Response characteristics of the resistivity and water content during the imbibition process in remolded coal without gas

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Abstract

The water content distribution in a coal body is closely related to the gas distribution. It is difficult to directly determine the water content distribution in the process of water imbibition. To retrieve the water content by the resistivity value and establish a relationship between the resistivity and water content, the response characteristics of the resistivity and water content of remolded coal formed under different loads are studied by a self-designed resistivity experimental system. The results show that the resistivity of the remolded coal decreases over time during the imbibition process, including a rapidly decreasing stage and a slowly decreasing stage. The resistivity of the remolded coal is related to the water in the macropore in the rapidly decreasing stage. In the slowly decreasing stage, the resistivity is related to the contact between coal particles. The pressing load, imbibition range, and imbibition speed are negatively correlated with porosity. The resistivity of the steady state is also negatively correlated with the water content and pressing load. The relationship between the resistivity of the steady state and the water content fit a power function. This study reveals the law of resistivity and the water content during the imbibition process and provides an effective methodology to bridge the gap for measuring water content distribution during the imbibition process.

KEYWORDS

imbibition, pressing load, remolded coal, resistivity, water content

1 | INTRODUCTION

Adsorbed state methane and free-state methane exist in coal bodies, and the adsorbed state usually accounts for more than 80% of these forms.1-3 Coal-bed methane has been increasingly recognized as a type of clean, unconventional natural gas resource.4-6 Therefore, it is very important to promote the conversion of adsorbed gas into free gas. However, most of the mines in China, India, and a few other countries are in a physical environment of high in situ stress and low permeability, with the mining depth increasing at a rate of 10-25 m/a.7-11 A series of hydraulic measures, including hydraulic fracturing,12-14 hydraulic slotting,15-17 and hydraulic flushing18-21 can promote the development of fractures and pores in the coal reservoir, which effectively improve the gas extraction rate. However, coal seam water injection technology for regional outburst elimination measures was cancelled in the Regulations on Prevention and Control of Coal and Gas Outburst promulgated by the Chinese Government in 2009. The reason for the cancellation was because the mechanism of controlling gas via coal seam water injection is unclear.
To elucidate the mechanism of coal seam water injection for preventing coal and gas outbursts, the complex comprehensive function process of water affecting the gas should be separated to research the mechanism and contribution degree of the single factor. Wang et al. proposed that the process of coal seam water injection is actually the process of imbibition. The concept of imbibition is the process of replacing non-wetting-phase fluids with wetting-phase fluids via capillary forces. Coal is conventionally known as a naturally fractured dual porosity medium that consists of micropores, mesopores, and macropores. The micro-porous and macro-porous fractures can then form a capillary network. Therefore, some water can be adsorbed under the capillary force action, and some gas can be replaced in the process of imbibition which is mainly attributed to the capillary effect and competitive adsorption. Yue et al. used a self-designed imbibition experimental device to analyze the imbibition effect in remolded coal containing methane under the condition of different water contents and adsorption equilibrium pressures. The results showed that adding water can replace the adsorbed gas. Since there are oxygen-containing functional groups in the coal and the hydrogen bond of water, water can easily occupy the high-energy sites, so only the low-energy site is available for methane. It can be seen that adding water imbibition in remolded coal containing methane can promote gas desorption and eliminate coal and gas outburst danger.

The imbibition effects obtained above, such as the imbibition quantity and the imbibition rate, are evaluated on the basis of the average water content. The wetting degree differs in the remolded coal after the process of imbibition is over. That is to say, the water content distribution differs between in the experimental coal samples. The gas content may vary in different wet areas because the ability of coal adsorb water molecule is greater than that of coal adsorb methane molecule. Therefore, the gas content may vary in different wet areas. For example, the water content distribution around the borehole is different during the implementation of coal seam water injection, and the amount of residual gas content around the borehole may be different at different distances. Therefore, the study of water distribution is of great significance to the development of coal seam water injection technology.

There are many ways to test the water content in coal, including the drying method, the nuclear magnetic resonance (NMR) method, the infrared method, the microwave method, the ray method, and the resistivity method. Yue et al. tested the axial and radial water content distribution in remolded coal using the drying method and the parallel sample method based on a saturated bottom water spontaneous imbibition test device. The axial water content distribution refers to the water content distribution along the axial (vertical) height of the remolded coal, and the radial water content distribution refers to the water content distribution along the radius direction of the same section. The test results show that the relationship between the water content and the axial (vertical) height can be described with a Boltzmann function that has a shape similar to an inverted S-curve and that the capillary force is the driving force of water transportation. However, real-time monitoring of the water content cannot be realized by the test device. Chen found that interstitial water, pore water, adsorbed water, and internal adsorbed water were present in lignite slurry based on the drying method. The drying method is a destructive method, so continuous observation is not possible. The NMR method is a nondestructive method. However, NMR system has an echo time, the minimum of which is 5.885 ms. The imaging test system cannot monitor the water signal with a relaxation time less than 5.885 ms. The infrared method testing water content is based on Bill's law. When the infrared method is used to detect the water content in the coal body, nonmoisture components in the coal also absorb infrared rays, which results in a deviation of the measurement results. The microwave method and ray method then detect a low moisture content. When the microwave method and ray method are used to detect the water content in the coal body, the steel coal sample tank absorbs energy. The resistivity method is a classical and nondestructive method that can be used to test the water content in the process of imbibition and to realize real-time monitoring. Our objective was to evaluate the water content distribution in the remolded coal. Therefore, inversion of the water content via the resistivity value remains to be reported. The relationship determined by calibration test was applied to determine the water content distribution during capillary imbibition. Therefore, an investigation of the response characteristics of the resistivity and water content during the imbibition process can provide a theoretical foundation for studying the water content distribution of remolded coal in the process of imbibition.

### 2. SPONTANEOUS WATER IMBIBITION CONDUCTIVITY MODEL IN REMOLDED COAL

Coal is a typical fracture-pore matrix, so some fluids can permeate and diffuse in space. Remolded coal can be seen as a dual porosity model. The micropores and macropores are represented by the subscripts \( m \) and \( M \), respectively. The average water saturation in remolded coal can be calculated using Equations (1) and (2).

\[
S_w = \lambda_m S_m + \lambda_M S_M
\]  
\[
\lambda_m + \lambda_M = 1
\]
where $\lambda_m$ and $\lambda_M$ are the volume fractions of the micropores and macropores, respectively; $S_w$ is the average water saturation; and $S_m$ and $S_M$ are the water saturation in the micropores and macropores, respectively.

When $S_W \geq S_1$, $S_m = 1$, and Equation (1) can be changed into Equation (3). 58 $S_1$ is the critical water saturation.

$$S_M = (S_w + \lambda_M - 1)/\lambda_M$$

(3)

When $S_W < S_1$, $S_m = S_w/S_2$ and Equation (1) can be changed into Equation (4). $S_2$ is the average water saturation at which the micropore is invaded.

$$S_M = (S_w + S_m - 1)/(\lambda_M S_2)$$

(4)

Equations (1) and (4) are the water saturations for the two cases. There is a close relationship between the conductivity of the remolded coal and the pore system.

When the water saturation of the remolded coal is equal to 100%, the conductivity of the remolded coal can be described by Equation (5).

$$f_0 = f_1 + f_2 = (1 + a)f_2$$

(5)

$$a = f_1/f_2$$

(6)

where $f_0$ is the conductivity of the remolded coal when 100% saturated, $S/m$; $f_1$ and $f_2$ are the conductivities of the remolded coal at the micropores and macropores, respectively, $S/m$.

The conductivities of the two cases can be described by Equations (7) and (8). $f_1$ is the conductivity of the remolded coal at any water saturation. $n_M$ and $n_m$ are the saturation exponents for the macropores and micropores, respectively.

For $S_W \geq S_1$

$$f_1 = S_m^{n_m} f_2 + f_1$$

(7)

For $S_W < S_1$

$$f_1 = S_m^{n_m} f_1 + S_M^{n_M} f_2$$

(8)

The resistivity index can be described by Equation (9). 59 Equation (9) was Archie’s equation, which was proposed by GE Archie, an oil logging engineer at the Shell Company in the United States.

$$RI = R_t/R_0 = f_0/f_1$$

(9)

where $RI$ is the resistivity index; $R_t$ is the resistivity at any water saturation, $\Omega \cdot m$; $R_0$ is the resistivity of the remolded coal in 100% saturated water, $\Omega \cdot m$; $f_0$ is the conductivity of remolded coal in 100% saturated water, $S/m$; $f_1$ is the conductivity of the remolded coal at any water saturation, $S/m$.

For $S_W \geq S_1$

$$R_t = \frac{1 + a}{S_M^{n_M} + a} R_0$$

(10)

Substituting Equation (3) into Equation (10), Equation (11) can be obtained.

$$R_t = \frac{1 + a}{((S_w + \lambda_M - 1)/\lambda_M)^{n_w} + a} R_0$$

(11)

For $S_W < S_1$

$$R_t = \frac{1 + a}{a S_m^{n_m} + S_M^{n_M}} R_0$$

(12)

Substituting Equation (4) into Equation (12), Equation (13) can be obtained.

$$R_t = \frac{1 + a}{a S_m^{n_m} + (S_w(S_2 + \lambda_M - 1)/(\lambda_M S_2))^{n_w} R_0}$$

(13)

Equations (11) and (13) are the resistivity at any water saturation for the two cases.

### 3 | MATERIALS AND METHODOLOGY

#### 3.1 | Experimental coal samples preparation

The experimental coal samples were taken from the Jiulishan coal mine in Jiaozuo, China. The location of the investigated coal mine and the structural outline of the Jiulishan coal mine are shown in Figure 1.

The geological structure of the Jiulishan coal mine is as follows. The Jiulishan coal mine is a monoclinal structure that runs toward N40°E and tends toward the South East (SE). The coal mine field structure is dominated by faults, and the folds are not developed. There are two groups of large and medium-sized faults in the minefield, all of which are high-angle normal faults. One is the Mafangquan fault, and the others are the Fangzhuang fault and Beibei village fault, the former of which cut by the latter.

The coal rank of the experimental coal samples belongs to anthracite. The main mining coal seam in the Jiulishan coal mine is the Second-1 coal seam. The experimental coal samples are obtained from the Second-1 coal seam and are typical tectonic coal, which is shown in Figure 2. The $f$ value of the coal samples is 0.46, which is called the Protodyakonov coefficient and is tested by the drop hammer method. The definition of tectonic coal is that the coal seam is subjected to a tectonic stress, and its primary structure is destroyed by strong cracking, resulting in such tectonic changes as fragmentation, rubbing, polishing surface, etc. Tectonic coal belongs to strongly destructive coal.
(III), which is based on the specification for the identification of coal and gas outburst mines. The strongly destructive coal (III) can be ground into powder by hand and is low in hardness. The lustre of the coal samples is bright and semi-bright.

The experimental coal samples used in this paper are remolded coals that are 50 mm in diameter and 30 mm in height. The reasons for choosing remolded coal as the experimental coal samples in this paper are as follows. The experimental coal samples used in this paper are tectonic coal which belongs to strongly destructive coal (III) based on the specification for the identification of coal and gas outburst mines. The experimental coal samples also belong to soft coal. Tectonic coal is not only closely linked to coal and gas outbursts but also is a necessary condition for some outbursts; namely, tectonic coal is prone to occurring coal and gas outbursts. The columnar coal core is difficult to obtain from the tectonic coal. However, the primary structure coal is not prone to occurring coal and gas outburst. The original occurrence state of tectonic coal is in the whole block state. To fully simulate the original occurrence state, this paper chose remolded coal as the research object.

The experimental coal samples are made using the WES-1000B hydraulic universal testing machine, which is controlled by a servo test system. The main production processes of the experimental coal samples are as follows.
1. The coal samples collected from the working face are crushed by a grinder and then screened by a vibrating screen. Coal samples with diameters of less than 0.25 mm are obtained. Then, the coal samples are put into a vacuum system for vacuum degassing. Some gas can be desorbed and extracted from the coal sample tank under the negative pressure. When the indication of the vacuum gauge is less than 20 Pa, it is considered to have finished vacuuming. The coal samples are then taken out from the coal sample tank. At this point, the coal samples taken out from the coal sample tank are considered to be without methane.

2. The coal samples with diameters of less than 0.25 mm are mixed with 5% pure water, and the wet coal samples are stirred thoroughly. The self-made briquette mold is used to make the remolded coal samples. The briquette mold includes three parts, namely, the hollow cylinder, the tamping head, and the retreat mold cylinder. The schematic diagram of the self-made briquette mold is shown in Figure 3.

3. The wet coal samples are added to the hollow cylinder. The WES-1000B hydraulic universal testing machine is used to compress the coal samples under a load pressure of 12 MPa for 30 minutes. The resulting remolded coal sample is 50 mm in diameter and 30 mm in height, as shown in Figure 4.

4. Remolded coal samples under four pressing loads are used in this paper. Therefore, steps (2) and (3) are repeated with the load with pressures 12 MPa, 16 MPa, 20 MPa, and 24 MPa. Some remolded coals formed under different loads are made for later use.

3.2 | The porosity of the remolded coal

The porosity of the remolded coal is evaluated using the Chinese national standards (MT/T 918-2002 and GB/T 217). The Chinese national standard (MT/T 918-2002) is used to measure the apparent relative density (ARD), and the Chinese national standard (GB/T 217) is used to measure the true relative density (TRD). The parameters of ARD and TRD are shown in Table 1. The equation for calculating the porosity of remolded coal is shown in Equation (14).

$$\phi = \frac{(\text{TRD} - \text{ARD}) \times 100}{\text{TRD}}$$  \hspace{1cm} (14)$$

where $\phi$ is the porosity, %; TRD is the true relative density, g/cm$^3$; ARD is the apparent relative density, g/cm$^3$.

The relationship curve between the pressing load and porosity is shown in Figure 5. As shown in Figure 5, the greater pressing load can result in a smaller porosity of the remolded coal. The larger the pressing load is, the closer the contact between the particles is. The relationship between the pressing load and the porosity can be described by Equation (15), which is a negative exponential function.

$$\phi = 0.4823e^{-0.1924R} \hspace{1cm} (R^2 = 0.98713)$$  \hspace{1cm} (15)$$

3.3 | Experimental device

The experiments are conducted using a self-made experimental device, which includes an Agilent data acquisition instrument, electrode slices, wires, a gripper, an infusion tube, and a water bottle. The schematic diagram of the
The experimental device is shown in Figure 6. The Agilent data acquisition instrument is a multifunctional online resistance measuring instrument including an external digital multimeter, an oscilloscope, a counter, and a power supply. The model of the Agilent data acquisition instrument is 37970A. The scanning time can be set artificially to test the resistance based on the time required for the experiment. The range of the Agilent data acquisition instrument is between 0 Ω and 120 M Ω. The data acquisition board has 20 channels.

3.4 | Experimental methods

1. To remove the water from the coal samples so that it does not affect the test results, the remolded coal samples are placed in an oven at a constant temperature of 378.15 K. During drying, the coal samples are weighed every 20 minutes until their weight is stabilized, after which the coal samples are stored in a dry container for later use.

2. A hole 10 mm in diameter and 10 mm in depth is drilled in the middle position of the remolded coal side. The remolded coal sample after treatment is shown in Figure 7.

3. Assembling the electrode slices and the remolded coal.
   ① The electrode slice is 50 mm in diameter and 0.1 mm in thickness. One side of the electrode slice is connected with one end of the remolded coal through the conductive paste. The other side of the electrode slice is connected with the acrylic board, and the centre of the other side of the electrode slice is connected with the wire, which is shown in Figure 8. ② The other end of the remolded coal is also treated according to the above method. ③ The remolded coal, acrylic boards, and wires are placed in an acrylic transparent glass tube, which is 60 mm in its external diameter, 50 mm in the length, and 3 mm in its wall thickness. There is a hole in the middle of the acrylic transparent glass tube side that is 10 mm in diameter. The centre of the hole in the middle position of the remolded coal side and the acrylic transparent glass tube side is in a straight line. ④ The wood stops are stuffed into the acrylic transparent glass tube. To make the electrode slice completely contact the remolded coal, a gripper is used to clamp the wood stops, and the wire is passed through the gripper. The assembled experimental coal sample is shown in Figure 8.

4. Adding water to the water bottle. The remolded coal is weighed, and the quality of water added to the water bottle can be obtained by the quality of remolded coal multiplied by the water content (4%, 6%, 8%, and 10%). After the quality of water is weighed, the water is added to the water bottle via a syringe.

5. Adding water to the remolded coal: For the purpose of simulating the occurrence temperature of the original coal seam, the test temperature is set at 303.15 K, which is controlled by a constant temperature and a humidity instrument. After a certain amount of water is added to the water bottle, one end of the infusion tube is connected with the water bottle. The other end of the infusion tube is then connected with a rubber stopper. The function of the rubber plug is to prevent water evaporation. After all of the water supply in the bottle is adsorbed, the water content of the remolded coal achieves the predefined the water content.

6. The wires are connected with the connection terminal. The Agilent data acquisition instrument is opened. The test data can be automatically recorded during each subsequent of time.

7. Calculation of resistivity. The data obtained from the test are resistance. Therefore, the resistance should be converted into resistivity. The resistivity can be calculated by Equation (16).

\[
\rho = \frac{RS}{L} \quad (16)
\]
RESULTS AND DISCUSSION

4.1 Wetting mechanism and imbibition range of remolded coal

The concept of wetting is a phenomenon in which the phase in a fluid is dispersed on the solid surface in a gas–liquid–solid or liquid–liquid–solid three-phase system to reduce the total interfacial energy of the system. The degree of wetting is usually expressed by the contact angle and the adhesion work. In the water–gas–coal system, the tangent of the gas–liquid interface is made by the intersection of three phases. The angle between the tangent and the solid–liquid interface is called the contact angle, which is shown in Figure 9. \( \sigma_{gl}, \sigma_{gs}, \) and \( \sigma_{ls} \) are the interfacial tensions of the water–gas, gas–solid, and water–solid interfaces, respectively.

For \( \theta > 90^\circ \), the remolded coal can be wetted by gas. For \( \theta = 90^\circ \), the ability of gas–water wetting to remolded coal is comparable and belongs to neutral wetting. For \( \theta < 90^\circ \), the remolded coal can be wetted by water. When the three phrases reach the equilibrium state, the Equation (17) can be obtained.

\[
\sigma_{gs} = \sigma_{ls} + \sigma_{gl} \cos \theta \tag{17}
\]

where \( \sigma_{gl} \) is the interfacial tension between the water and gas, N/m; \( \theta \) is the contact angle, °; \( \sigma_{gs} \) is the interfacial tension between the gas and solid, N/m; and \( \sigma_{ls} \) is the interfacial tension between the liquid and solid, N/m.

Capillary water adsorption can be described by Equation (18) which is the Hagen–Poiseuille Equation.\(^6\) Fries and Dreyer\(^6\) presented the exact solution of the imbibition range, which can be solved using Maple software. The imbibition range of water can be described by Equation (19). From the properties of Equation (19), the imbibition range of water increases with increasing imbibition time. However, the increase rate gradually decreases. When the capillary force, gravity force, and viscous force reach an equilibrium state, the value of the imbibition range reaches a maximum.

\[
\frac{dH}{dt} = \frac{r^2}{32 \mu h} \left( \frac{4 \sigma \cos \theta}{r} - \rho g H \right) \tag{18}
\]

\[
H = \frac{a}{b} \left[ 1 + \frac{1}{W \left( -e^{-1.5/e^2} \right)} \right] \tag{19}
\]
where $a = \frac{r \cos \theta}{4 \mu}$, $b = \frac{\rho g r^2}{4 \mu}$, $W(x)$ is the Lambert W function, which is shown in Figure 10, $t$ is the imbibition time, hours; $H$ is the imbibition range of water, m; $r$ is the capillary radius, m; $\theta$ is the contact angle, °; $\mu$ is the viscosity coefficient, Pa⋅s; $g$ is the gravitational acceleration, m/s$^2$; and $\rho$ is the liquids density, kg/m$^3$.

4.2 | Analysis of the effect of water content on the resistivity

This experiment tested the resistivity of the remolded coal with water contents of 4%, 6%, 8%, and 10% and loads with pressures 12 MPa, 16 MPa, 20 MPa, and 24 MPa. The resistivity of the remolded coal under the conditions of different water contents is shown in Figure 11. As shown in Figure 11, when water does not intrude into the remolded coal, the resistance of the remolded coal exceeds the test range of the Agilent data acquisition instrument, which can measure a maximal value of 120 MΩ. The remolded coal has a high resistance and can be regarded as nonconductive. The water has a low resistance and is a benign conductor. When the porous media material and liquid water are in a system, the resistance of the porous media material will change. The contact angle is 65°, which is measured by the pendant drop method. According to the wetting mechanism of the remolded coal described above, the remolded coal can easily be wetted by water. When the remolded coal is in contact with the water, the air in the remolded coal filling the porosity is replaced by the water without applying any external force. As the imbibition time increases, the water saturation increases in the remolded coal, and the resistivity of the remolded coal can be tested.

There are two main factors affecting the current passing through the remolded coal: the quantity or concentration of conductive ions in the remolded coal and the transport rate of the carriers under the action of an applied electric field. The change in the resistivity with the water content is due to the change of the carriers. The resistivity of the remolded coal then decreases with increasing time. The cause of this phenomenon is that the imbibition range of water and the average water saturation gradually increase under the action of gravity, capillary forces, and viscous forces. The transport rate of the carrier increases with increasing imbibition range and average water saturation. The resistivity curves can be divided into two stages, namely, the rapidly decreasing stage and the slowly decreasing stage. The cause of the rapidly decreasing stage is that the remolded has a larger matrix potential, which results in the water being adsorbed quickly. The water and movable water mainly exist in the macropore, and the water saturation in the remolded is greater than the critical saturation. The pathways are easily formed at both ends of the electrode. According to Equation (11), the resistivity of the remolded coal decreases with increasing water saturation. The cause of the slowly decreasing stage is that the matrix potential decreases with increasing water content. The water in the macropore is then gradually adsorbed by the micropores, and the movable water gradually decreases. The water saturation of the remolded coal gradually becomes smaller than the critical saturation. The conductivity of the remolded coal mainly depends on the contact between the particles. Although the water saturation of the remolded coal gradually becomes smaller than the critical saturation, the water saturation of the remolded coal increases. Therefore, according to Equation (13), the resistivity of the remolded coal also decreases with increasing water saturation. Finally, the resistivity of the coal body reaches a relatively stable state. As shown in Figure 11, under the same load pressure, the resistivity of the relatively steady state decreases with increasing water content.

To reveal the effect of the water content on the resistivity, the relation curves of the resistivity and time in Figure 11 are fitted. The resistivity of the remolded coal and time meet the exponential function which is shown in Equation (20). As shown in Figure 11, the resistivity of the remolded coal decreases very slowly in the later stage. Therefore, it is very difficult to test the resistivity when the resistivity does not change. Additionally, Equation (20) has a limit value. When the limit of Equation (20) is solved, the value of Equation (20) can be obtained, whose limit value is $a$. The value of
a can be considered to be the resistivity of steady state. The fitting parameters of the relationship between the resistivity and time are shown in Table 2.

\[ \rho = a + bc^t \]  

where \( a, b, \) and \( c \) are fitting parameters; \( \rho \) is the resistivity, \( \text{M}\Omega \cdot \text{m} \); and \( t \) is the imbibition time, hours.

The relationship between the resistivity of the steady state and water content is shown in Figure 12, and the fitting parameters are shown in Table 3. As shown in Figure 12, the resistivity of the steady state decreases with increasing water content under the same pressing load. The relationship between the resistivity of the steady state and the water content can be described by the power function, which is shown in Equation (21). Equation (21) can be used to estimate the water content distribution the remolded coal formed under the same pressing load during the imbibition process.

\[ \rho_s = a_1 w^{b_1} \]  

where \( \rho_s \) is the resistivity of steady state, \( \text{M}\Omega \cdot \text{m} \); \( w \) is the water content, %; and \( a_1 \) and \( b_1 \) are the fitting parameters.

### 4.3 Analysis of the effect of the pressing load on the resistivity

This experiment also tested the resistivity of the remolded coal with load pressures of 12 MPa, 16 MPa, 20 MPa, and 24 MPa and water contents of 4%, 6%, 8%, and 10%. The resistivities of the remolded coal under the conditions of different load pressures of 12 MPa, 16 MPa, 20 MPa, and 24 MPa are shown in Figure 13.

As shown in Figure 13, the resistivity of the remolded coal decreases with increasing amount of time under the same water content supply and load because the amount of capillary water adsorption of the remolded coal gradually increases over time. Figure 13 also indicates that the resistivity of the remolded coal decreases with increasing load under the same water content. The resistivity curve also has two stages, namely, the rapidly decreasing stage and the slowly decreasing stage. The greater the pressing load, the faster the resistivity decreases during the rapidly decreasing stage. The reasons for this phenomenon are as follows. The greater pressing load can result in a smaller porosity of the remolded coal. The remolded coal can be assumed as a straight capillary bundle model because the remolded coal is a dual porosity medium that has an abundant capillary network. When porous media is taken as the object of study, many scholars assume that it is a straight capillary bundle model. As shown in Figure 5, a greater pressing load can result in a smaller porosity of the remolded coal. The

**FIGURE 11** Resistivity of the remolded coal with different water contents
smaller porosity of the remolded coal can result in a smaller capillary radius. According to Equation (22), the contact angle and interface tension are the same, and a smaller capillary radius can result in a larger capillary force. Compared to remolded coals under different pressing loads, the speed of the imbibition is fast under a larger pressing load. As time going on, the greater the pressing load, the larger the wetting range. Therefore, the resistivity of the remolded coal decreases with increasing pressing load under the same water content. Finally, the resistivity of coal body also reaches a stable state, which is shown in Figure 13.

\[ P_c = \frac{2\sigma \cos \theta}{r} \]  

where \( P_c \) is the capillary pressure, Pa; \( \sigma \) is the interface tension, N/m; and \( r \) is the capillary radius, m.

The effect of load with pressures 12 MPa, 16 MPa, 20 MPa, and 24 MPa on the resistivity of the steady state can be obtained from Table 2. The relationship curve between the resistivity of the steady state and the load with pressures 12 MPa, 16 MPa, 20 MPa, and 24 MPa is shown in Figure 14. The relationship between the resistivity of the steady state and the load can be described by Equations (23) and (24). The fitting parameters are shown in Table 4. Substituting Equations (23) and (24) into Equation (15), Equation (24) can be obtained, which shows the relationship between the porosity and resistivity of steady state. The resistivity of the steady state decreases with increasing pressing load under the same water content because a greater pressing load can result in a smaller porosity of remolded coal, which has a greater imbibition range. Therefore, the remolded coal has a larger wetting range.

\[ \rho_s = A\delta^B \]  

**TABLE 2** Fitting parameters of the relationship between resistivity and time

| Pressing load (MPa) | Water content (%) | \( a \)   | \( b \)   | \( c \)   | \( R^2 \)   |
|---------------------|------------------|-----------|-----------|-----------|-------------|
| 12                  | 4                | 1.53307   | 4.74276   | 0.95855   | 0.98321     |
|                     | 6                | 1.20538   | 2.90159   | 0.90951   | 0.94222     |
|                     | 8                | 0.7867    | 5.25608   | 0.96917   | 0.98836     |
|                     | 10               | 0.68424   | 2.46634   | 0.94638   | 0.98058     |
| 16                  | 4                | 1.11472   | 4.725     | 0.95377   | 0.9943      |
|                     | 6                | 0.93604   | 2.18702   | 0.94254   | 0.96543     |
|                     | 8                | 0.74044   | 12.10269  | 0.88184   | 0.9977      |
|                     | 10               | 0.62948   | 2.36887   | 0.87594   | 0.93492     |
| 20                  | 4                | 0.90564   | 3.86202   | 0.95582   | 0.99013     |
|                     | 6                | 0.85654   | 4.1569    | 0.85041   | 0.95437     |
|                     | 8                | 0.64847   | 4.15821   | 0.86208   | 0.91335     |
|                     | 10               | 0.5468    | 2.01887   | 0.71862   | 0.93454     |
| 24                  | 4                | 0.66384   | 7.43197   | 0.7223    | 0.98444     |
|                     | 6                | 0.47377   | 6.18873   | 0.80951   | 0.98858     |
|                     | 8                | 0.44643   | 8.137965  | 0.54458   | 0.97066     |
|                     | 10               | 0.24818   | 15.05171  | 0.21303   | 0.98769     |

**TABLE 3** Fitting parameters of the relationship between the resistivity of the steady state and time

| Pressing load (MPa) | \( a_1 \) | \( b_1 \) | \( R^2 \) |
|---------------------|-----------|-----------|-----------|
| 12                  | 5.3048    | −0.8179   | 0.94339   |
| 16                  | 2.6186    | −0.603    | 0.9646    |
| 20                  | 1.9313    | −0.516    | 0.89988   |
| 24                  | 2.1586    | −0.841    | 0.8420    |
where $A$ and $B$ are the fitting parameters.

### 4.4 Discussion of the application test

The imbibition process of the remolded coal is a continuous and invisible process. Therefore, it is difficult to study the water distribution during the process of imbibition. If we want to determine the water content distribution during the imbibition process, the remolded coal should be monitored continuously and dynamically. Some test methods, including the drying method, NMR method, infrared method, microwave method, and ray method, have some drawbacks in testing the water content distribution of remolded coal, which was analyzed in the introduction section. Therefore, the method of measuring the water content distribution of remolded coal by resistivity method is proposed, which can be used to realize real-time monitoring. In the process of remolded coal imbibition, it is necessary to arrange the electrodes inside the remolded coal to test the water content distribution. At the same height section, the electrodes can be arranged by cross section, which is shown in Figure 15. The electrodes were connected with the Agilent data acquisition instrument. As is shown in Figure 15A, the remolded coal

\[
\rho_s = A \left( \frac{\phi}{0.4823} \right)^{-5.1975B}
\]

TABLE 4 Fitting parameters of the relationship between the resistivity of the steady state and the pressing load

| Pressing load (MPa) | $A$     | $B$     |
|---------------------|---------|---------|
| 12                  | 25.62498| -1.13148|
| 16                  | 16.20803| -1.0363 |
| 20                  | 4.17849 | 4.17849 |
| 24                  | 7.85279 | -0.65286|
has four electrode layers of. As is shown in Figure 15B, each layer of electrode has nine measuring points. Two adjacent test points are a complete test channel. Therefore, there are eight channels in each layer. Top-down or bottom-up imbibition can be achieved by adding water through the upper or lower nozzle of the coal sample tank, which can simulate either the water imbibition top-down or bottom-up imbibition process of water injection boreholes. If the coal sample tank is placed horizontally, it can simulate the left and right imbibition process of water injection boreholes. The resistances of the two measuring points \((a_1 \sim a_2, a_2 \sim a_3, a_3 \sim a_4, a_4 \sim a_5, a_1 \sim b_2, b_2 \sim b_1, a_1 \sim b_2, b_2 \sim b_1, a_3 \sim b_3, b_3 \sim b_4)\) can be obtained during the process of imbibition. The resistivity of the two measuring points \((a_1 \sim a_2, a_2 \sim a_3, a_3 \sim a_4, a_4 \sim a_5, a_3 \sim b_2, b_2 \sim b_1, a_3 \sim b_3, b_3 \sim b_4)\) can be calculated by Equation (16). In practical application tests, the number of measurement layers and the number of measurement electrodes can be determined according to the test requirements.

The inversion of the resistivity value to the water content needs to establish the corresponding relationship between the resistivity and water content in advance, which is the aim of this paper. Using the relationship between the resistivity and water content obtained in the laboratory, namely, Equation (21) and Table 3, the water content distribution can be determined during the process of the remolded coal imbibition. That is to say, it can be used to invert the water content distribution during the process of remolded coal imbibition. This method is of great significance to the study of adding water imbibition in porous media. The adsorption quantity can be obtained by the adsorption experiments, and the imbibition quantity under different water content conditions can be obtained by the imbibition experiments. The residual gas amount is equal to adsorption quantity minus the imbibition quantity under different water content conditions. By changing the direction of adding water addition, the imbibition can be realized in different directions, and the direction of the imbibition around the water injection borehole can be simulated. Finally, the distribution law of the residual gas content in different water content areas can be grasped.

5 | CONCLUSIONS

Water content distribution in a coal body is closely related to the gas distribution. To retrieve the water content via the resistivity value and bridge the gap for analyzing the water content distribution during the imbibition process, the response characteristics of resistivity and water were studied by a self-designed resistivity experimental system. Some major conclusions can be drawn from this paper.

1. The resistivity at any water saturation was deduced based on the dual porosity model when the water entered the micropores and macropores. The wetting mechanism and imbibition range of the remolded coal imbibition were then revealed. The pressing load, imbibition range, and imbibition speed are negatively correlated with the porosity.

2. The resistivity of the remolded coal decreases with increasing time during the imbibition process, which can be divided into the rapidly decreasing stage and the slowly decreasing stage. During the rapidly decreasing stage, the resistivity of the remolded coal is related to the water in the macropore. During the slowly decreasing stage, the resistivity is related to the contact between coal particles. The resistivity of the remolded coal and the time fit an exponential function during the imbibition process.

3. The resistivity of the steady state is negatively correlated with the water content and pressing load, respectively. With increasing water content, the resistivity of the steady state exhibits a decreasing trend under the same load. With increasing pressing load, the resistivity of the steady state exhibits a decreasing trend under the same water content, and the relationship between the resistivity of the steady state and the water content can be described by the power function.

4. As for future perspectives of this work, with the knowledge of the specific relationship between the resistivity and water content, this method can be applied together
with the resistivity experimental system during the process of remolded coal imbibition to obtain the water content distribution during the imbibition process.

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CONFLICT OF INTEREST

The authors have declared no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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