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Ultrasonic vibrations and coal permeability: Laboratory experimental investigations and numerical simulations

Zhang Junwen [a,*], Li Yulin [a,b]

[a] Heilongjiang University of Science and Technology, School of Mining Engineering, Harbin 150022, China
[b] China University of Mining and Technology, School of Mechanics and Architectural Engineering, Beijing 100083, China

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ABSTRACT

Ultrasonic vibrations in coal lead to cavitation bubble oscillation, growth, shrinkage, and collapse, and the strong vibration of cavitation bubbles not only makes coal pores break and cracks propagate, but plays an important role in enhancing the permeability of coal. In this paper, the influence of ultrasonic cavitation on coal and the effects of the sonic waves on crack generation, propagation, connection, as well as the effect of cracks on the coal permeability, are studied. The experimental results show that cracks in coal are generated even connected rapidly after ultrasonic cavitation. Under the effect of ultrasonic cavitation, the permeability increases between 30% and 60%, and the number of cracks in coal also significantly increased. Numerical experiments show that the effective sound pressure is beneficial to fracture propagation and connection, and it is closely related to the permeability. Moreover, the numerical simulations and physical experiments provide a guide for the coal permeability improvement.

1. Introduction

Ultrasonic waves can promote mass transfer and accelerate chemical reactions [1–5]. Ultrasonic waves have been applied in hydraulic drilling and industrial cleaning. In coal, these waves cause cavitation bubbles to oscillate, grow, shrink, and collapse, and the strong bubble vibrations cause the pores in the coal to break and cracks to propagate, which play an important role in enhancing the coal's permeability. Ultrasonic cavitation refers to the activation of the micro-bubble's nucleus by ultrasonic waves in a liquid [6–10]. This activation is the dynamic oscillation, growth, shrinkage, and collapse of the bubble nucleus.

Many investigators have conducted research on ultrasonic cavitation and the research has embraced both different physical research methods and mathematical modeling. Jiang et al. [11] carried out an experiment to study acoustic vibrations to promote methane desorption from coal. Li et al. [12] carried out research on coal-bed methane desorption and emissions under the action of sound waves and obtained coal methane gas desorption and diffusion parameters. Li et al. [13] developed a mechanical coal sorption/desorption test system and used it to study coal adsorption under low frequency vibrations. Klobes et al. [14] determined rock porosity with a combination of X-ray computerized tomography and mercury porosimetry. Goodwin et al. [15] investigated particulate interactions within opencast coal mine backfill by the use of X-ray computer tomography. Ren et al. [16] performed an experimental study on the effect of power ultrasound on coal and rock. That study looked at crack generation and development and the change in the stress state and the mechanical properties of the coal and rock. The study also presented a qualitative analysis of the changes in compressive strength and elastic modulus of coal and rock under ultrasonic vibration. This study provided an experimental basis for the changes of coal mechanical properties caused by cracks which are generated by ultrasonic vibration. Jiang et al. [11] studied the desorption of methane gas in coal under ultrasonic waves and the thermal effect of the waves. Li [12] using a self-developed acoustic field coal gas desorption device, established a physical model for coal gas emissions and monitored the emission of total pressure, gas pressure, and gas emission rates. Nie et al. analyzed the influence of changes in the porosity and permeability of coal caused by power ultrasonic waves on coal-bed methane. Yu et al. [17] explored ultrasonic interference for improving the permeability of coal reservoirs and increasing the coal-bed methane desorption rate. Using ultrasonic waves at 20 kHz, Shao et al. [18] studied the effect of ultrasound on rock permeability. A number of other investigations conducted by Li et al. have looked at how to solve the problems of coal bed micro cracks, low permeability, high gas adsorption, and the difficulty of draining methane by using cavitation water jet acoustic shocks to improve methane

* Corresponding author.
E-mail address: zhangjunwen1977@163.com (J. Zhang).

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desorption and seepage flow [19–23]. Lu et al. [24] determined how temperature affects coal permeability by studying the thermal effects produced at the moment of cavitation bubble breaking. They also studied the cavitation noise sound field produced during tests of coal temperature and tested methane permeability under different cavitation conditions (pump pressure and cavitation pressure). Abramov et al. [25] found that when used on oil wells with a permeability greater than 20 md and a porosity of more than 15%, ultrasonic technology could increase oil production by 30–50% or more. Another experimental study, by Alhomadhi et al. [26] was done to investigate improving oil recovery by using ultrasonic waves during water flooding.

Many previous studies have focused on the effects of ultrasonic waves on coal methane desorption and diffusion, while less attention has been paid to research the effects of sound waves on crack propagation and permeability in coal. The way in which strong ultrasonic cavitation enhances permeability in coal is still not very clear. In this paper, the method used combines theoretical analysis with physical experiments to analyze cavitation bubble oscillation, growth, shrinkage, and collapse, and discuss ultrasonic cavitation in coal. The experiments determined the permeability of the coal and used computed tomography (CT) to study coal crack generation, propagation, and connectivity along with the changes in permeability under ultrasonic cavitation. In addition, stress wave loading reproduced ruptures in the coal caused by ultrasonic mechanical effects. The study showed that sound pressure promotes crack propagation and connection. The experimental results can provide a foundation for the study of ultrasonic cavitation rupture to enhance coal permeability.

2. Ultrasonic cavitation experiments on coal rupture and permeability enhancement

2.1. Sample description

Coal samples used in these experiments were collected from the Jincheng Tiandiwangpo No. 3 coal bed, Shanxi Province, China. The coal mines there are high methane mines but the excavated coal is not prone to spontaneous combustion. The Wangpo coal mine is located in the southern Taihang Mountain area, the watershed of the Qin and Long Rivers. The area is moderately mountainous and dissected by gullies. Terrain slopes are more than 20–30°. The highest areas in the Wangpo mine are in the northeast central area, the lowest are in the north, south, and east areas. The highest topographic point is on the northeast ridge at an elevation of 1327.5 m, the low point is in the Long River valley, elevation 877.2 m. The No. 3 coal bed is hosted by the lower Permian Shanxi Formation in the lower part of the mine. The No. 3 coal bed ranges from 4.10 to 6.70 m in thickness (averaging 5.76 m) and it has simple structure only containing 0–2 layers of carbonaceous shale 0.02–0.90 m thick. The longwall face on the No. 3 bed is about 350 m long.

The coal samples used for this study were rectangular blocks 50 mm on each side and 100 mm long. The purpose of the experiment was to study the effect of ultrasonic waves on the evolution of the cracks in the coal and the ultrasound's effect on the coal permeability. Some of the coal samples used for these experiments are shown in Fig. 1.

2.2. Experimental apparatus

The device used for ultrasonic excitation of the coal was a ZJS-500N type ultrasonic generator, which will work in an indoor environment if the humidity is less than or equal to 85% relative humidity and the temperature is between 0 °C and 40 °C. The specific components of the ultrasonic device include: (1) an ultrasonic vibration source (drive power): this converts the 50–60 Hz current to a higher power and frequency (15–100 kHz) to supply the transducer; (2) a transducer (controller transducer): this converts the high frequency electric current into mechanical vibration energy; (3) an amplitude transformer: connected to the fixed transducer and the tool head, this device amplifies the vibrations from the transducer and sends them to the tool head; (4) the tool head (guide rod): this transfers the mechanical energy and the pressure to the sample. It also independently increases the amplitude; (5) connecting bolts: these connect the components mentioned above. The three axis penetration apparatus and ultrasonic probe component connect the ultrasonic generator to the experimental equipment. The three axis penetration instrument, the precision digital flow meter, the ZJS-500N ultrasonic generator, and a schematic diagram of experimental assembly used for the experiments are shown in Fig. 2.

2.3. Experimental design

To analyze the effects of ultrasonic cavitation, confining pressure, and pore pressure on the coal's permeability, the experiments were run under two sets of experimental conditions. First, the experiments were run both with and without ultrasound with the confining pressure set to 4.0 MPa and pore pressures of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 0.7 MPa [27,28]. Then, the confining pressure was increased to 12 MPa and the experiments were run again at pore pressures of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.1, and 1.6 MPa. The experimental scheme is shown in Table 1.

2.4. Ultrasonic coal permeability analysis

A triaxial permeability measuring system, based on the principle of a steady state method, was used to determine the permeability of the coal samples to compare the permeability of the samples before and after ultrasonic treatment. According to

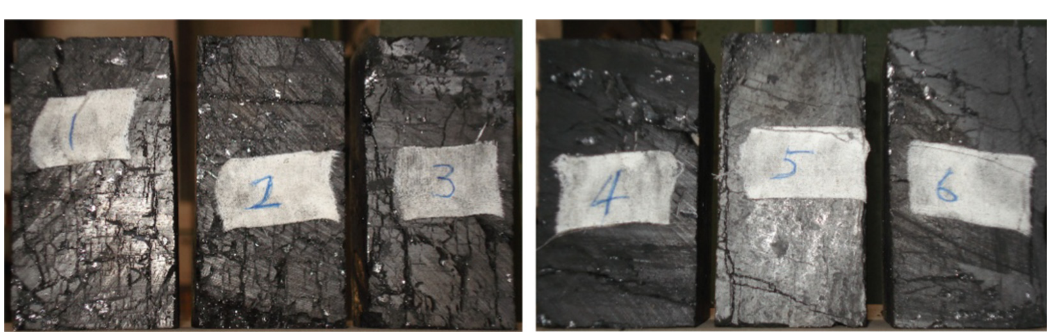

Fig. 1. Photographs of some of the coal samples used in the experiments.