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Improvement of the electrical disintegration of coal sample with different concentrations of NaCl solution

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ABSTRACT

The application of high-voltage electrical pulse (HVEP) technology to the improvement of pore structure of coal has achieved encouraging results. However, the very high breakdown voltage of some kinds of coal seriously affects the application of HVEP technology. In this study, the relationship between the concentration of NaCl solution and the breakdown voltage of coal sample was studied by improving the electrical breakdown effects of Linhua anthracite coal and Hongliu bituminous coal with different concentrations of NaCl solution, and a negative exponential relationship was established. The results indicate that the breakdown voltages of coal samples decrease with the increase of the concentration of NaCl solution, but there is a limit to the magnitude of the decrease. Additionally, nuclear magnetic resonance (NMR) and X-ray photoelectron spectrometer (XPS) were adopted in this study to investigate variations in pore structure and functional groups before and after the electrical breakdown. The NMR analysis demonstrates that the electrical breakdown mainly improves the number of mesopores and macropores and enhances the connectivity between them, thus providing a smoother channel for gas extraction. The XPS analysis reveals that a new oxidation reaction appears where the current flows through, which promotes gas desorption from surfaces of coal samples.

1. Introduction

Recently, as coal mining proceeds deeper year by year, problems such as high matrix density and low permeability seriously restrict the recovery of coalbed methane (CBM) [1,2]. Therefore, it is necessary to enhance the permeability of coal seams for the improvement of CBM production. In addition, CBM is a kind of clean energy that can be used to generate electricity [3]. Despite the wide usage of hydraulic fracturing, hydraulic slotting and deep hole presplitting blasting in the field of gas extraction, these methods are limited in terms of their coverage and effective influence scopes [4–6]. Therefore, there is an urgent need for developing a simple and practical method to improve the permeability of coal seam. In recent years, the high-voltage electrical pulse (HVEP) technology has been proposed to enhance the permeability of coal seam, and encouraging results have been reported [7–9].

The HVEP technology is a way of storing small energy into a capacitor by compression and conversion and finally releasing greater energy to the load instantaneously [10,11]. Since the research on it started in the 1930s and developed into an independent discipline in the 1960s [12], it has experienced rapid development over the past few decades [13,14]. In 1955, Yutkin found that the HVEP technology can be used for crushing solids [15]. In 2000, the Russian Academy of Sciences developed a high-power pulse generator according to electrohydraulic fragmentation mechanism [16]. Timoshkin et al. evaluated the pulsed plasma drilling machine for miniature hole drilling [17].

The HVEP technology has been widely used in many fields owing to its multiple advantages, such as the discharge channel is optional; the energy required for electrical breakdown is much smaller than that of electrohydraulic fragmentation and the crushing effect is very good [18–20]. Since the 1970s, many scholars have applied the electrical pulse technology in petroleum plugging and have achieved satisfactory results [21,22]. In 1993, Noranda Technology and Marwell Laboratory studied the fragmentation of rock by electrical pulse [23]. In 1995, Andres proposed the use of HVEP technology for separating diamonds from kimberlite ores [18]. In 2015, Duan investigated the separation of valuable materials from waste circuit boards with the aid of HVEP technology [24]. In recent years, many scholars proposed to apply the HVEP technology to the enhancement of coal seam permeability [25–27].

Crushing coal samples using the HVEP technology in an air environment has been proved to be a practicable and novel method to

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improve the pore structure of coal, i.e. the permeability of coal seam [7,28]. However, the very high electrical breakdown voltage of some types of coal seriously restricts the application of this technology in coal mines; for example, the minimum breakdown voltage of a Guhanshan coal sample with a diameter of 10 cm and a height of 1 cm is approximately 10 kV [29]. Furthermore, high voltage may pose insulation and safety problems, and the higher the voltage, the greater the energy consumed [30]. Hence, it is very meaningful to take measures to improve the breakdown voltage of coal samples.

In the HVEP technology, solid materials are crushed by two methods: electrohydraulic fragmentation and electrical fragmentation [29]. In the experiment of electrohydraulic fragmentation, the solid materials are dipped in a liquid medium. A high-voltage electric pulse is then discharged in the liquid medium, which eventually produces a powerful shock wave. As a result, solids produce cracks under the action of shock waves. By contrast, electrical fragmentation involves crushing the material by directly applying high voltage to both ends of the solid medium. The solid medium is eventually crushed by tensional forces. Because the tensional forces produced during rock material damage are far less than the compressional forces produced, the energy needed for electrical fragmentation will be much less than that required for electrohydraulic fragmentation.

The process of injecting electrons into coal includes three steps [31]. First, in the initial stage, electrons detach from the metal electrode; this step depends on the electrode's work function that refers to the minimum electrical energy required to move an electron from one solid to another and usually equals half of the ionization energy of a free atom. Next, as soon as electrons separate from the electrode, a contact surface is formed between the electrode and the coal, and it plays a vital role in transporting electrons. Finally, the electrons injected into the coal sample move directly under the action of electrical field, which depends on the mobility of electrons and the resistivity of coal. Thus, changing the resistivity and electron mobility of coal is an effective way to improve the breakdown voltage. It is well-known that the conductivity of NaCl solution increases with the rise of its concentration [32]. Therefore, saturating coal samples with a NaCl solution is an effective method to improve their conductivities [33] and change their breakdown voltages and electrical breakdown effects.

The coal seam, a special kind of underground rock, is surrounded by stratum water for a long time [34]. The conductivity of underground rock mainly depends on the concentration of ions in the stratum, and these ions are generally considered to be a combination of sodium and chloride [35]. Therefore, the conductivity of underground rock is mainly determined by contents of chloride and sodium ions in groundwater. The contents of chloride and sodium ions are different, which determines the various conductivity of rock. Therefore, the experimental study on the relationship between the concentration of NaCl solution and the breakdown voltage of coal samples has guiding significance for the application of HVEP technology in coal mines.

Although the HVEP technology has developed rapidly over the past few decades, many problems still need to be addressed. In this study, a NaCl solution was adopted to improve the electrical breakdown effects of Linhua anthracite coal and Hongliu bituminous coal; the relationship between the concentration of NaCl solution and the breakdown voltage was studied; and their electrical breakdown characteristics were analyzed. The study results are of guiding significance for the application of HVEP technology in coal mines.

2. Laboratory equipment, sample preparation and experimental procedure

2.1. Laboratory equipment

As shown in Fig. 1, the laboratory equipment used in this experiment consists of a transformer, a capacitor, a high-voltage (HV) switch and a discharge cavity. The transformer can output the alternating current 220 V to an adjustable voltage in the range of 0–50 kV. The capacitor has a capacitance of 8 μF and maximal output energy of 10 kJ. The HV switch performs the function of instantaneously electrifying a circuit. Pin electrodes were symmetrically installed in the discharge cavity.

2.2. Sample preparation

In this experiment, anthracite coal from Linhua Coal Mine in Guizhou Province and bituminous coal from Hongliu Coal Mine in Shanxi Province were selected as coal samples and drilled into cylinders that were 5 cm in diameter and 3 cm in height, as displayed in Fig. 2. Proximate analysis results of Linhua and Hongliu coal samples are presented in Table 1. The energy-dispersive spectrum (EDS) point scanning test was carried out using an electric refrigeration system (Bruker QUANTAX 400-10) to study the distribution of elements of Linhua and Hongliu coal samples, and their elemental compositions are exhibited in Fig. 3. The EDS analysis results suggest that both kinds of coal samples contain metal elements (such as Al, Na, K, Ti and Si), and Linhua coal contains more metal elements compared with Hongliu coal. This indicates that Linhua coal is endowed with better conductivity [7].

2.3. Experimental procedure

60 samples (30 Linhua anthracite coal samples and 30 Hongliu bituminous coal samples) were prepared to study the effects of different concentrations of NaCl solution on the electrical breakdown of coal samples, as shown in Fig. 2. The experiment was performed according to the procedure given in Fig. 4. Raw coal samples were drilled into cylinders that were 5 cm in diameter and 3 cm in height by means of coring and then dried in a 60 °C vacuum environment so as to allow them to get saturated easily. The dried coal samples were weighted, and the weights obtained were recorded as the original weights of coal samples. Next, the samples were saturated with different concentrations (0 mol/L, 0.2 mol/L, 0.4 mol/L, 0.6 mol/L, 0.8 mol/L and 1.0 mol/L) of NaCl solution, after which they were weighted again. Then, a nuclear magnetic resonance (NMR) test was conducted to study the pore structure of raw coal. An "electrical breakdown test" was performed to investigate the minimum breakdown voltages of Linhua and Hongliu coal samples in an air environment. After the test, another NMR test was conducted to study the pore structure of electrically broken coal. Besides, an X-ray photoelectron spectrometer (XPS) test was conducted to study the variations of functional groups of coal samples before and after the electrical breakdown.

To study variations in the pore structure of Linhua and Hongliu coal samples, the NMR test was performed. The NMR instrument allowed the exploration of the spatial pore structure of coal sample, including micropores, mesopores and macropores & microfractures. Additionally, an ESCALAB 250Xi XPS analyzer was employed to examine variations on the surfaces of coal samples before and after the electrical breakdown.

To obtain the minimum breakdown voltages of Linhua and Hongliu coal samples, they were fixed with a set of symmetrical needle electrodes in the center (see Fig. 1). The capacitor was charged from 1 kV, and the high-voltage switch was then turned on. If the coal failed to be broken down, the capacitor would be charged again at a step size of 0.3 kV until the coal was broken down. The voltage at the breakdown moment was recorded as the minimum breakdown voltage of the coal sample with a diameter of 5 cm and a height of 3 cm. Additionally, to confirm the validity of the minimum breakdown voltage of the coal sample, additional 5 Linhua anthracite coal samples treated with single pulse in air environment were prepared. In this experiment, the average breakdown voltage of the coal sample which were saturated with 0.2 mol/L NaCl solution was chosen as an example to verify.