Experimental Study on Characteristics of Reactance Dispersion of Water Bearing Coal

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Abstract

As an emerging geophysical exploration method, complex resistivity method is a potential non-invasive one for evaluating hydrofracturing effect. Reactance X is an important parameter of complex resistivity method. Compared with the traditional parameter resistance R , reactance has advantages such as distinct dispersion characteristics, clear conduction mechanism and rich information. In this paper, reactance X of four kinds of coal sample with different water saturation was tested, their dispersion characteristics were analyzed, and their conductive mechanism was studied. The results show that, (1) the characteristic curve of reactance dispersion presents a three-stage law when the water saturation is low, and a two-stage law when the water saturation is high, to some extent, the water content of coal body and the effect of hydraulic fracturing are distinguished; (2) polarization is the cause of dispersion, in which low frequency is induced polarization, high frequency is dielectric polarization, and electromagnetic induction is the interference phenomenon in the frequency band of induced polarization; (3) spectrum extremum frequency point is sensitive to changed water saturation. Extremum points of different coal rank are concentrated in 100-1000Hz. This frequency band can serve as the dominant frequency band for evaluating coal seam water saturation. This paper gives new insight into the evaluation of coal seam hydrofracturing effect by complex resistivity method.

1 Introduction

Enhancing coal seam permeability is the key to efficient gas drainage and safe coal mining. In recent years, hydrofracturing as a permeability enhancement technology for low permeability oil and gas reservoirs has been widely used in underground coal seam gas drainage (Wang Zhen 2016). In the application of hydrofracturing technology, evaluation of fracturing effect is essential. Present parameters, such as drilling cuttings and water content, are unexceptionally "*point evaluation*" for the potential impact area by hydrofracturing. However, it is difficult to realize "*surface evaluation*" for the whole time-space continuity of fracture propagation in coal and rock mass in the area. Hence, a new evaluation method is imminent.

Complex resistivity method, an emerging geophysical exploration method, realizes high-density measurement of frequency domain and space domain in a wide frequency range. Compared with other geophysical approaches, it can obtain more electrical parameters and geoelectric information, so has attracted the attention of many scholars. The complex resistivity logging method in frequency domain was based on the dispersion characteristics of complex resistivity of coal and rock (Chen, Zhao and Zhu 2001). Many scholars (Tong, Li, Wang et al 2005; Tong, Tao, Ding, Zhang and Zhang 2007; Xiao, Xu, Luo et al 2006; Sun, Tang, Sun and Dou 2006) experimentally studied the complex electric dispersion of argillaceous sandstone. Khairy and Harith (2011) found the effect of pore geometry, confinement pressure and partial water saturation on coal-rock complex electricity. Li et al. (2019) studied the influence of water content of coal and rock and pear type on the electrical recovery. Binley et al. (2005) investigated the complex resistivity response of British sandstone aquifer samples and compared the physical and hydraulic properties with the measured parameters, proving complex resistivity method

could be a potential method to evaluate the effect of coal seam hydrofracturing. Wu et al. (2016) considered that the difference of complex resistivity was caused by the geology and characteristics of the study area, and the aquifer could be distinguished from the coal seam. Zisser et al. (2010) and Revil et al. (2015) used complex resistivity in studying the permeability of coal and rock. Some scholars (Dias. C A 2000; Sacks, Pfeffer, Moye L A, et al .1996; Pelton, Ward, Hallof P.G.et al 1978; Zonge K 1972; Luo, Wu, 1992; Guan, Cheng and Yu 2011) put forward the theory and mathematical model of rock complex electrical dispersion. Personna et al. (2013) measured complex resistivity in the laboratory, and applied Debye decomposition to fit CR data, showing that CR has a potential in monitoring underground organic pollution. Ntarlagiannis et al. (2016) resented that the real and imaginary parts of complex conductivity were consistent with the conceptual model of LNAPL pollutants produced by biodegradation, so electrogeophysical methods could identify and monitor the pollution caused by OOMW.

So far, few studies were made on the complex resistivity of coal at home and abroad. Direct current is mostly used, while the influence of medium polarization in coal is ignored. Studies of complex resistivity of coal (Song, Liu, Wang,Qiu, Gao and Xu 201; SALAM, SOULAYMAN, GIUNTINI J C,et al 1996; Liu, Xu, Xian et al 2004; Xu 2005) mostly use resistivity as measurement parameter for analysis. Guo et al. (2015) found the dominant frequency band in complex resistivity measurement by analyzing the relationship between resistivity and coal physical parameters at the frequency of 100–100 kHz. However, the analysis results are not convincing because of the strong homogeneity of resistivity measurement results. Compared with resistance R, reactance X is of obvious dispersion characteristics, clear conduction mechanism and rich information. Liu et al. (2017) measured the resistance R and reactance X of coal samples with different metamorphic degrees and analyzed their dispersion characteristics, but did not describe their mechanism. Yang (2017) fitted the Debye model of coal reactance X and analyzed its relaxation mechanism, but did not study the effect of different water saturation on dispersion characteristics. In general, the pores of coal skeleton and its non water bearing part have no conductivity and can be regarded as insulator, while the conductive channel formed by solution ions in the pores of coal body is regarded as resistance. Therefore, the pore structure and shape can be characterized by the coal water saturation to a certain extent. In this paper, the reactance X of four kinds of coal with different water saturation was measured, its dispersion characteristics and conductive mechanism were analyzed, which laid a foundation for the application of complex resistivity method in coal field geology and the evaluation of coal seam permeability and hydrofracturing effect.

2 Sample And Experiment

2.1 Sample preparation

In this paper, coal samples of four metamorphic degrees from Hebi, Pingdingshan and Guhanshan mining areas are processed into cubes with 60 mm edges according to the test requirements, and the ends and corners of the samples are polished smoothly and smoothly with sandpaper to ensure full contact between the ends of the coal samples and the conductive plate. Finally, the coal samples are wrapped with fresh-keeping film to prevent oxidation metamorphism.

The water saturation(S_w) of coal samples was measured by the gravimetric method. Firstly, putting the coal samples in the drying oven and drying them for 12 hours continuously at 105 °C, the weight of the dried coal samples was $m(d)$. Secondly, immersing the coal samples in water, because they absorb water quickly at the beginning, taking out and weigh them every 6 hours, after 12 hours, they are taked out and weighed every 12 hours, and they could be considered as the saturated after soaking for 72 hours. The weight of the saturated coal samples was $m(s)$. Calculating S_w is expressed as Eq. (1):

$$SW = \frac{m-m \text{ (d)}}{m(s)-m \text{ (d)}} \times 100\% . \tag{1}$$

- m : the quality of coal sample after immersion;
- $m(s)$: the quality of fully saturated coal samples;
- $m(d)$: the quality of completely dry coal samples.

2.2 Sample Coal Rock Analysis

According to “the Industrial Analysis Method of Coal” (GB/T 212–2008), the basic parameters of moisture M_{ad} , ash A_{ad} and volatile Ad of four kinds of coal samples were determined in the laboratory. The experimental results are shown in Table 1.

Table 1
Standard processed coal samples

Number	Coal type	Mining area	$M_{ad}/\%$	$A_d/\%$	$V_{daf}/\%$	$R_{0,max}/\%$
a	Fat coal	Pingdingshan No.8 Mine	0.84	7.99	32.84	0.94
b	Coking coal	Pingdingshan No.8 Mine	0.78	5.94	25.14	1.01
c	Lean coal	Hebi No.6 Mine	0.86	9.37	16.71	1.84
d	Anthracite	JiaozuoGuhanshan Mine	3.09	10.95	8.12	3.86

3 Experimental Measurements

In this experiment, quadrupole method was used to measure the reactance, the complex parameter of the coal samples. Two measuring electrodes served as power supply electrodes, and a pair of measuring electrodes were added to the samples. According to the current flowing through the power supply electrodes, the voltage drop between the two measuring electrodes was measured, and the resistivity value of the samples was calculated according to the calculation formula of resistivity. Because no contact resistance was available on the supply electrodes and the measuring electrodes, the polarization near the electrodes were eliminated. The current would pass through the internal circuit and the external shielding circuit. The opposite direction between the two avoided the mutual inductance in the circuit,

thus avoiding the interference by the electromagnetic field around the circuit. Therefore, the accuracy of the measurement results were greatly improved.

IM3533-01LCR test instrument adopted in the experiment is a high-speed and high-precision impedance tester. Its main parameters include: (1) the measurement frequency ranges from 1 mHz to 200 kHz, covering wide range measurement conditions; (2) measuring voltage ranges from 5 mV to 5 V/2.5 V (low Z high precision mode); (3) measuring time 2 ms for high-speed complex parameter measurement; (4) scanning frequency ranges from 2 to 801 points; (5) internal DC bias ranges from -5 V to 5 V.

Start-up preheating: connect IM3533-01 LCR tester with power supply, and preheat for more than 60 minutes.

Compensation work: Select the measurement parameters as reactance X , and the measurement frequency range is 1-100 kHz. Open circuit compensation, short circuit compensation and line compensation are applied to the instrument to reduce the influence of cable residue and parasitic admittance and improve the measurement accuracy.

Accuracy test: The standard resistance with known resistance value is connected in series to the measuring circuit for measurement and correction.

Coal sample reactance measurement: The test coal sample will be connected in series according to the relevant requirements as shown in the circuit shown in Fig. 1 to carry out the coal sample reactance test.

In order to ensure the accuracy of measurement results, the following requirements should be noted:

- (1) The portion of the samples bare in the air was wrapped with fresh-keeping film to reduce water loss and prevent measurement errors caused by the change of ion concentration in the crack channel of the samples. Therefore, reactance parameters were continuously measured for 4–5 times, taking the average value and controlling the total measurement time within 30 minutes.
- (2) Because of the high precision of LCR instrument, higher demand came for external environment. The measurement should be as quiet and stable as possible to avoid the interference of external noise.
- (3) The conductive plate should have large flatness, and the surface contact method be used to measure the electrical properties. Therefore, good coupling between the conductive plate and the samples should be ensured.

4 Results And Discussion

The reactance X of four kinds of coal sample obtained in Hebi, Pingdingshan and Jiaozuo mining areas with different water saturation and at different frequency points is similar to the hindrance of resistance against DC current. The resistance of the capacitor or inductor in alternating current is known as reactance. Because X is negative in the course of measurement, the following X is absolute. The curve of

X varying with frequency is called reactance dispersion curve. In order to keep the figure clear, 10 interval measuring points are selected to plot the dispersion the curves of four kinds of coal samples with different water saturation, as shown in Fig. 2.

4.1 Relation between Water Saturation and Coal Reactance X

Compared with the real part R , the reactance X shows more complex law. The characteristic curve of X dispersion demonstrates three-section law in low water saturation and two-section law in high water saturation, by which the hydrofracturing effect can be distinguished indirectly. The low frequency band of induced polarization is the main frequency band of medium polarization. The high frequency band is influenced by electromagnetic induction interference, so the low frequency band is worthy of research.

The X dispersion characteristic curve in Fig. 2 suggests that: (1) when the water saturation is low, the absolute value of reactance X decreases first, then increases and finally decreases with the change of frequency. When the water saturation is high, the absolute value of reactance X decreases first and then increases with the change of frequency. Among them, such characteristics are the most obvious in (b) coking coal, (c) lean coal and (d) anthracite; (2) the higher water saturation is, the weaker the dispersion of reactance X becomes. For example, such feature is the most obvious in (b) coking coal, and its dispersion at S_w of 58% and 76.5% is stronger than that at S_w of more than 90%; (3) the X amplitude decreases gradually with the increase of water saturation, implying that less obstruction of coal is exerted on electric current. (4) the X of the four types of coal decreases with the increase of metamorphism. Pingdingshan coking coal X is the largest and Jiaozuo anthracite the smallest. The order is coking coal b > fat coal a > lean coal c > anthracite d.

4.2 Coal Reactance X Dispersion Mechanism

Dispersion results from the dielectric polarization in coal. In the study of dispersion mechanism of rock complex resistivity, some scholars believe that in low frequency band, induced polarization dominates; in intermediate frequency band, electromagnetic induction does; in high frequency band, dielectric polarization does (Xiao, Xu, Luo, et al 2006). Under the excitation of external electric field, there are four polarization forms in the coal body, namely, electronic displacement polarization, ion displacement polarization, turning polarization and space charge polarization. The completion time of polarization increases in turn, that is to say, the frequency points corresponding to the completion of each polarization decrease in turn. Under the action of electric field, the electronic conductor solution system formed by water bearing coal body has a negative charge on the interface of pores and fissures contacting with the fluid, which will attract the positive ions in the solution to move to the interface, and the negative ions will be repelled away from the interface, which will change the previous natural potential. The charge inside the electronic conductor will be redistributed, and the double electric potential on the interface of the electrode and the solution will be changed. The difference between the difference and the previous natural potential is called "overpotential". In addition, in the double electric layer at the interface of coal particle

and solution, the migration of cation and anion in the tight layer and diffusion layer, the difference of ion concentration formed corresponds to a new electric barrier, and gradually reaches a new dynamic balance. As the main form of space charge polarization in the low-frequency stage of water bearing coal, the two are also called coal induced polarization; With the increase of frequency, the induced polarization of coal becomes weaker and weaker. At the same time, the changing electric field and the changing magnetic field are mutually induced and cause and effect each other, forming the electromagnetic interference propagating in the medium. The frequency range of electromagnetic induction is $10^2 \sim 10^8$ Hz, which is called electromagnetic induction; When the frequency is higher and higher, the molecules, atoms and ions in the mineral components of coal are deformed on the surface of the electronic shell under the action of the external electric field, and the positive and negative ions are relatively displaced. At the same time, there is asymmetry in the molecules, which leads to the intrinsic electric moment caused by the molecular structure gradually turning to the direction parallel to the electric field under the action of the external electric field. That is to say, the polarization is mainly electronic displacement polarization, ion displacement polarization and turn polarization, that is, the high frequency stage is dielectric polarization.

For the same coal body, when the water saturation is low, the number of ions dissolved in the solution in the coal is small, resulting in the number of ion separation and migration is small, the migration rate is small, the completion time of induced polarization is long, and the corresponding frequency domain time period is low; At the same time of induced polarization, the coal will produce a certain degree of electromagnetic induction. With the increasing of loading frequency, under the action of external electric field, the electronic displacement polarization in the coal, the completion time of ion displacement polarization and turning polarization is shorter, the corresponding frequency band is higher, the dielectric polarization is more significant, and the frequency dispersion curve of coal reactance presents three-stage type; When the water saturation is high, the concentration of ions in coal increases, the migration rate of ions is higher, the completion time of induced polarization is greatly shortened, the frequency range is larger, and the electromagnetic induction is more obvious with the influence of coal humidity. However, the dielectric polarization caused by the directional distribution of polarized molecules has no obvious effect in the measured frequency range. The coal reactance dispersion curve shows a two-stage type, moreover, the electrical conductivity of coal body is enhanced, the current blocking ability is weakened, and the reactance $\times$ amplitude of high water saturation coal body is smaller than that of low water saturation coal body, As shown in Fig. 2 (b), the law reflected by the measured data of coking coal (c) lean coal and anthracite (d) is consistent with the theory. With the increase of water saturation, the frequency band of X first occurrence reduction becomes larger and larger, while the frequency band of dielectric polarization gradually decreases.

With the escalating metamorphism degree, the aromatic rings of macromolecular structure in coal rise, and the degree of coal condensation expands. In various groups of coal, the energy barrier ΔE to be overcome from capture state to free state decreases with the growing number of aromatic atoms, so the

hindrance of coal against electric current becomes weaker and the reactance of coal decreases with the increase of metamorphism degree, That is, $X_{\text{coking coal}} > X_{\text{fat coal}} > X_{\text{lean coal}} > X_{\text{anthracite}}$.

There are two kinds of currents in the alternating electric field. One is the conduction current j_C caused by the directional motion of electrons and plasma particles, which exists in conductors, that is induced polarization. The other is displacement current j_D caused by polarization caused by changing electric field, which phase differs from the former in the way of $\pi/2$. That is, charged particles propagate in polarized media, that is dielectric polarization. In conductive medium, the total current density j is:

$$j = j_C + j_D = \sigma E + i\omega \varepsilon E = (\sigma + i\omega \varepsilon) E \quad (2)$$

Among them, j_C is the conductive current density, ; j_D is the displacement current density, ; σ denotes the conductivity of conducting current; ε is the dielectric constant describing the dielectric polarization characteristics $\omega = 2\pi f$ is the angular frequency

For heterogeneous coal body, under the action of external electric field, the current density of conduction through coal body medium is j_C and the displacement current density j_D caused by polarization, which together constitute the current density of supply through external electrodes to the circuit is j .

In the previous experiments of R-dispersion characteristics of real resistivity of water-bearing coal, we found that the resistivity of coal decreases monotonously with the increase of frequency, which accords with the general law of rock induced polarization. When the frequency increases gradually, the medium is less and less susceptible to polarization, so the low frequency band dominated by induced polarization is the main frequency band of the study. Induced polarization occurs in coal and rock medium. The charge separation is caused by the excitation of external current inside the medium, which results in a physical and chemical phenomenon of additional "over potential". The following is a schematic diagram of induced polarization.

Both ends of AB are power supply electrodes, if the medium is non-polarized and the current supplied from the outside is stable, the potential difference between the measured MN will be a constant value (J. S. He 2006). If the dielectrics are polarizable, the dielectrics will be polarized into primary batteries due to electrochemical action, and secondary current will also be generated inside the primary batteries. Secondary electric field will generate secondary electric field, and secondary electric field will produce corresponding secondary potential difference, which will lead to the difference between the potential difference measured between MN and the potential difference provided by the original external electric field and the secondary potential difference caused by polarization. And the formation of secondary potential difference is a process, at first fast and then slow. However, when we cut off the applied electric field, we noted that the potential difference between MN did not change back to 0 instantaneously, but gradually became smaller and disappeared at last.

4.3 Predominant Frequency Band for Complex Resistivity Measurement of Coal

The relationship between water saturation and reactance X of coal is shown in Fig. 3. In the measured frequency band, the law shows that: (1) for the coal with four metamorphic degrees, with the increase of water saturation, X decreases gradually; (2) for fat coal, the extreme value of the characteristic curve of reactance X dispersion concentrates around 100 Hz, so in 100 Hz band, X changes most quickly, as shown in Fig. (a); for coking coal, the extreme points of the X -dispersion characteristic curve are concentrated around 1000 Hz, so the corresponding X -frequency band changes the fastest, as shown in Fig. (b); for lean coal, the extreme points of the X -dispersion characteristic curve are concentrated at 100 Hz, so the X -variation of the corresponding frequency band is fast, but it is not obvious in Fig. (c); for anthracite, the extreme points of X -dispersion characteristic curve are concentrated in 100 Hz-1000 Hz, so the X -changes of these two frequency points are faster, as shown in Fig. (d). Compared with the relationship between water saturation and real resistance R , reactance X is more complex, and the X of coal with four metamorphic degrees changes more obviously at the extreme point; (3) at the high frequency band of $f = 10^5$ Hz, with the increase of water saturation, the coal with four metamorphic degrees hardly change. As shown by the green line in the figure, the dispersion characteristics are obvious at $f < 10^5$ Hz. In conclusion, the variation of coal reactance x with water saturation is the most obvious in the frequency range of $f \approx 10^5$ Hz. It is difficult to distinguish the difference of coal water saturation in the high frequency stage, that is to say, the frequency band of induced polarization of coal is more easily used to distinguish the difference of coal water saturation.

5 Conclusion

(1) The influence of water saturation on coal complex electricity can not be neglected. Fat coal and coking coal have the most obvious effect in this experiment. Under other given conditions, with the increase of water saturation, the dispersion curve of the coal reactance X changes from a three-section law to a two-section law, the change and the amplitude of reactance X of coal all become smaller and smaller. With the increase of coal metamorphism, the reactance X gradually decreases, that is, $X_{\text{coking coal}} > X_{\text{fat coal}} > X_{\text{lean coal}} > X_{\text{anthracite}}$.

(2) Polarization is the cause of reactance X dispersion. That is, low frequency is induced polarization, high frequency is dielectric polarization, and electromagnetic induction is the interference phenomenon in the frequency band of induced polarization. The induced polarization stage is the space charge polarization of the dielectric, which is mainly manifested in the double-layer structure formed by the interface between the electronic conductor and the rock particles and the solution. Dielectric polarization is transformed into electron displacement polarization, ion displacement polarization, steering polarization and other microscopic polarization.

(3) The extreme frequency point of reactance X dispersion curve is closely related to the change of water saturation. The frequency band of extreme value point can be used as the dominant frequency band for evaluating coal seam water saturation. Such characteristics are obvious in fat coal, coking coal and anthracite in this experiment. Within the frequency range of extreme point, reactance X changes most

obviously, while lean coal changes little. At the high frequency band of $f = 10^5 \text{Hz}$, with the increase of water saturation, the coal with four metamorphic degrees hardly change, and the dispersion characteristics are obvious at $f < 10^5 \text{Hz}$. Combined with the three-stage law, the intermediate frequency band is the stage of electromagnetic induction interference, so it is better to select the low frequency (100-1000Hz) induced polarization stage to evaluate the coal seam aquifer.

Declarations

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Figures

Figure 1

Schematic diagram of complex resistivity test device. 1-IM3533-01 LCR Tester; 2-Data Collector; 3-Testing Coal Samples; 4-Data Processor; 5-Frequency Transmitter; 6-LCUR Terminals: Current Detection Terminals; 7-LPOT Terminal: LOW side voltage detection terminal; 8-HCUR Terminals: Current Generating Terminals; 9-HPOT Terminal: HIGH side voltage detection terminal;10-Conductive Electrode Plate

Figure 2

The dispersion curve of coal body resistivity with different water saturation Note: a Pingdingshan Fat Coal; b Pingdingshan Coking Coal; c Hebi Lean Coal; d Jiaozuo Anthracite; SW Water Saturation

Figure 3

Relationship between coal resistivity and water saturation in different frequency Note: a Pingdingshan Fat Coal; b Pingdingshan Coking Coal; c Hebi Lean Coal; d Jiaozuo Anthracite; S_w Water Saturation