifested in the displacement effect of pressure water on gas and the displacement effect of water on gas during imbibition. Among them, displacement mainly occurs during the water injection stage, while imbibition continues to affect the desorption of gas after water injection is stopped, with a broader range of influence on coal gas and a longer action time [12–16].

Clarifying the characteristics of water movement and distribution under the condition of spontaneous imbibition has important guiding significance for the use of water injection to prevent coal seam gas. The basic principle of the electrical resistance method is that different moisture content of materials leads to different DC resistivity. The size of moisture content can be calculated indirectly by measuring the change of conductivity or resistivity. Compared with the traditional mass method and slice method, the electrical resistance method has the characteristics of being fast, accurate, and providing real-time monitoring. It is often used to determine the migration characteristics of moisture in coal and is generally accepted by scholars. S. MARLAND et al. [17] used the circular resonator method to measure and study the dielectric constant of coal in the microwave channel, and the results showed that the increase in coal humidity changes its dielectric properties. Under the condition of water content, the change in fracture volume and the degree of water saturation jointly determine the change in the degree of the overall resistivity of the coal sample. The expansion leads to an increase in the total fracture space of the coal body, the decrease in water filling degree, and the increase in resistivity [18–20]. Zhang Xin [21] used the electric bridge method to measure the dielectric constant of coal. By establishing the mathematical model of water distribution, it was found that the dielectric anisotropy of coal can indicate the water distribution. The resistivity response during the deformation and failure process of dry and wet coal bodies is closely related to the stress state of the coal body, and the expansion point of the coal body also corresponds to the inflexion point of the resistivity from decreasing to increasing [22]. Song Da [23] and Peng Ye [24] studied, respectively, the resistivity and other corresponding characteristics of middling coal rock mass during hydraulic fracturing through the hydraulic fracturing apparent resistivity experimental system and field test system. The apparent resistivity of coal and rock mass is not evenly distributed in space, and the distribution of apparent resistivity is closely related to the distribution and evolution of water. Dong [25] found that with the increase in water content, the resistivity of the coal body gradually decreased and finally maintained a stable value. Before the gas adsorption equilibrium of the coal body and the desorption of the gas-bearing coal body, its resistivity was negatively correlated with the gas content. Wang Bin [26] tested the change in coal resistivity by arranging electrode discs at both ends of the briquette and studied the response characteristics of electrical resistivity of gas-free

coal to water content. The results showed that the limit value of coal resistivity gradually decreased with an increase in water content, and the relationship between them followed a nonlinear function.

To sum up, the resistivity method offers the advantages of continuous testing and real-time data recording and the resistivity of the coal body changes in response to changes in water content during imbibition. Previous studies have primarily focused on the qualitative analysis of water movement and the change in resistivity of coal with different metamorphic degrees, as well as the change in coal body resistance caused by the expansion of coal fissure pores. At the same time, there are few studies on the law governing the change in resistivity and water content during the process of gas-bearing coal imbibition. Based on this, through the spontaneous imbibition experimental system of gas-bearing coal, the long-term imbibition test of gas-bearing coal under the conditions of overburden stress 10 MPa, gas adsorption equilibrium pressure 0.74 MPa, and different external moisture was carried out. Based on this, through the spontaneous imbibition experimental system of gas-bearing coal, the long-term imbibition test of gas-bearing coal under the conditions of overburden stress 10 MPa, gas adsorption equilibrium pressure 0.74 MPa, and different external moisture was carried out, the dynamic response characteristics of coal resistivity with external moisture were obtained, and the quantitative function model of gas-bearing coal resistivity and moisture content in the imbibition process was constructed, which provided a scientific theoretical reference for determining the water injection volume and water injection time of coal seam water injection.

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2. Materials and Methods

2.1. Coal Sample Preparation

The test coal sample was collected from the Guhanshan mine of the Henan Coking Coal Group, which is a high metamorphic anthracite. The mine is located in the east of the Jiaozuo mining area, with a design production capacity of 120 Mt/a. It is a coal and gas outburst mine. The central coal seam of the mine is the No.21 coal seam, which is a soft and hard composite coal seam. In order to ensure the uniform compression of coal samples, it is necessary to reshape the coal samples. First, samples were taken from the freshly exposed coal wall using the grooving method, sealed, and sent to the laboratory for crushing. After that, the pulverized coal particles with particle sizes of 0.25~0.42 mm and 0.09~0.178 mm were screened out by a vibrating screen for drying treatment and then mixed according to the mass ratio of 1:2 and thoroughly stirred with 10% distilled water. Finally, the coal sample was pressed in layers with a pressing load of 90 MPa. After pressing, it was put into the drying oven for drying, during which the electrodes were evenly arranged in each layer. The process of coal sample collection and preparation is shown in Figure 1. At the same time, the basic physical parameters of coal samples were determined according to GB/T212-2008 [27], and the test results are shown in Table 1.

Table 1. Industrial Analysis of coal samples.

Sampling Location	Metamorphic Degree	M_{ad}/%	A_{ad}/%	V_{daf}/%	Calorific Value (MJ/kg)
Guhanshan mine	Anthracite	1.04	10.85	7.25	19.68

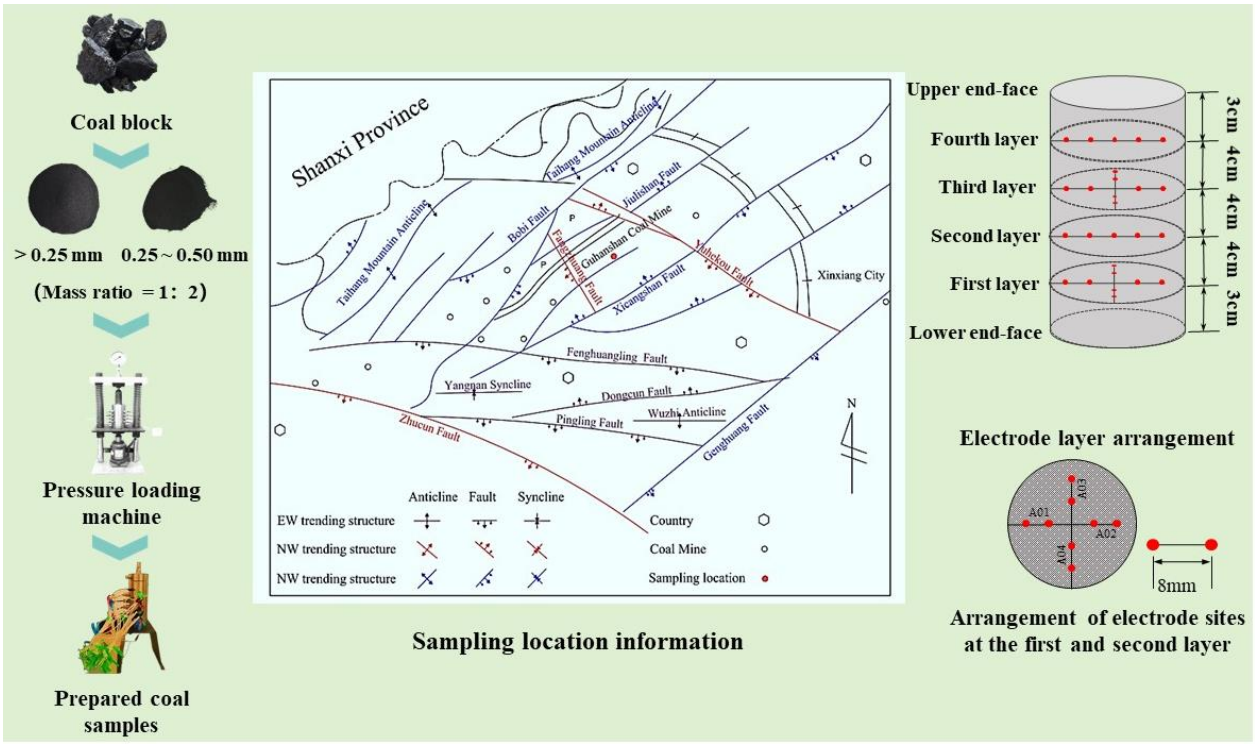


Figure 1. Geographical location of the mine and coal sampling map.

2.2. Test Equipment

The test utilizes a self-developed gas-bearing coal plus water imbibition test platform, which is primarily composed of a coal sample tank, a vacuum degassing system, an isothermal control system, an overburden pressure loading system, an isobaric water addition system, and a resistivity test system. The resistivity test system enables the real-time measurement of coal resistivity during the imbibition process. The principle of the test system is shown in Figure 2.

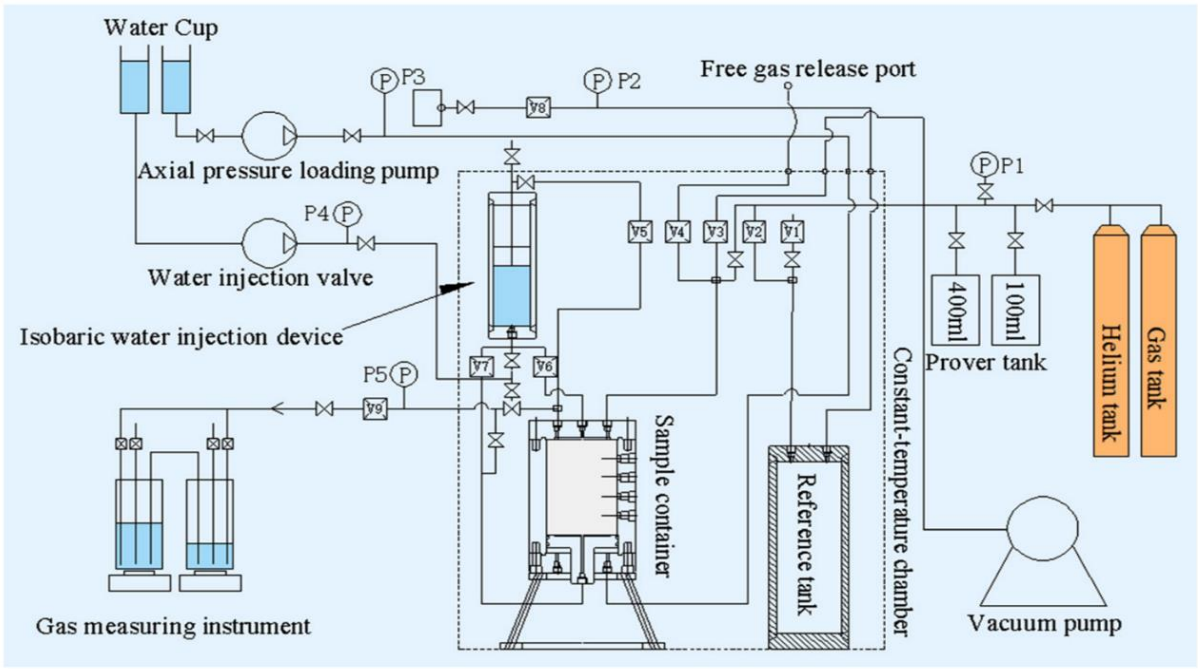


Figure 2. Schematic diagram of gas-bearing coal seepage test system.

The principle of the resistivity measurement function is to install the electrode pieces at different heights of the coal body by pressing the coal samples in layers and reflecting the added water in the coal body according to the different resistivity of the dry coal body and the wet coal body. Resistivity is usually used to describe the resistance characteristics of a medium, and the physical symbol is ρ. The physical meaning is as follows: at room temperature, the resistance of a conductor consisting of a medium with a length of 1 m and a cross-sectional area of 1 mm^2, the unit is $\Omega \cdot m$, and the symbol is $\Omega \cdot m$.

$$\rho = \frac{RS}{L} \tag{1}$$

where ρ is material resistivity, Ω·m; R is material resistance, Ω; S is material cross-sectional area, m^2; L is material length, m.

In this test, an Agilent 34970A resistance tester is used to measure the resistance value of a coal sample based on voltammetry, and the resistivity value is calculated using the formula above. The instrument can output a 9 V DC voltage to the briquette sample at room temperature and directly output the resistance value at each time through software calculation and control. The experiment was carried out to investigate adsorption and desorption under specific gas pressures. Through the spontaneous imbibition of added water, the resistivity at different positions of the coal body was measured in real time. When the desorption volume is less than 5 mL/h, the imbibition is considered to stop.

2.3. Test Process

In order to obtain the dynamic response characteristics of coal resistivity with applied water, the resistivity method is used to test the change in water content at each measuring point of the coal body. The resistance values at both ends of the measuring point are continuously collected and converted into resistivity values to obtain the resistivity changes over time and determine the stable resistivity value of long-term imbibition. The corresponding stable value of resistivity can be obtained by varying the amount of added water; that is, the resistivity method is used to determine the water content. The slice drying method is used to verify the reliability of the resistivity method in measuring water content. The specific test process is described below.

2.3.1. Resistivity Method

In this paper, the resistivity method is proposed to measure the change in moisture content at each measuring point within the coal body. By continuously measuring the resistance value at both ends of the measuring point, the resistivity value is obtained, and the change in resistivity over time is determined. The stable resistivity value resulting from long-term imbibition is then obtained. The corresponding stable value of resistivity can be obtained by changing the amount of added water; that is, the resistivity method is used to test the water content.

(1) Instrument connection: Put the coal sample tank in the experimental system, connect each pipeline-interface of the system, confirm that all valves of the system are closed, connect each test electrode with the resistance tester, and turn on the main power supply of the equipment. The electrode connection is shown in the following Figure 3.
(2) Constant temperature and loading: Set the temperature of the incubator at 16 °C, open the suction valve of the axial pressure loading pump, close the suction valve after suction, and load the axial pressure 10 MPa on the control panel.
(3) Air tightness test: Open the helium bottle to fill the coal sample tank with helium of about 1 MPa, then close the air inlet valve and read the pressure gauge reading of the coal sample tank after the reading is stable. If the pressure does not drop within half

an hour, it indicates that the air tightness is good. Otherwise, soap water should be used for leak detection. Open the exhaust valve to release helium in the coal sample tank after ensuring that the air tightness is good;

(4) Dead volume calibration: Fill the calibration tank with helium at a certain pressure, read the gas pressure in the tank after the indication is stable, then connect the calibration tank with the coal sample tank and reread the balance pressure after the indication is stable. The dead volume of the coal sample tank can be obtained according to Formula (2). Repeat the operation three times and take the average to reduce the experimental error:

$$V_f = P_{H0}V_{H0}Z_{H1}/P_{H1}Z_{H0} - V_0 \quad (2)$$

where V_f is the free volume of the adsorbed sample, mL; Z_{H0} and Z_{H1} are the helium compression factors; V_0 is the volume of the helium reference column, mL.

(5) Vacuum pumping: Open the exhaust valve to release the gas in the coal sample tank and close all valves. After that, open the connecting valve between the coal sample tank and the vacuum pump and start the vacuum pump for vacuum degassing of the coal sample tank; when the reading of the vacuum gauge drops below 20 Pa, close the connecting valve between the coal sample tank and the vacuum pump and close the vacuum pump switch.

(6) Gas adsorption: Open the switch of the methane cylinder and the inlet valve in turn, let a small amount of methane enter the coal sample tank many times, and make the coal sample adsorb and balance under the pressure of 0.74 Mpa.

(7) Quantitative water adding: Open the water inlet valve of the advection pump and piston container, input the flow rate and water injection volume of the advection pump on the control panel, then start the advection pump and close the advection pump and water inlet valve after adding water.

(8) Resistivity measurement: Open the isobaric valve and water injection valve between the piston container and the coal sample tank to allow water to infiltrate into the coal naturally. At the same time, quickly open the resistance tester to record the resistivity of the coal sample in real time.

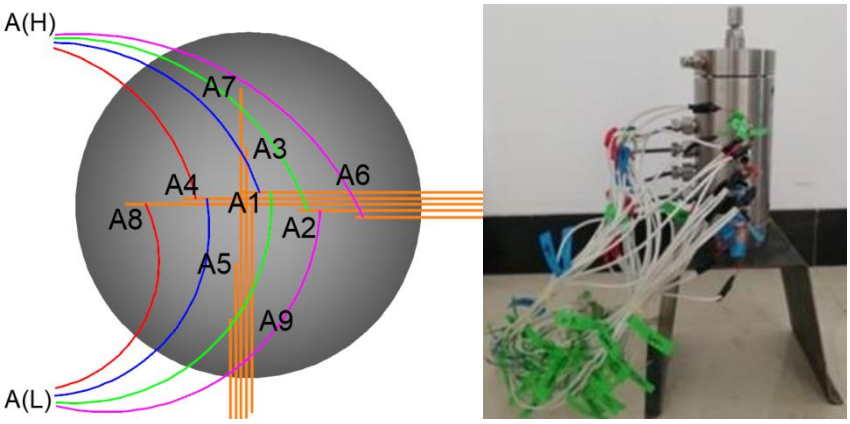


Figure 3. Schematic diagram of electrode arrangement.

Repeat the above steps to carry out the spontaneous imbibition test of coal under different external water conditions.

2.3.2. Slice Drying Method

The slice drying method was used to verify the reliability of the resistivity method in measuring water content. The test process is as follows:

(1) When the coal sample is pretreated, only the first layer of electrode is arranged in the briquette pressing stage, which is located in the middle of the briquette. At the same time, in order to reduce the difference in moisture content at different heights of the briquette, the height of the briquette should be reduced as much as possible.
(2) A certain amount of water is injected into the water injection container and the spontaneous imbibition test of coal is carried out. To thoroughly wet the coal with water and facilitate the later determination of water content, the test time is set at 48 h.
(3) After the test, the electrode wire is pulled out, and the briquette is completely withdrawn using the calibration block built into the tank and the servo press. The moisture content of the briquette is then measured using the slice drying method. First, the briquette is equally cut into two coal slices from the middle, and the two coal slices are circumferentially cut according to the way shown in Figure 4.
(4) Each coal slice is weighed after cutting, its initial mass m_{ij} is measured, its residual mass is measured m_{ij} after it is put into the drying oven for full drying, and the moisture content of each coal slice after cutting is calculated.
(5) The data are sorted, the resistance value between the collected two measuring points is converted into the resistivity value, the difference of moisture content measured by the slice drying method and the resistivity method is analyzed, and the reliability of moisture content measured by the resistivity method is also examined.

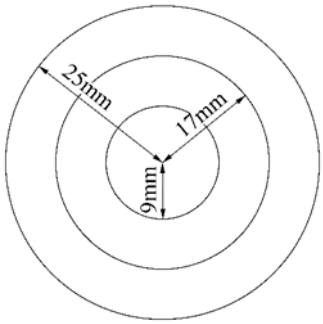


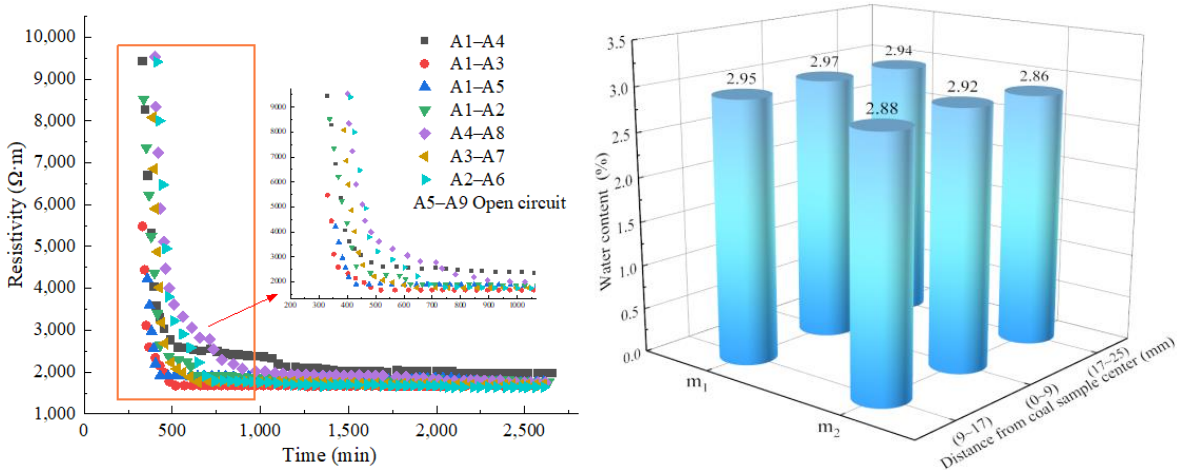
Figure 4. Circular section of briquette.

3. Results and Analysis

3.1. Feasibility Verification Based on Slice Drying Method

Taking water with 3% briquette mass as an example, the resistivity change and final stability value of each group of electrodes during the spontaneous imbibition process were tested according to the above process. After the test, the slice drying method was used to obtain the distribution of moisture content of the briquette, and the test results are shown in Figure 5.

It can be seen from Figure 5a that the final resistivity of each measuring section inside the coal body after long-term imbibition is between 1641.02 and 1887.33 Ω·m. The main reason for the difference is that the pore structure of each part inside the briquette is not entirely consistent. Even in the same plane, there are subtle differences in the moisture content of the coal body. In order to reduce the impact of this error on the later data analysis, the measured final resistivity value is averaged to represent the final resistivity value corresponding to the moisture content of 3%, i.e., 1756.39 Ω·m.



(**a**) Resistivity measurement results (**b**) Moisture content test results

Figure 5. Distribution of final resistivity and water content.

It can be seen from Figure 5b that the internal moisture content of the coal body after long-term imbibition is nearly the same, but there are still slight differences. m_1 represents coal flakes located below the electrode measurement section using the slice drying method, while m_2 represents coal flakes located above the electrode measurement section. The moisture content of the m_1 coal slice below the plane where the electrode section is located is between 2.94% and 2.97%, with an average value of about 2.95%, while the moisture content of the m_2 coal slice is slightly lower than the m_1, with an average value of about 2.89%, between 2.86% and 2.92%. This difference is mainly the result of the combined action of capillary force and gravity. Taking the average moisture content of m_1 and m_2 coal slices as the moisture content on the contact surface, the moisture content of the plane where the electrode section is located is 2.92%, the relative error measured by resistivity method is only 2.67%, and the error is within the acceptable range. It can be seen from the above analysis that the resistivity method can be used for quantitative characterization of coal moisture content.

3.2. Measurement of Coal Resistivity Under Different External Moisture Conditions

In order to obtain the corresponding relationship between electrical resistivity and moisture content of gas-bearing coal, based on the previous research, according to the test steps, the long-term imbibition test of gas-bearing coal was carried out under the overburden stress of 10 MPa and the adsorption equilibrium pressure of 0.74 MPa, and the moisture content was controlled to 2%, 4%, 6%, 8%, and 10%, respectively. Based on the resistivity test results after long-term infiltration, the curve of resistivity variation with time was drawn, as shown in Figure 6.

It can be seen from Figure 6 that the resistivity of the coal body decreases with increasing imbibition time, which can be divided into three stages: rapid change, gradual change, and stability. In the rapid change stage, the main reason is that the water continuously displaces the gas in the coal body, and the water is adsorbed on the surface of the coal particles, which changes the electric field strength at both ends of the electrode so that the current has a dominant path. At the same time, the water continuously migrates to other macropores and fractures, forming multiple dominant paths, which shows a rapid decline in resistivity. In the gradual change stage, the water content in the macropores and larger fractures gradually increases, and the water begins to migrate to the micro pores and more minor fractures. The number of carriers and their transport rate in the system gradually increases, indicating that the declining trend of coal resistivity is slowing down. In the

stable stage, under the influence of capillary force, the internal moisture content of coal gradually tends to be consistent, the number of carriers and transport rate in the system no longer increases, and the resistivity of coal tends to be constant.

Under the condition of the duplicate water content, the resistivity change curves of different measurement sections appear to be a crossing phenomenon. This is because there are a large number of open and semi-closed pores in the coal, and the time of water passing through these pores and fissures is different. Additionally, the resistance tested by the Agilent tester is susceptible to changes in water content, and even slight changes in resistance value can be recorded.

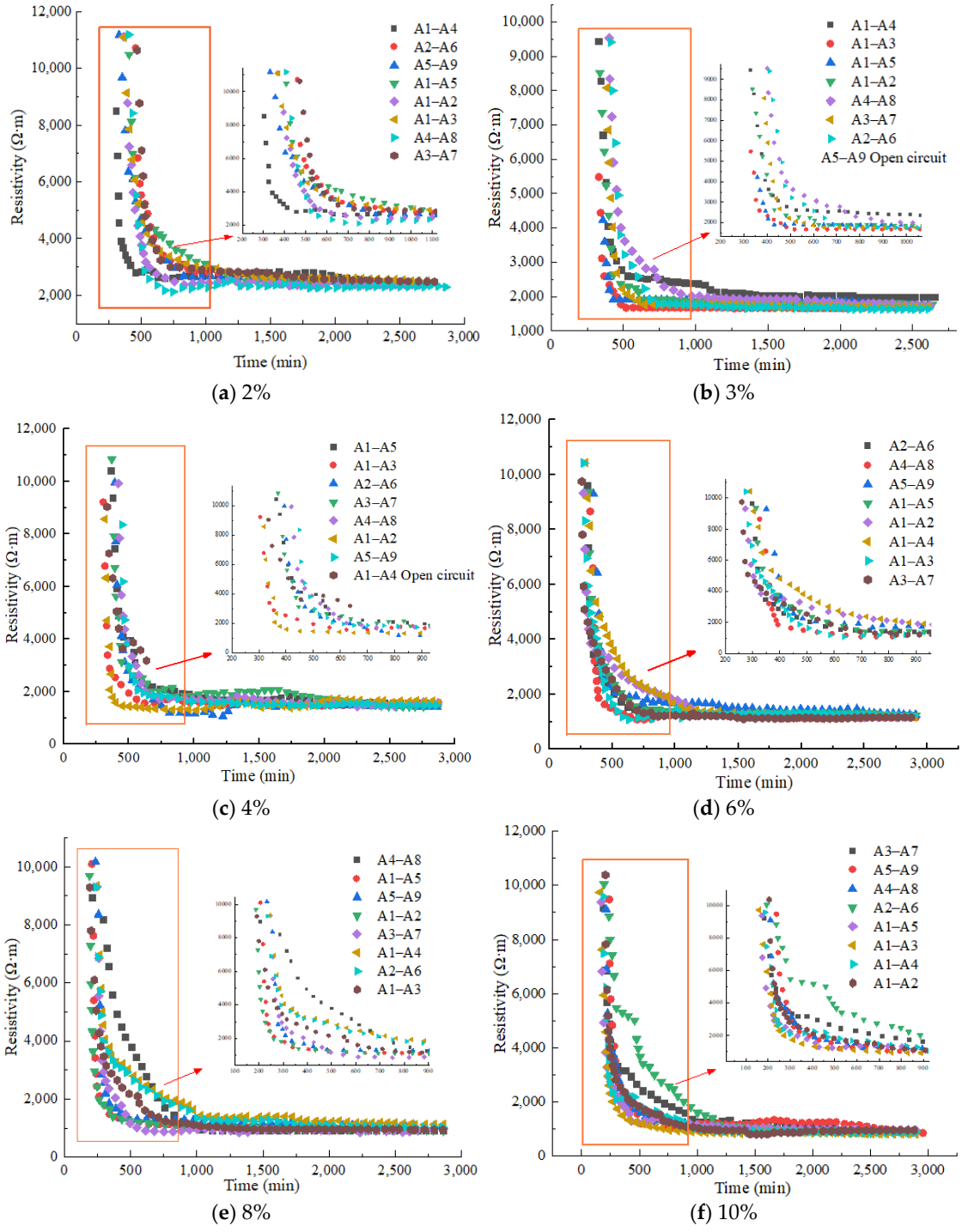


Figure 6. Variation curve of coal resistivity under different external moisture conditions.

3.3. Temporal and Spatial Distribution Characteristics of Electrical Resistivity of Gassy Coal

Due to the sufficient drying of the experimental coal sample beforehand, the moisture content in the coal can be ignored. Therefore, it is believed that when the moisture content reaches 1%, the coal body begins to be wet [28]. In order to grasp the temporal and spatial distribution characteristics of the electrical resistivity of gas-bearing coal, the axial and radial resistivity changes in gas-bearing coal under the condition of quantitative (8%) water supply were analyzed, and the dynamic change process of coal resistivity was summarized. The change process of coal resistivity is shown in Figure 7.

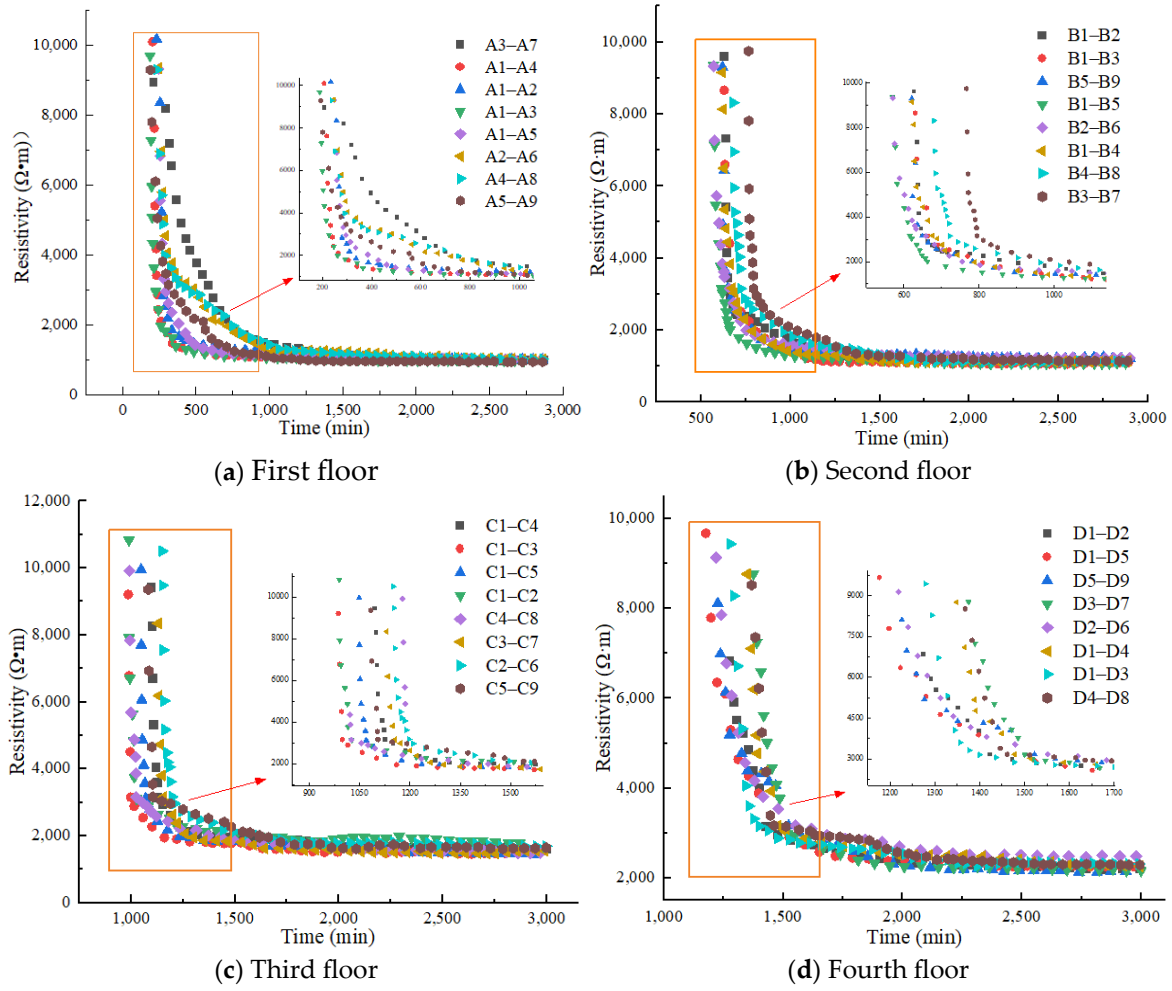


Figure 7. Variation curve of coal resistivity (8%) under the condition of quantitative water supply.

It can be seen from Figure 6 that under the condition of quantitative water supply, the resistivity of each measurement section of the first layer in the coal body suddenly changes about 230 min after the start of the experiment, and the resistivity decreases rapidly in a short time after the sudden change. Then, the decline rate gradually slows down, and finally remains relatively stable at about 1000 Ω·m. When the experiment lasted about 600 min, the resistivity of each measurement section of the second layer in the coal body suddenly changed, and the resistivity finally maintained at about 1150 Ω· m. After about 1000 min of the experiment, the resistivity of each measurement section of the third layer in the coal body suddenly changed, and finally stabilized at about 1600 Ω· m. When the experiment lasted about 1250 min, the resistivity of each measurement section of the fourth layer in the coal body suddenly changed, and finally stabilized at about 2000 Ω· m.

See Table 2 for the statistics of sudden change time of resistivity of all measuring sections at different layers in the coal body.

Table 2. Mutation time of each measurement section in coal body under 8% water supply condition.

First Floor	A1–A2	A1–A3	A1–A4	A1–A5	A2–A6	A3–A7	A4–A8	A5–A9
Time/min	216	190	205	246	243	207	235	286
Second floor	B1–B2	B1–B3	B1–B4	B1–B5	B2–B6	B3–B7	B4–B8	B5–B9
Time/min	627	601	621	570	570	694	630	681
Third floor	C1–C2	C1–C3	C1–C4	C1–C5	C2–C6	C3–C7	C4–C8	C5–C9
Time/min	989	986	1035	1048	991	1004	1150	1083
Fourth floor	D1–D2	D1–D3	D1–D4	D1–D5	D2–D6	D3–D7	D4–D8	D5–D9
Time/min	1374	1378	1448	1375	1401	1475	1367	1295

It can be seen from Table 2 that with the increase in height, the time range of sudden change in electrode measurement section in different layers is gradually expanding, and the sudden change time of resistivity of each measurement section in the same layer is different but within a specific range. In the same radial direction, the sudden change time of resistivity of the measurement section close to the center of the coal body (hereafter referred to as "inner ring measurement section") is slightly earlier than that far away from the center of the coal body (hereafter referred to as "outer ring measurement section"), indicating that in the same plane, water first migrates to the center of the coal body and then spreads around. However, there are also a few cases where the mutation time of the outer ring measurement section is earlier than that of the inner ring measurement section. This is primarily due to the small size of the briquette and the proximity of the measurement points. It is challenging to ensure the consistency of the internal pores and fissures of the briquette during the compaction process. When there is a dominant channel between the outer ring coal body and the coal body below it, the water first migrates to the outer ring measurement section along this path and then spreads to the center of the coal body.

3.4. Corresponding Relationship Between Coal Resistivity and Moisture Content

According to the variation relationship of coal resistivity with time under different external water conditions obtained in Figure 6, the resistivity mutation time and final stable value of each measurement section in the coal body are extracted, as shown in Table 3.

Table 3. Corresponding table of sudden change time and final value of coal resistivity under different external water conditions.

Different Added Moisture (%)	Average Mutation Time (min)	Average Resistivity Stability Value (Ω m)
2	389	2416.07
3	365	1756.39
4	332	1503.56
6	299	1202.45
8	218	996.68
10	194	886.61

By comparing the resistivity change curves under different external moisture conditions and combining them with Table 3, it can be seen that the average mutation time and average resistivity stability value of coal resistivity exhibit a downward trend with increasing moisture content. This is because with the increase in water content, the time required for water to reach the same imbibition height is reduced, and the number of

conductive ions in water increases, which improves the number of carriers and transport rate, resulting in the reduction in coal resistivity.

In order to more accurately obtain the response characteristics of electrical resistivity of gas-bearing coal to water content, based on the stable value of resistivity in Table 3, the mathematical software is used to fit it, and the fitting curve is shown in Figure 8. It is found that the stable value of coal resistivity ρ and water content w meet the lower test relationship. The fitting formula can better reflect the variation law of resistivity stability value and water content.

$$\rho = 3446.39/\exp(w/2.62) + 811.13 \quad (3)$$

where ρ is the stable value of average resistivity, Ω m; w is moisture content, %

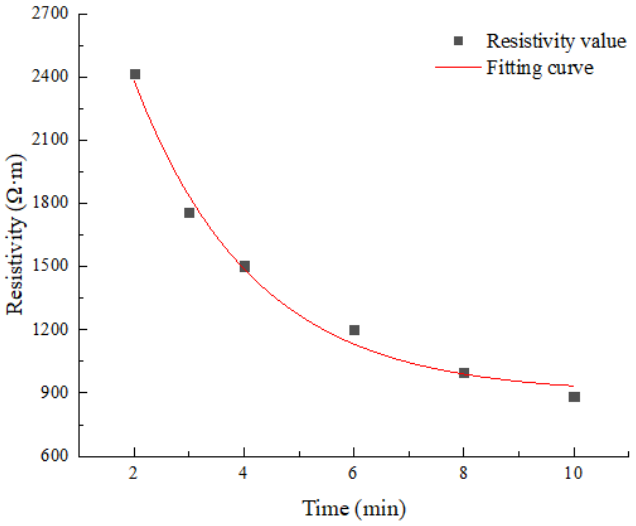


Figure 8. Fitting curve between resistivity and moisture content of gas-bearing coal.

It can be seen from Figure 8 that the increase in coal moisture causes the number of carriers and transport rate in the system to increase continuously, indicating that the stable value of the average resistivity of coal decreases with the increase in moisture content, but the downward trend gradually slows. When the moisture content reaches 10%, the number of carriers and transport rate in the system remain constant, and the resistivity also tends to balance. This phenomenon is consistent with the corresponding relationship between electrical resistivity and moisture content of gas-free coal tested by Dong [22] using the resistivity method.

4. Conclusions

(1) Taking the 3% added water test group as an example, the final resistivity values of each measurement section in the coal body after a long-term imbibition process are within a certain range, and the average stable resistivity value is 1756.39 Ω ·m. The equivalent moisture content of the plane of the electrode measurement section obtained by the slice drying method is 2.92%. Compared with the measurement results of the resistivity method, the relative error between the two is only 2.67%, indicating that the resistivity method can be used for the measurement and research of coal moisture content.

(2) With the increase in imbibition time, the resistivity of coal shows a downward trend, and its change process can be divided into three stages: rapid change, gradual change, and stability. With the increase in water content, the average mutation time point and average resistivity stability value of coal resistivity gradually decrease. Under the

condition of the duplicate water content, the resistivity curves of different sections have the phenomenon of crossing.

(3) In the axial direction, with the infiltration of water layer by layer from shallow to deep, the sudden change time of resistivity is delayed with the deepening of the layer. The resistivity of each layer drops suddenly when the water reaches, and then the rate of decline slows down and tends to be stable. The stable value of resistivity increases gradually with the depth of the layer. Radially, the abrupt change time of resistivity in the section near the center of the coal body is slightly earlier than that far away from the center of the coal body, indicating that in the same plane, water first migrates to the center of the coal body and then spreads around.

(4) The stable value of coal resistivity decreases with the increase in water content, but the downward trend gradually slows down. When the water content exceeds 10%, the resistivity basically does not change with the change in water content, and the stable value of coal resistivity ρ and water content w satisfy the exponential function relationship.

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