Research Article

Complex Resistivity Dispersion Characteristics of Water-Bearing Coal Based on Double Cole-Cole Model

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Reservoir fracture evaluation is an important research topic in the coalfield. In recent years, complex resistivity (CR) has been widely used in oil logging and achieved good results, such as permeability evaluation, water saturation (Sw) prediction, and aquifer identification. Therefore, the method has the potential to evaluate coal seam fracture. In the experiment, the real part $R$ and imaginary part $X$ of bituminous and anthracite coal with different Sw were measured by the impedance measuring instrument, then the Double Cole-Cole model was used to fit experimental data and analyze conductive mechanism. The main results are as follows: (1) the dispersion of CR parameters $R_{\rho}$ and $I_{\rho}$ is closely related to the metamorphism degree, frequency, and Sw; (2) induced polarization is the fundamental reason for the variation of coal samples’ complex resistivity parameters with frequency change; and (3) the Double Cole-Cole model agrees well with the experimental data, and the model parameters $m_1$ and $\tau_2$ are strongly correlated with Sw. The parameters $m_1$ and $\tau_2$ can be used to evaluate the Sw of fractures in coal seams and thus to evaluate the effect of hydraulic fracturing.

1. Introduction

Coalbed methane extraction guarantees to prevent gas accidents and improve the utilization rate of mine resources. At present, hydraulic fracturing [1] and other fracturing measures [2] are mainly adopted to increase the permeability of low-permeability coal seams in China. The practice has proved that hydraulic fracturing can relieve the coal seam pressure, increase the permeability, and greatly improve the efficiency of coalbed methane extraction [3]. Many scholars have carried out experimental [4, 5] and theoretical research [6] on hydraulic fracturing, presented some evaluation methods [7, 8] of coal brittleness, and established the relevant theoretical model [7, 9], which can facilitate the field application of coal fracturing. However, there are few studies on the evaluation of hydraulic fracturing effect, since the hydraulic fracturing still remains in the traditional means, such as drilling bits, water content, and other indicators [10]. These parameters are no exception “point evaluation”, which is a localized method to characterize and explore the physical properties of coal but cannot achieve “face evaluation”, which means a comprehensive evaluation method for the whole coal body by the hydraulic fracturing is a must. Thus, it is essential to develop new evaluation methods.

Complex resistivity (CR) is a high density measurement in frequency domain and spatial domain. Compared with other methods, it can obtain more electrical parameters and geoelectric information [11]. The technology has been widely used in many fields such as geological exploration, soil environmental assessment [12], and ocean exploration [13]. Under the action of additional electric field (primary electric field), rocks or ores due to electrochemical action will produce induced polarization (secondary electric field), and
the interval where the secondary electric field lags behind the primary electric one is called relaxation time, which can be obtained by complex resistivity parameters. Because different rocks and ores have different electrochemical properties, so we can find out mineral resources by CR. In 1978, Pelton et al. [14] first applied the Cole-Cole model in the induced polarization of rocks; Luo and Wu [15] applied the Cole-Cole model parameters in mineral resources exploration; Zhao et al. [16] researched the theoretical basis of shale gas exploration with CR; Ke [17] studied the CR logging technology in the field of oil and gas geology; and Qiang and He [18] invented dual frequency-induced polarization method. In recent years, CR has been developed rapidly in the petroleum field. Xiao et al. [19] used CR to evaluate rock wettability and distinguished oil-bearing layer and water-bearing layer; Latt and Giao [20] established a model for predicting the permeability of petroleum reservoir rocks by CR, which matched well with the measured permeability. In the study of CR conductive mechanism, Liu [21] believed that the micromechanism of induced polarization was mainly caused by dielectric polarization and the polarization forms could be divided into electron polarization, atomic polarization, ion polarization, steering polarization, and spatial polarization; Xiao et al. [22] considered that induced polarization mainly occurs in the low-frequency period of the applied alternating electric field, with the increase of frequency, electromagnetic interference gradually increases and dominates and induced polarization gradually weakens, and when the electric field increases to a very high frequency, the polarization form turns into electron polarization.

Electric prospecting technology has evolved quickly since it was applied to the coal mines in China in 1990s. As the most widely used method, the DC method (direct current method) is based on the difference of conductivity between coal and rock strata. Through artificial supply of stable current to the underground, the earth’s current field is observed so as to reveal the law of the physical properties of the rock and ore body. It has achieved good results in mine water disaster prevention [23]. Because of the sensitivity of electrical method to measure water, fracture propagation effect can be reflected by measuring fracture water. However, the DC method cannot reflect the information of induced polarization which is caused by ion accumulation at fracture interface, so the CR is a potential method to evaluate the effect of hydraulic fracturing. Few research studies of CR were carried out in coalfield. Wang et al. [24] tested the resistivity of dry coal samples and wet ones at two frequencies. Guo et al. [25] measured the impedance Z of four metamorphic coal samples at continuous frequency of 0.1–100 kHz, but few research studies were conducted on the CR model. Based on the previous research studies [26], we analyzed the microconducting mechanism of coal-induced polarization, fitted the experimental data by double Cole-Cole model, and found the model parameters have a strong correlation with the coal samples’ water saturation (Sw). This study lays a foundation for the application of CR and the evaluation parameters selection in the coalfield.

2. Materials and Methods

2.1. Materials. In this experiment, bituminous coal and anthracite are selected as research objects. Bituminous coal was collected from Pingdingshan No. 8 Coal Mine in Henan Province, and anthracite coal was selected from Guhanshan Coal Mine in Jiaozuo City, Henan Province. The coal samples were cut into 60 mm × 60 mm × 60 mm blocks. The copper material with good conductivity was selected as an electrode plate material. The copper material was processed into a plate with thickness of 2 mm and area of 65 mm × 65 mm so that the electrode plate completely covered the coal sample. And in order to reduce the face effect, the contact surface of the electrode plate and the coal samples should be polished smoothly. The material objects of the processed coal samples are shown in the Figure 1.

2.2. Measurement Method of Coal Sample Water Saturation. The water saturation (Sw) of coal samples was measured by the gravimetric method. Firstly, put the coal samples in the drying oven and dry them for 12 hours continuously at 105°C, the mass of the dried coal samples was m(d). Secondly, immerse the coal samples in water because they absorb water quickly at the beginning, take them out and weigh them every 6 hours; after 12 hours, they are taken out and weighed every 12 hours, and they could be considered as the saturated after soaking for 72 hours. The mass of the saturated coal samples was m(s). The mass of coal is measured in the electronic balance. Two coal samples’ water immersion mass and Sw are shown in Table 1. Calculating Sw is expressed as the follows:

\[ Sw = \frac{m - m(d)}{m(d) - m(d)} \times 100\% \]  

where \( m \) is the mass of the coal sample after immersion; \( m(s) \) is the mass of fully saturated coal samples; and \( m(d) \) is the mass of completely dry coal samples.

2.3. Measurement Method of Coal Sample CR Parameters. The experimental instrument is the IM3533-01 LCR impedance measuring instrument. The measuring schematic diagram is shown in the Figure 2. The instrument has four terminals: \( H_{\text{CUR}} \) terminal is the current occurrence terminal, \( H_{\text{POT}} \) terminal is the high-voltage detection terminal, \( L_{\text{POT}} \) terminal is the low-voltage detection terminal, and \( L_{\text{CUR}} \) terminal is the current-detection terminal. Before the test, the instrument was first placed in a silent environment and preheated for 1 hour. Then, the instrument was compensated by line, short circuit, and open circuit. After the compensation was completed, the coal sample was placed in the middle of the electrode plate and was in good contact with the plate. The measuring parameters of the instrument were set to CR real part \( R \) and imaginary part \( X \), the measuring mode was a constant current mode, frequency range was 1–200kHz, and the measuring data point was 200. The measurement was started after the setting was completed.
The R and X measured in the experiment were converted into resistivity according to equations (2) and (3). In order to distinguish easily, Reρ is real part resistivity and Imρ is imaginary part resistivity. S is the contact area between coal and plate, m²; L is the distance between two plates, m.

\[
Re\rho = \frac{R \times S}{L}, \quad (2)
\]

\[
Im\rho = \frac{X \times S}{L}. \quad (3)
\]

3. Results and Discussion

3.1. Experimental Result. The experimental results are shown in Figure 3. The abscissa is Reρ and the ordinate is Imρ. Different colors represent different Sw. The frequency of points on each curve increases gradually from left to right.

The influence of coal metamorphism on the measurement results cannot be ignored. Compared with Reρ and Imρ of the bituminous coal sample and anthracite coal sample, the parameters values of the anthracite coal sample are obviously smaller than that of the bituminous coal sample. The reason is that anthracite has a higher metamorphism degree and a more developed benzene ring structure, so it has a better conductivity.

The Reρ-Imρ curve shows obvious dispersion. With the increase of frequency, the Reρ-Imρ curve is divided into three stages: firstly decreasing, then increasing, and finally decreasing. Reρ monotonically decreases with the frequency increase, but Imρ decreases first, then increases and decreases again. It suggests that Imρ can reflect the dispersion characteristics of coal better than Reρ. So, we can fit the model with Imρ curve.

With the increase of Sw, the amplitude of the curve gradually decreases and shifts to the left. The resistivity also gradually decreases with the increase of Sw. It can be explained from two aspects: on the one hand, the soaking time would lead more and more charged ions in coal samples to be dissolved in water to form conductive solution; on the other hand, the longer soaking time, the more cracks in the coal sample contain water, and the more conductive channels formed. The frequency of Imρ curve peak is considered as the characteristic frequency, which increases with the increase of Sw.

3.2. The Research on the Dispersion Mechanism of Coal Sample Complex Resistivity. Induced polarization is the fundamental reason for the variation of coal samples complex resistivity parameters with frequency change. Figure 4(a) is the induced polarization diagram of ore, A and B are power supply electrodes and M and N are measurement electrodes. When power is supplied to the formation, the charge in the ore body will migrate, negative charge will gather on the positive side, and positive charge will gather on the negative side, forming a double electric layer. The induced polarization electric field (secondary electric field) will be generated inside the ore body, as shown in the right figure. The value of the induced polarization electric field will be measured through the MN electrodes, which changes with the frequency of the external electric field. The microforms of induced polarization are interface polarization, orientation polarization, ion polarization, and electron polarization, as shown in Figure 4(c). In the previous study, we introduced these polarization forms in detail [26]. The interfacial polarization is caused by the electric charge accumulation in the coal fracture surface, and the produced double electric layer forms a dipole moment, which is closely related to fractures. As shown in Figure 4(c), the relaxation time of four micropolarizations are \(\tau_{\text{electro displacement polarization}} \leq 10^{8}\text{s}, \tau_{\text{molecule turning polarization}} \leq 10^{14}\text{s}, \tau_{\text{ion displacement polarization}} \leq 10^{11}\text{s}, \text{ and } \tau_{\text{electron displacement polarization}} \leq 10^{16}\text{s}\); in the second part, the frequency band we measured is 1–200 kHz, so the induced polarization of coal in the experiment is mainly caused by the interface polarization, the electric field generated by the dipole moment inside coal is the induced polarization electric field.

3.3. Double Cole-Cole Model Fitting of Imρ Curve of Water-Bearing Coal. At present, Cole-Cole model is the most widely model to describe the induced polarization. In the previous study [26], we fitted the complex resistivity parameters and found that the double Cole-Cole model has a better fitting effect. Therefore, on the basis of this, in order to figure out the relationship between the model parameters and the coal Sw, the Imρ curves of bituminous and anthracite coal are fitted by the double Cole-Cole model, from which the best correlation parameters with the Sw are selected. The parameters serve to predict the water content of the coal seam.

The mathematical expression of the double Cole-Cole model is as follows [14]:

\[
\rho(i\omega) = \rho_0 \left\{ 1 - m_1 \left[ 1 - \frac{1}{1 + (i\omega \tau_1)^{\alpha_1}} \right] \right\} \times \left\{ 1 - m_2 \left[ 1 - \frac{1}{1 + (i\omega \tau_2)^{\alpha_2}} \right] \right\}. \quad (4)
\]

In equation (4), \(\rho_0\) is resistivity on zero frequency; \(m_1\) and \(m_2\) are polarizabilities; \(\tau_1\) and \(\tau_2\) are time constants; and \(c_1\) and \(c_2\) are frequency dependent coefficients. Figure 4 shows the fitting effects of the double Cole-Cole model.

As shown in Figure 5, the points represent the measured data, different colors are different Sw, and lines represent
Table 1: Two coal samples water immersion weight and Sw.

<table>
<thead>
<tr>
<th>Coal grade</th>
<th>Soaking time (h)</th>
<th>m (g)</th>
<th>m(d) (g)</th>
<th>m(s) (g)</th>
<th>m(d) − m(s) (g)</th>
<th>M − m(d) (g)</th>
<th>Sw (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous coal</td>
<td>0</td>
<td>303.2</td>
<td>303.2</td>
<td>315.4</td>
<td>12.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>310.3</td>
<td>310.3</td>
<td>326</td>
<td>6.7</td>
<td>7.1</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>312.5</td>
<td>312.5</td>
<td>329.9</td>
<td>7.4</td>
<td>9.3</td>
<td>76.5</td>
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<tr>
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<td>314.8</td>
<td>327.5</td>
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<td>11.5</td>
<td>94.1</td>
</tr>
<tr>
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<td>36</td>
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<td>314.8</td>
<td>326</td>
<td>8.2</td>
<td>11.6</td>
<td>95.2</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>315</td>
<td>315</td>
<td>332.5</td>
<td>7.5</td>
<td>11.8</td>
<td>97.1</td>
</tr>
<tr>
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<td>60</td>
<td>315.2</td>
<td>315.2</td>
<td>334</td>
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<td>12</td>
<td>98.3</td>
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<td>315.4</td>
<td>315.4</td>
<td>334.2</td>
<td>8.2</td>
<td>12.2</td>
<td>100</td>
</tr>
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<td>Anthracite</td>
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<td>326</td>
<td>334.2</td>
<td>8.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>329.5</td>
<td>329.5</td>
<td>332.5</td>
<td>7.0</td>
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<td>42.1</td>
</tr>
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<td>329.9</td>
<td>333.8</td>
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<td>3.9</td>
<td>47.4</td>
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<td>330.7</td>
<td>334</td>
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<td>334</td>
<td>334.2</td>
<td>8.2</td>
<td>8</td>
<td>97.4</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>334.2</td>
<td>334.2</td>
<td>334.2</td>
<td>8.2</td>
<td>8.2</td>
<td>100</td>
</tr>
</tbody>
</table>

Sw: coal samples’ water saturation.

Figure 2: Schematic diagram of the four-terminal complex resistivity test device.

Figure 3: Rep-Imp dispersion curves of coal complex resistivity with different Sw: (a) bituminous coal; (b) anthracite.
fitting curves by the double Cole-Cole model. When the Sw is small, the fitting of the anthracite coal has a poor effect because in this stage the moisture content is low and leads to less dispersion. When the Sw increases, the curves can be well fitted. For bituminous coal, the double Cole-Cole model can well fit for all Sw curve. The model parameters are
Table 2: Double Cole-Cole model parameters of two kinds of coal resistivity.

<table>
<thead>
<tr>
<th>Coal grade</th>
<th>Sw (%)</th>
<th>ρ (kΩ-m)</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$τ_1$</th>
<th>$τ_2$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous coal</td>
<td>58</td>
<td>44.5</td>
<td>0.40</td>
<td>1</td>
<td>0.56</td>
<td>0.72</td>
<td>0.09</td>
<td>$5.6 \times 10^{-5}$</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>76.5</td>
<td>18.9</td>
<td>0.45</td>
<td>1</td>
<td>0.49</td>
<td>0.70</td>
<td>0.50</td>
<td>$3.3 \times 10^{-5}$</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>94.1</td>
<td>15.4</td>
<td>0.47</td>
<td>1</td>
<td>0.40</td>
<td>0.51</td>
<td>0.30</td>
<td>$2.6 \times 10^{-6}$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>95.2</td>
<td>17.3</td>
<td>0.50</td>
<td>1</td>
<td>0.44</td>
<td>0.52</td>
<td>0.07</td>
<td>$2.2 \times 10^{-6}$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>97.1</td>
<td>14.8</td>
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<td>0.43</td>
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<td>$3.4 \times 10^{-6}$</td>
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<td>0.29</td>
<td>$1.3 \times 10^{-6}$</td>
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</tr>
<tr>
<td></td>
<td>100</td>
<td>14.9</td>
<td>0.63</td>
<td>1</td>
<td>0.26</td>
<td>0.60</td>
<td>1.05</td>
<td>$1 \times 10^{-6}$</td>
<td>0.96</td>
</tr>
<tr>
<td>Anthracite</td>
<td>42.1</td>
<td>1.05</td>
<td>0.10</td>
<td>1</td>
<td>0.10</td>
<td>0.70</td>
<td>0.03</td>
<td>$8 \times 10^{-4}$</td>
<td>0.73</td>
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<tr>
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<td>0.23</td>
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<td>0.94</td>
<td>0.70</td>
<td>0.07</td>
<td>$3 \times 10^{-4}$</td>
<td>0.90</td>
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<tr>
<td></td>
<td>57.9</td>
<td>0.65</td>
<td>0.28</td>
<td>1</td>
<td>0.80</td>
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<td>$1.6 \times 10^{-4}$</td>
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<td>1</td>
<td>0.57</td>
<td>0.43</td>
<td>0.17</td>
<td>$2 \times 10^{-5}$</td>
<td>0.96</td>
</tr>
<tr>
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<td>1</td>
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<td>0.37</td>
<td>0.23</td>
<td>$1 \times 10^{-5}$</td>
<td>0.98</td>
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<td>0.39</td>
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<td>0.40</td>
<td>0.15</td>
<td>$9.1 \times 10^{-6}$</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Figure 6: Continued.
obtained by fitting, as shown in Table 2. In order to find which model parameters have strong correlation with the Sw, we analyzed the relationship between 5 model parameters and Sw, as shown in Figure 6.

Compared with $c_1$, $c_2$, and $\tau_1$, the polarization rate $m_1$ tends to increase monotonously with the increase of Sw; the $\tau_2$ shows a monotonous decreasing trend with the increase of Sw. It is shown that the model parameters $\tau_2$ and $m_1$ have a good correlation with Sw, which is of significance to predict the water content of coal seam. Then, we fitted the two parameters with empirical formulas.

As shown in Figure 7, according to fitted model parameters $m_1$, $\tau_2$, and Sw, it is found that $m_1$ and Sw are in agreement with the logarithmic expression:

$$m_1 = a \times \ln (Sw - b). \quad (5)$$

And $\tau_2$ and Sw coincide with the exponential expression:

$$\tau_2 = e^{-0.168 \times Sw}. \quad (6)$$

Different types of coal have different $a$, which is a constant. It is noted from the fitting results that the double Cole-Cole model parameter $m_1$ conforms to the logarithmic
function with Sw, while $\tau_2$ and Sw conform to the exponential function. In a word, the model parameters $m_1$ and $\tau_2$ have potential in evaluating the coal Sw. In the future research, we can get the model parameters to predict the water content of coal seam so as to evaluate the effect of coal seam hydraulic fracturing.

4. Conclusion

In the paper, we measured the real part $R$ and the imaginary part $X$ of bituminous coal and anthracite, analyzed the dispersion mechanism and fitted data by the double Cole-Cole model. The conclusions are drawn as follows:

(1) The test results show that the dispersion of CR parameters $\text{Rep}$ and $\text{Im} \rho$ is closely related to the metamorphism degree, frequency, and Sw. The parameter values of the anthracite coal sample are obviously smaller than that of the bituminous coal sample; with the increase of frequency, the $\text{Im} \rho$ first decreases, then increases, and finally decreases again, while the $\text{Rep}$ decreases gradually; the $\text{Rep}$ and $\text{Im} \rho$ also gradually decreases with the increase of Sw, and the curve gradually shifts to the left. It suggests that $\text{Im} \rho$ can reflect the dispersion characteristics of coal better than $\text{Rep}$.

(2) The induced polarization is the fundamental reason for the variation of coal samples complex resistivity parameters with frequency change, and the induced polarization of coal in the experiment is mainly caused by the interface polarization; the electric field generated by the dipole moment inside coal is the induced polarization electric field.

(3) The complex resistivity data of coal can be well fitted by the double Cole-Cole model. Analysis of the relationship between the 5 model parameters and Sw finds that the model parameter $m_1$ and $\tau_2$ are monotonically related to Sw, while the other three model parameters have poor correlation with Sw. The relationship between $m_1$ and Sw is well represented by logarithmic function and that between $\tau_2$ and Sw is well represented by exponential function. This study helps to predict the water content of coal seam and evaluate the hydraulic fracturing effect by CR.

Nomenclature

- CR: Complex Resistivity
- Sw: Water saturation of coal sample, %
- $R$: The real part of complex resistivity, $\Omega \cdot m$
- $X$: The imaginary part of complex resistivity, $\Omega \cdot m$
- $\text{Rep}$: Resistivity of $R$, $\Omega \cdot m$
- $\text{Im} \rho$: Resistivity of $X$, $\Omega \cdot m$
- DC method: Direct current method
- $m$: The mass of coal sample after immersion, g
- $m(s)$: The mass of fully saturated coal samples, g
- $m(d)$: The mass of completely dry coal samples, g
- $S$: The contact area between coal and plate, $m^2$
- $L$: The distance between two plates, m
- $\rho_0$: Resistivity on zero frequency
- $m_1$, $m_2$: Polarizability
- $\tau_1$, $\tau_2$: Time constant
- $c_1$, $c_2$: Frequency dependent coefficient.

Data Availability

The data used to support the findings of this study were supplied by author under license and so cannot be made freely available. Requests for access to these data should be made to leidongji@126.com.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

The experiment was carried out under normal temperature and atmospheric pressure; we adopt IM3533-01 impedance measuring instrument, measuring frequency was 1–200 kHz, and the measurement parameters were real part $R$ and imaginary part $X$ of complex resistivity. The first page of the submitted excel file is the data of bituminous coal under different water saturation, the second page is the data of anthracite under different water saturation, and the third page is the model parameters of two coal sample data were fitted with the double Cole-Cole model. (Supplementary Materials)

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