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Mechanical behavior and fracture spatial propagation of coal injected with liquid nitrogen under triaxial stress applied for coalbed methane recovery

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ABSTRACT

Fracturing technology through liquid nitrogen (LN_2) injection alters the physical properties of coal and rock masses because of the thermal and pressure effects. In order to investigate heat transfer and fracture propagation behaviors under *in situ* geological condition with LN_2 injections, experimental work was conducted to study the LN_2 induced rock/coal failures under true triaxial stress conditions. During the experiments, the temperature, ultrasonic waves, and acoustic emission location detection were monitored to determine the intensity and complexity of specimen failure under singular or cyclic LN_2 injections. The results show that a single LN_2 injection mainly transfers heat through the solid skeleton and only damages areas adjacent to the injection tube. However, cyclic injections formed a propagated fracture network and the heat can sequentially transfer further along the induced fractures. Moreover, plastic deformation occurred in the entire volume of the sample and the main fractures coalesced until the sample failed. Based on the spatial locations of the acoustic emission sources, the dynamic fracturing within the sample progressed after LN_2 injection was clarified. The experimental results can provide evidences for the proposed crack propagation model for the coal masses. The research revealed that high-pressure nitrogen gas transferring liquid water to the tips of new fractures is essential for cyclic LN_2 injection to form effective frost-heaving forces and fracturing. Therefore, the fracturing efficiency of the cyclic LN_2 injection is far higher than that of singular LN_2 injections.

1. Introduction

In the course of coal production, the existence of CBM can lead to serious accidents such as gas outburst and explosion. In addition, as a strong greenhouse gas, CBM exhibits a greenhouse effect with a magnitude 21 times that of CO_2. Therefore, effectively extracting CBM can not only moderate energy shortages but also prevent gas disasters in underground coal mines and reduce greenhouse emissions (Kong et al., 2016; Mark and Gauna, 2016). Most gas in coal is storage as adsorbed gas in the pores (Zhang et al., 2016). Because coal seams are typically under high stress with low permeabilities (Liu and Harpalani, 2013), the seams have to be stimulated before CBM extraction to provide suitable channels for desorption and migration (Zhai et al., 2016). It is well-known that the conventional water-based hydraulic fracturing consumes tremendous amount of water and can damage groundwater reservoirs, thus it is being used sparsely for dry regions (Javadpour et al., 2015). Anhydrous fracturing techniques are now being widely explored by various researchers, mainly techniques using liquid nitrogen (LN_2) and carbon dioxide (Fei et al., 2015; Hong et al., 2016).

Liquid nitrogen's temperature is 77 K at atmospheric pressure, and it expands 696 times after gasification (at 294 K), during which the latent heat of vaporization is 5.56 kJ/mol. With these characteristics, a large amount of heat is absorbed during vaporization (Qin et al., 2016). Because natural joints in the coal, termed as “cleats,” contain water, when encounter with LN_2, water in the cleats is quickly frozen and expands due to the expanding LN_2. Because of the 9% volume expansion of the water-ice phase transition, and in theory this produces up to 207 MPa of frost heaving force in fissures in the coal (Sandström et al., 2012). Because of the influence of freeze–thaw on the stability of rocks and soil masses, many earth scientists and foundation engineers have conducted a large number of studies on freeze–thaw in the natural geomaterials (Cárdenes et al., 2012; Jamshidi et al., 2016; Liu et al., 2016; Lu et al., 2016; Wang et al., 2016).

In terms of fracturing techniques, McDaniel et al. (1997), Coetzee et al. (2014), and Grundmann et al. (1998) used LN_2 as a fracturing fluid for oil and gas stimulation. These pilot projects demonstrated LN_2 can effectively fracture the formation and increase the permeability of the reservoir rocks. Cai et al. (2016) studied the mechanical properties

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of coal before and after single LN_2 freezing events and pointed out that LN_2 freezing can damage coal and promote the development of induced fractures. The degree of damage positively correlates with the water saturation and water content. In another study, Cha et al. (2014) investigated the physical changes and crack propagation in samples of cement and sandstone during single episodes of LN_2 injection. These studies were performed without applying confining stresses, and it was found that the water expansion resulting from water-to-ice phase change was the main factor for fracture initiation and propagation in rocks (Cai et al., 2016; Cha et al., 2014). Quantitatively evaluating failure behavior of rock with LN_2 injections under triaxial stress condition is of great interest for understanding of the CBM formation stimulation.

Previous studies mainly focused on the structural alteration of coal or rocks after a single injection of LN_2 without applying confining stress to samples in the laboratory or testing the technique in the field where natural pressures existed. These studies also seldom investigated the fracturing mechanisms. Based on previous studies (Coetzee et al., 2014; Li et al., 2016), cyclic LN_2 fracturing of coal reservoirs was proposed. This technique increases the permeability of coal reservoirs and the production of CBM by means of multiple effects including cyclic freeze–thaw effects and LN_2 vaporization (Qin et al., 2016; Qin et al., 2017; Zhai et al., 2016). Owing to the expansion and repeated fracturing effects of the water-ice phase transition (Arosio et al., 2013; Sandström et al., 2012), LN_2 injection results in fracturing efficiency superior to that produced by traditional fluid fracturing approaches.

In terms of the fracturing of *in situ* coal seams using LN_2, this study explores the heat transfer and fracturing of coal seams during LN_2 injection under true triaxial stress. The induced damages caused by single and cyclic LN_2 injections are compared. This study revealed mesoscopic fracturing mechanisms and dynamic crack propagation after injecting LN_2 under true triaxial stress in an attempt to provide a theoretical basis for LN_2 fracturing so that it can be transformed for industrial-scale applications.

2. Experiments

2.1. Experimental system

To simulate the dynamic fracturing of coal using LN_2 under *in situ* conditions, the experimental system for triaxial LN_2 fracturing is shown in Fig. 1. The experimental system includes a true triaxial loading system capable of testing a sample up to the size of 200 mm cube, a LN_2 injection system, and a data monitoring and acquisition system. These three major sub-units are described in detail as below.

(1) The true triaxial loading system consisting of a hydraulic loading system and a stress servo-control system was used to mimic the *in situ* stress condition of subsurface formations. Through the multi-channel hydraulic loading system, the three principal stresses applied on the cubical sample can be applied and controlled independently. Loads were applied on samples by plates on which several sensors, like acoustic emission sensors and a temperature detector, were installed. The load control mode was used during triaxial loading and a maximum load of 2000 kN could be applied in the three orthogonal directions. A constant temperature heating system surrounded the loading chamber to simulate *in situ* desirable underground formation temperature. In this study, the temperature was maintained at constant of 323 K.

(2) The LN_2 injection system was composed of a self-pressurized LN_2 tank YDZ-180 (Sichuan Sheng Jie Cryogenic Equipment Manufacturing Co., Ltd.) and a reciprocating LN_2 pump BPN-35 (Hangzhou Pengya Gas Equipment Co., Ltd). The volume of the LN_2 tank was 180 L. In order to ensure adequate injection time, the maximum flowrate and maximum working pressure of the pump were chosen as 60 L/h and 20 MPa, respectively. 60 L/h can provide three hours of continuous injection of LN_2.

(3) The data monitoring and acquisition system included a pressure monitor, an acoustic emission instrument, strain gauges, and temperature detectors. Acoustic emission signals were recorded by a DDS5-32B acquisition system with eight channels (Beijing Softland Times Scientific & Technology, Co., Ltd., China). Acoustic emission sensor is NANO-30. The frequency range of the sensor is 100 Hz–1 MHz, and peak frequency is 230 kHz. Threshold of the collected data is 60 db.

2.2. Sample preparation

As shown in Fig. 2, the samples used in the experiments were $200 \times 200 \times 200\ mm^3$ cubical samples. It is difficult to collect and cut large cubic specimens for coals due to the richness of the fractures/cleats. All these factors pose difficulties for studying fracture propagation mechanisms for virgin coals (Huang and Li, 2015; Huang et al., 2014). Thus, analogous specimens, such as coal powder and cement, were used to manufacture samples for these experiments (Huang and Li, 2015). To ensure that the manufactured samples had similar mechanical properties to those of natural coal, published research on similar materials was consulted (Huang and Li, 2015) and the mechanical properties of samples made with different ratios of starting materials were tested. It was found that samples prepared with coal powder + plaster + cement + sand in a 4:1:3:2 ratio was most similar to natural coal. The physical and mechanical properties of the manufactured samples are shown in Table 1. When the samples were molded, the LN_2 injection tube was cast into the samples as shown in Fig. 2(a). There are many methods for evaluating the uncertainty (Hamdia et al., 2017; Vu-Bac et al., 2016), but the research reduce the uncertainty of the tests through sample screening tests. In the experimental protocol, specimen density and wave-velocity tests were conducted on all the samples and the samples with very similar density and wave-velocity were finally selected for the subsequent freezing-thaw measurements. During LN_2 injection, temperature sensors were placed on the surface of the samples and at the bottom of 50 mm deep temperature monitoring holes; the locations of these holes and sensors are shown in Fig. 2(c). Four acoustic emission probes were placed on two sides of the sample as shown in Fig. 2(b). Three samples were used in each test for repeated testing. As the samples are uniformity and similarity, the experimental results were very similar. Therefore, this research chose one of them for analysis.

To study crack propagation in *in situ* coal seams fractured by LN_2, the triaxial stresses used to simulate the pressure environment for *in situ* seams were determined according to the previous studies and confining pressures on a typical coal seam (Huang et al., 2014; Li et al., 2014). The stresses used in the experiments were $\sigma_1 = 8.17$ MPa, $\sigma_2 = 6.62$ MPa, and $\sigma_3 = 3.34$ MPa. The loading mode is shown in Fig. 2(b).

2.3. Experimental procedures

These experiments investigated sample fracturing using both single and cyclic LN_2 injections. Before each experiment, the sample was first saturated with water and then placed in the triaxial pressure chamber; the temperature of the constant heating system was set to 323 K. The acoustic emission and temperature probes were attached and connected with the monitoring equipment and the LN_2 pump was connected to the LN_2 injection tube through soft metal tube. Then the pressures in three directions were increased to reach the desired pressures ($\sigma_1 = 3.34$ MPa, $\sigma_2 = 6.62$ MPa and $\sigma_3 = 8.17$ MPa) by using the servo mechanism. The LN_2 pump was turned on to inject LN_2 into the samples through the injection tube for fracturing. The rotation speed of the LN_2 pump was maintained at 140 r/min during the injection, and the constant flow was 60 L/h. Therefore, we can calculate the output of LN_2 by multiplying the flow by the LN_2 injection time.

The single LN_2 injection was conducted for 10,000 s, and the cyclic LN_2 injections were cycled through nine cycles for a total time of 10,000 s. Each cycle lasted for about 500 s and then thawed at 323 K for