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Effects of moisture content on fracturing and heating processes during ultrasonication

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ABSTRACT

Anhydrous fracturing methods which increase permeability during the mining of coalbed methane (CBM), shale gas, etc. are promising techniques for future development. One such technique, ultrasonic fracturing, has several advantages over other methods. These advantages include a wide range of application, low consumption of energy, concentrated application of energy, high efficiency, and lack of pollution generation. Ultrasonic waves mainly fracture coal masses through cavitation and heating processes but there are numerous factors influencing the effect of the ultrasonic excitation. Therefore, it is important to investigate these other effects. Of particular interest is the effect of moisture content. For this study, we carried out physical experiments using ultrasonic fracturing technology to investigate this factor. Coal masses with different moisture contents were subjected to ultrasonication and the fracturing and thermal effects were investigated using nuclear magnetic resonance (T_2 spectra) and infrared thermal imaging. Moreover, the effect of the moisture content on the ultrasonic fracturing was studied by employing the concept of fractal dimension. The results show that the moisture content has a significant effect on the ultrasonic fracturing of a coal mass. The increase in the number of pores in the coal mass is significantly greater when the moisture content is 8% compared to those in coal masses with lower moisture contents (samples with 6%, 4%, 2% and 0% were also tested). Samples with higher moisture contents exhibit larger left shifts in the extreme T_2 values and greater changes in fractal dimension. On the other hand, the temperature of the coal gradually decreases along the axis of the specimen (from the end where the ultrasound is generated to the other end). The higher the moisture content is, the smaller the temperature increase due to ultrasonic excitation. The ultrasonic waves accelerate the vaporization of moisture inside the coal mass, and this vapor promotes the development of pores and overflows. As a result, a virtuous circle is formed: the porosity and permeability of the fracturing coal mass are increased, which further promotes the desorption of the CBM. This, to some extent, also increases the connectivity between the pores in the coal mass.

1. Introduction

China has abundant coalbed methane (CBM) resources. It is estimated that there are approximately $3.7 \times 10^{13}\,m^3$ of this valuable resource buried in China in reservoirs shallower than 2 km, ranking the country third in the world (Lin H et al., 2016; Li H et al., 2016; Tang Z et al., 2016). CBM is classed as one of the new clean energies. Therefore, developing methods for its rapid and efficient extraction can be of great benefit with respect to improving China's energy structure. In addition, its extraction reduces the likelihood of gas accidents occurring in China's coal mines and helps relieve the effects of climate change. However, these CBM reservoirs are generally characterized by low permeability (70% have permeabilities lower than 1 mD) and are highly compact, which seriously inhibits the efficient extraction of CBM. Thus, it is necessary to improve the permeability of coal seams by using efficient permeability-increasing measures (Huang, 2016; Ye, 2000; Xian, 2000).

Ultrasonic technology shows numerous advantages in this respect. These advantages include being non-polluting, involving low energy consumption, being highly efficient, and having a concentrated form of energy. Therefore, ultrasonication is widely used in various situations involving the treatment and removal of plugs from oil reservoirs,

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increasing production from oil wells, and increasing injection efficiency (Nie B et al., 2004; Carette and Staquet, 2016).

Toozandehjani et al. directly explored the relationship between the characteristics of the ultrasound and microstructures inside substances (Toozandehjani M et al., 2015). Hamidi simulated the change in the viscosity of oil and heavy oil in porous media due to the effect of ultrasonic excitation (Hamidi H et al., 2015; Grybas I et al., 2016; Mohammadian E et al., 2013; Hamidi H et al., 2014). The development of ultrasonic technology and equipment for extracting shale gas from waste oil wells has also been studied (Mullakaev M S et al., 2015; Abramov V O et al., 2013). Korkut used experimental simulations to investigate the effect of varying the power and frequency of the ultrasonic waves on the process used to prepare biodiesel (Korkut and Bayramoglu, 2016). On the basis of a conceptual model built via laboratory tests, Couvreur studied the attenuation of ultrasonic waves in limestone and described the steps involved in rock failure (Couvreur JF et al., 2001). Kodama et al. investigated the distribution of bubbles within an acoustic field, the behavior of cavitating bubbles, the interactions between bubbles and shock waves, and energy changes caused by cavitation (Kodama and Tomita, 2000; Vichare NP et al., 2000). Shchukin theoretically analyzed the effect of ultrasonic cavitation on a solid surface, thus providing a theoretical basis for the study of cavitation and shock waves inside coal masses resulting from ultrasonic waves (Shchukin DG et al., 2011). Tang verified the feasibility of using ultrasonic technology to increase gas permeability by promoting coal fracturing (Tang ZQ et al., 2016). Zhao explored ultrasound-mediated adsorption/desorption of CBM and noted that ultrasonic waves mainly induce coal fracturing through a combination of cavitation, mechanical vibration, and heating effects (Zhao, 2016). Using experimental and numerical simulations, Hu et al. revealed the mechanism of the heating effect that causes temperature increases and cracks in concrete subjected to ultrasonic excitation (Hu ZH et al., 2013). By using ultrasound to fracture coal, Xiao established the mechanism for the increase in methane permeability caused by the ultrasonication process (Xiao XC et al., 2013). Zhang et al. illustrated the mechanism responsible for the temperature increase during the ultrasonic excitation process and Alahmer explored the mechanical effects of ultrasonic vibration in the ultrasonic excitation process (Zhang CH et al., 2009; Alahmer and Aladayleh, 2016).

Although much research has been conducted on using ultrasound to promote coal fracturing, previous work has mainly concentrated on the effect of ultrasonication on the coal mass and its permeability and the laws governing CBM desorption. In contrast, the moisture content, a crucial factor influencing the ultrasound-induced fracturing effect, has rarely been addressed. In this study, we establish an experimental ultrasonic system to investigate the influence of the moisture content on the coal fracturing effect. The changes in the pores and temperatures inside a coal mass are determined by employing nuclear magnetic resonance (NMR) and infrared (IR) thermal imaging before and after ultrasonic fracturing. By analyzing the changes in the fractal dimensions of the pores inside the coal mass and in the distribution of the surface temperatures of the coal mass, the effect of moisture on the ultrasound-induced fracturing and heating effects is investigated. Our aim is to promote the development of coal fracturing using ultrasonic technology.

2. Experimental mechanism and procedures

2.1. Experimental system and devices

To study the influence of moisture content, coal fracturing experiments were carried out using the ultrasonic fracturing system shown in Fig. 1. The system is mainly composed of four parts: an ultrasound-generating system, a coal clamping system, an IR thermal imager, and an NMR detection system (shown as Fig. 1):

(1) Ultrasound generator: An intelligent NC ultrasonic transmitter was used with a generating frequency of 28 kHz (scanning range: 27.75–28.7 kHz). A liquid-crystal display provided access to various operating parameters such as current output power, working time, and frequency. The device had a maximum output power of 1 kW and could be operated continuously for a long time.
(2) Coal clamping system: To fix the specimens and transducer, we designed, assembled, and welded together a self-designed coal clamping system composed of a base, a lower holder, a specimen holder, and an upper holder. To avoid problems with resonance and reduce the attenuation of the ultrasonic waves, the holders were made of resin and the transducer was fixed through combined connections to the upper and lower holders (via grooves cut in the middle). The lower part of the transducer connected to the ultrasound generator (referred to as the 'ultrasound-generating end').
(3) NMR detection system: The system used employed a main field of 0.51 T, a radiofrequency (RF) source with a power of 300 W and an impulse frequency in the range 1.0–49.0 MHz (aimed at the H proton resonance frequency of 23 MHz), a controllable temperature in the range 25–35 °C, and magnets with a uniformity of 12.0 ppm. On this basis, the attenuation time inversed using the measured NMR transverse relaxation time (T2) ranged from 0.1 ms to 10 s.
(4) IR thermal imager: A Ti450 thermal imager (Fluke Company, US) was used in these experiments. Materials radiate electromagnetic radiation when their surface temperatures are above absolute zero, and the intensities and characteristic wavelengths of the electromagnetic radiation emitted also change with temperature. Electromagnetic radiation with wavelengths in the range 0.75–1 μm correspond to the IR part of the spectrum, and images observed by collecting this radiation can be used to deduce the surface temperatures of the substance emitting the radiation.

2.2. Experimental samples

The experimental coal sample is a cylindrical specimen made from the core of the rock; it is 120 mm long and has a diameter of 50 mm. The industrial analysis results for the coal samples are shown in Table 1. The data obtained in this experiment are based on the coal samples, and the variation law and the crack development law of the internal pore diameter of coal rock mass under different powers and working times are discussed.

2.3. Experimental procedure

The essential steps involved were as follows:

(1) Coal specimens were placed in a vacuum water saturation tester for 12 h under a negative pressure of 0.1 MPa. Their T_2 distribution spectra were then measured using NMR. The specimens were then centrifuged at 6000 r/min until the masses of the coal specimens remained unchanged (i.e., fluctuated by ± 0.001 g). Their masses and T_2 distributions were measured once again.
(2) Coal specimens were successively saturated in the vacuum water saturation tester for different durations of time. Mass measurements were used to adjust the moisture content of the different coal specimens to 0%, 2%, 4%, 6%, and 8%. IR thermal images were then taken of the coal specimens with different moisture contents.
(3) The coal specimens with different moisture contents were then subjected to ultrasonic excitation and the change in the temperature of the coal was detected using the IR thermal imager as fracturing proceeded. After 5 min, the coal specimens were weighed, and their T_2 curves and porosities were determined using NMR. Next, the specimens were saturated in the vacuum water saturation tester, and then a further measurement of their T_2 distributions and porosities was made. The coal specimens were then naturally dried to their original moisture-containing states.