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Experimental study on characteristics of water containing coal complex resistivity dispersion

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ABSTRACT

In recent years, there have been great advances in the evaluation of complex resistivity method for rock permeability.

Using a complex resistivity method, as a potential non-contact detection method, it is feasible to forecast the permeability of coal seam and evaluate the effect of hydraulic fracturing. In this paper, measurement and numerical simulation are both carried out based on electrical properties of rock. For this purpose, the authors attempted to measure real and imaginary parts of the complex resistivity of two kinds of metamorphic coal in different values of water saturation (*Sw*) under normal temperature and pressure conditions. The achieved experimental results are presented as follows: (1) The influence of polarization on the complex resistance is very important, which is the cause of frequency dispersion; (2) Regarding real and imaginary parts of the complex resistivity of coal's dispersion characteristics, the real part always gradually decreases with the increase of frequency, while the imaginary part is changed, and the curve has obvious extreme point; (3) the amplitude of real and imaginary parts gradually decrease with increase of *Sw*; (4) The curve of imaginary part is two segments (only peak), the Cole-Cole model is applicable, while curve is three segments (trough-peak), the double Cole-Cole model is applicable. The results show that the effect of medium polarizability on coal complex resistivity cannot be ignored, indicating that complex resistivity method possesses a great capability in terms of development of coalbed methane and coal mining.

1. Introduction

The strategic measurements of the gas treatment and control is extracting gas from coal mine as much as possible in China, and satisfactory results have been accordingly achieved. Currently, hydraulic fracturing is regarded as an effective technique and is frequently used to enhance the permeability of coal seam (Ivakhnenko et al., 2017), while developing a reliable mechanism to evaluate the effect of hydraulic fracturing is still a main challenge. Previous studies have focused on description of the fracture morphology from a macroscopic perspective (Huang et al., 2016), the process is complicated and the effect is not ideal. Hence, measuring the water containing coal through the use of complex resistivity method, which is significant to develop a new non-contact and fast approach to evaluate the permeability of coal seam. In recent years, several studies have investigated the complex resistivity of the rock. Liu et al. (2017) studied dispersion characteristics of rocks. Cole and Cole (1941) and Farias et al. (2013) experimentally tested the complex resistivity models. In addition, some scholars (Ruffet et al. (1991), Lesmes et al. (2001), Moss et al. (2002), Toumelin et al. (2009), and Garrouch and Sharma (2012)) have reported that the effect of frequency dispersion was associated with pore-scale fluid distribution and accordingly, degree of wetting (wettability). Taherian et al. (1990) and Man (1999) discovered frequency dispersion of permittivity exponentially increasing with water saturation (*Sw* can be calculated based on frequency dispersion of resistivity and permittivity. Moreover, Revil et al. (2013) distinguished water and oil layers available in the rock by complex resistivity experimental measurements. Norbisrath et al. (2016, 2018) and Latt et al. (2016) reported measurements of complex resistivity spectra (CRS), which are directly correlated with pore structure of carbonate rocks, and permeability, and cementation factors could be predicted using CRS. Gajda-Zagórska et al., 2015 and Gorbatenko and Sukhorukova, 2016 applied the complex resistivity spectrum logging method in the oil field. Furthermore, the complex resistivity method has been widely used in the detection of seabed sediment (Souza, 2001), heavy metals in soil (Bentz, 2010), etc. The findings demonstrated that complex resistivity measurement method

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has distinguished capabilities to be used as a non-invasive technique to assess reservoir wettability and predictive permeability.

Coal is an organic rock and lots of researches were conducted to study electrical properties of coal on the basis of direct current methods (Yao et al., 2011; Chen et al., 2015; Song et al., 2015), and dielectric properties of anthracite, and bituminous coals were investigated in the low-terahertz (low-THz) band (Fan et al., 2015, 2017). Additionally, researchers also measured the electrical parameters of coal's single frequency, double frequency, and multi-frequency (Liu et al., 2015). It should be noted that few experimental studies were performed on the continuous-frequency measurements (Guo et al., 2017) and few studies on different water containing coal, and previous studies neglected the effect of dielectric polarization. Thus, this paper uses the dielectric theory, with the help of measuring the real and imaginary parts of the complex resistivity as well as investigating dispersion curves' features to explore the feasibility of evaluating the permeability of coal seams by using the complex resistivity method.

2. Experimental methods and results

2.1. Sample preparation

In this experiment, two metamorphic grade coal samples were selected from Pingdingshan and Jiaozuo mining areas, and along the coal seam direction, the samples were cut into the blocks with dimensions of 60 mm × 60 mm, with smooth edges and surfaces. The samples are shown in Fig. 1, and the physical parameters of the two kinds of coal samples are listed in Table 1.

The prepared coal samples were fully dried, immersed in distilled water, removed at intervals of 12 hours, the surface water was wiped, and weighed for 72 hours until the samples' weight reaches a stability. In other words, the coal samples were completely saturated. Calculating *Sw*, Eq. (1) is expressed as:

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

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

2.2. Experimental instruments and tests

The experiment adopted IM3533-01LCR test instrument, in which the main parameters are (1) measurement frequency at the range of 1 mHz ~ 200 kHz; (2) measurement voltage equal to 1 V; (3) measurement time is 2 ms; (4) scanning frequency is 200 points.

The mechanism of the execution of the performed test is shown in

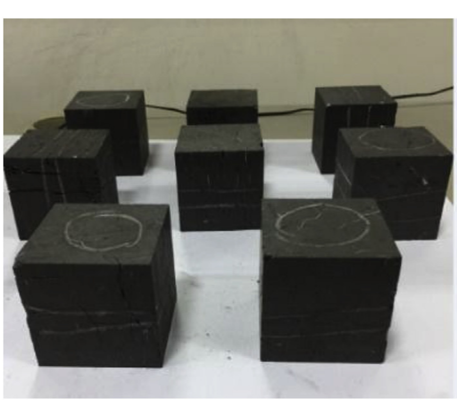

Fig. 1. Physical map of standard coal processed by standard.

Table 1
Standard processed coal samples.

number	Coal type	Mining area	M_{ad}/%	A_d/% V_{daf}/% $R_{0,max}$/%
A	bituminous coal	Pingdingshan mining	0.78	5.94 25.14 1.01
B	anthracite	Jiaozuo mining	3.09	10.95 8.12 3.86

Notes: M_{ad}—mass fraction of air dry base ash, %.
V_{daf}—mass fraction of dry ash free volatiles,%.
$R_{0,max}$—maximum vitrinite reflectance,%.

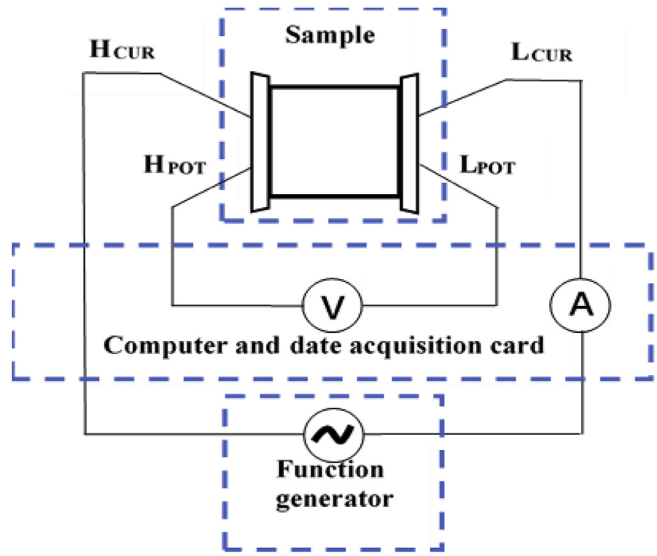

Fig. 2. Schematic diagram of four terminal complex resistivity test device. HCUR terminal: current occurrence terminal; HPOT terminal: HIGH voltage detection terminal; LPOT terminal: LOW voltage detection terminal; LCUR terminal: current detection terminal.

Fig. 2.

The advantages of a four-terminal configuration approach involve passing current through an internal circuit and an external shielding circuit, so that it can avoid the occurrence of mutual inductance at an element of a circuit, as well as preventing an interference caused by the electromagnetic field around the wire. Parameters of experimental measurements involve real (*Re*) and imaginary (*Im*) parts of the complex resistivity.

$$Z = R + jX \tag{2}$$

In Eq. (2), Z is impedance; R denotes resistivity; X is reactance; and j represents an imaginary unit.

The complex resistivity is calculated by Eq. (3) as

$$\rho = \frac{R \times S}{L} \tag{3}$$

ρ-complex; S represents the cross section are; and L denotes the length.

The calculation method for resistance and reactance is the same, and the measurement result is shown in Fig. 3.

2.3. Dispersion mechanism

The cause of frequency dispersion is attributed to the dielectric polarization. The dielectric polarization in coal mainly includes interface polarization, orientation polarization, and ionic polarization, as shown in Fig. 4. The interface polarization is occurred when many free electric charges (ions in pore water and fissure water) are accumulated in the interface between water and coal, the variation of distribution is