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Changes to coal pores and fracture development by ultrasonic wave excitation using nuclear magnetic resonance

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HIGHLIGHTS

- The closed pores and connected pores in the coal are differentiated with nuclear magnetic resonance technique.
- The amount and proportion of connected pores in the coal increase significantly after the treatment of ultrasonic.
- After the fracturing of the ultrasonic, a fracture network forms in the coal.

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ABSTRACT

To maximize the extraction efficiency and quantity of coalbed methane, we improved reservoir permeability by fracturing coalbed methane reservoirs using ultrasonic wave excitation. Changes in number and diameter of pores in coal masses were determined by using nuclear magnetic resonance analysis of coal masses that had been fractured using ultrasonic waves. The development of coal fractures was monitored and analyzed using thermal imaging, a digital camera, and a measurement system for P-wave velocities in rocks. The development of fractures induced by ultrasonic waves, the pore diameters, and the number of pores in the coal masses increased, and the porosity increased by 111.8%. The entire fracturing process was divided into three stages; the initiation of micropores occurred earlier than that of mesopores, and was followed by macropore development and fracturing. P-wave tests and photographs showed that fracture networks formed inside or on coal mass surfaces under ultrasonic wave excitation, which improved the coal mass permeability significantly. Because pores that contain water provide initiation points for fractures that are caused by ultrasonic waves, the ultrasonic waves impact larger ranges and require less energy than with traditional fracturing measures. By promoting oil production using ultrasonic waves, a design concept for industrializing ultrasonic wave-based fracturing was proposed to improve coalbed methane extraction.

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1. Introduction

China has the third-largest proven coalbed methane (CBM) reserves, globally, with reserves of 37 trillion cubic meters. CBM is a disposable and clean mineral resource, but is also associated with the largest number of accidents in coal mines. According to statistics, gas-explosions account for approximately 70% of coal mine accidents [1,2]. CH_4 is the main component of CBM, with 20 times more CH_4 than CO_2, and is a potent greenhouse gas. Therefore, from an energy utilization, safety, and environmental protection perspective, development of CBM is imperative. However, because of the geological structures and burial conditions of CBM in China, generally reservoirs are compact and less permeable, which results in a low CBM extraction efficiency. Much research has gone into measures for stimulating CBM reservoir fractures (such as hydraulic slotting, hydraulic fracturing, freeze–thaw damage, and gas injection) [3,4]. Some advancements have been made to improve the permeability of low-permeability reservoirs. Although the application of hydraulic measures (such as hydraulic slotting and hydraulic fracturing [5–7]) in mining areas such as Shanxi, Inner Mongolia, and Xinjiang can improve the permeability of CBM reservoirs to some extent, these hydraulic measures often consume excessive amounts of water. Moreover, fracturing fluids and proppants used in hydraulic fracturing are likely to contaminate groundwater, which further exacerbates

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water shortages in mining areas and endangers local ecological environments. Therefore, novel technology is urgently required to enhance CBM reservoir permeability with no pollution and low energy consumption. This technology should be able to function under different geological conditions, environmental factors, and complex stress impacts.

Ultrasonic technology has been used widely recently in many fields owing to its pollution-free operation, low energy consumption, rapid effect, good results, and energy concentration [8–10]. Since the 1950s, the treatment of oil reservoirs using ultrasonic waves has been carried out in the United States and the Soviet Union and good results have been achieved [11]. In the 1990s, Xian Xuefu proposed the idea of improving CBM extraction rates through physical excitation methods using ultrasonic waves with controllable power. Xiao et al. [12], Jiang et al. [13] and Jianlou et al. verified that ultrasonic waves improved fracture development, gas desorption and reservoir permeability of CBM extraction.

Nuclear magnetic resonance (NMR) is a research technique that exploits quantum magnetic properties at the atomic scale. NMR influences hydrogen atoms in water molecules to yield the distribution of water molecules in coal-rock masses, and by using NMR, the distribution of pores of different diameters in coal-rock masses can be obtained. Yao et al. [14] showed experimentally and by modeling techniques the feasibility of describing the distribution characteristics of pores with different diameters in coal masses using the T_2 distribution curve produced through NMR. By analyzing changes in the number of pores with different diameters in coal-rock masses after microwave treatment by NMR, Li et al. [15] obtained the evolution of the pore diameter in coal-rock masses after microwave-induced fracturing. According to the T_2 curve from NMR, Cai et al. [16] established the evolution law of the pore diameter of different coal types at different temperatures.

Previous studies have shown that ultrasonic waves can improve the permeability of CBM reservoirs and increase the gas desorption rate. However, limited investigation has been conducted on the evolution of pores with different diameters and fracture development in coal masses under the effect of ultrasonic waves. In this study, by using a self-made ultrasonic fracturing system for coal and rock masses, the evolution of pores and fracture development in coal masses under ultrasonic waves was determined. The effect of ultrasonic wave excitation on the fracturing of coal masses was analyzed from three parameters: P-wave velocity, fracture generation, and porosity. These results provide a theoretical and experimental basis for developing fracturing technologies for low-permeability reservoirs using ultrasonic waves.

2. Experimental theories and methods

2.1. Mechanisms for measuring pores by using NMR

Coal permeability is governed mainly by the size, number, and distribution of pores and fractures in coal masses. Methods that are commonly used to measure the pore distributions in coal masses include scanning electron microscopy, computed tomography, mercury intrusion, and N_2/CO_2 adsorption [17–19]. Disadvantages of these methods include a long detection time, damage to coal samples, and a limited measurement range for pore diameters. NMR is a new technology with a short detection time, is less damaging to the sample, has a wide measurement range for pore diameters (see Fig. 1), and is used extensively in the fields of medicine and to measure rock pore diameter distributions.

NMR is a physical process in which nuclei with non-zero magnetic moments undergo Zeeman splitting at spin-energy grades under the action of an external magnetic field, followed by resonance absorption for radio-frequency radiation at a certain frequency. NMR uses a magnetic field to create a dipole moment, the amplitude of which is proportional to the number of hydrogen atoms within the fluid, and thus can be used to measure pore volume. The dipole moment can be expressed as a spectrum of transverse (T_2) relaxation time given by:

$$\frac{1}{T_2} = \rho \times \frac{S}{V}$$

where S represents the pore surface area (m^2), V is the pore volume (m^3), and ρ denotes the transverse surface relaxivity ($m\ s^{-1}$).

For coal masses, $T_2 < 10$ ms corresponds to micropores; T_2 from 10 to 100 ms corresponds to mesopores and $T_2 > 100$ ms corresponds to macropores and microfractures. The area included in the T_2 curve and the horizontal axis (X axis) can be used to characterize the content of hydrogen atoms in the same relaxation time, which indicates the content of pores in the same state (size).

2.2. Experimental samples

The coal samples were anthracitic coal from Jincheng in Shanxi, China. Cylindrical (50-mm diameter × 60-mm height) coal samples were prepared using a coring drilling rig. An industrial analysis of the coal samples is given in Table 1. Experimental data were obtained by studying coal samples to discuss the evolution of pore diameters and fracture development in coal masses with time under ultrasonic wave excitation.

2.3. Experimental procedures

A cyclic ultrasonic wave experiment was designed, as illustrated in Fig. 2a. During a fracturing cycle that is induced by ultrasonic waves, ultrasonic waves at 28 kHz and 30 W were radiated to coal samples for 50 s. Changes in the coal samples that underwent a cycle of ultrasonic wave excitation were monitored for 50 s by P-wave detection, digital and infrared imaging, and NMR. Coal samples were treated in a centrifuge for 10 min at 6000 r/min and were then placed in a vacuum drying oven for 8 h at 60 °C to eliminate moisture in permeable pores. In this way, the coal samples reached an irreducible water condition (Sir), under which the first NMR test was conducted. Before performing the remaining NMR tests, coal samples were placed in a vacuum for 8 h at 0.01 MPa and in distilled water to absorb water for 8 h, which allowed the coal samples to reach a 100% water-saturated condition (Sw). Before the experiment, coal samples that had undergone NMR tests were dried at room temperature until their change in mass was within 0.3% compared with that of the coal samples before they were wet (see Fig. 3).

2.4. Experimental equipment

2.4.1. Ultrasonic stimulation equipment

Fig. 2b shows that the fracturing system for coal masses by using ultrasonic stimulation consists mainly of an ultrasonic generator, a holder, and an oscillator. A type V6.3 intelligent and numerical ultrasonic generator (Hangzhou Chenggong Ultrasonic Co., Ltd., Hangzhou, China) was used as an ultrasonic generator. This equipment with an occurrence frequency of 28 kHz (frequency-scanning range of 27.75–27.8 kHz) has a liquid-crystal display that shows the current output power, time and frequency. Because it has a maximum output power of 1000 W, the equipment can work continuously for an extended period.

2.4.2. Measurement of P-wave velocity

P-wave velocity was tested by using the HS-YS4 Ultrasonic analyzer (Fig. 2c), which consists of a pulse generator, signal reception

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