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Evaluation of coal damage and cracking characteristics due to liquid nitrogen cooling on the basis of the energy evolution laws

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ABSTRACT

Liquid nitrogen used as fracturing fluid can significantly reduce reservoir temperature and cause damage and cracking effect on rock because of its extremely cryogenic characteristic. To investigate the cryogenic damage and cracking characteristics of liquid nitrogen on coal, coal samples were cool-treated with liquid nitrogen. Then, uniaxial compression tests were conducted on the cool-treated coal samples and intact samples (not cool-treated). The energy evaluation laws of intact and cool-treated samples during deformation and failure were compared. Results showed that liquid nitrogen cooling was able to improve the initial damage degree of coal, thereby leading to a significant effect on the energy evolution laws of coal. The elastic energy, dissipated energy, and absorbed energy of cool-treated samples were less than those of intact samples when the samples ruptured. During the initial loading stage, the ratio of dissipated energy of cool-treated samples was greater than that of intact samples. However, as the coal samples were about to rupture, the ratio of dissipated energy of intact samples was greater than that of cool-treated samples. The change in energy evolution laws of coal was mainly caused by the growth of micro-cracks inside coal, which can reflect the damage characteristics due to liquid nitrogen cooling. After liquid nitrogen cooling, the amount of micro-cracks inside coal increased, resulting in the deterioration of mechanical properties and the improvement of the fracturing performance in coalbed methane.

1. Introduction

Coalbed methane (CBM) is regarded as an important natural gas resource, which has been the focus of increasing attention around the world. However, hydraulic fracturing treatment has to be conducted to keep production at an economical rate because of the extremely low natural productivity of CBM (Aguilera et al., 2014). Coal contains numerous natural fractures and has a strong adsorption characteristic. As such, coal is likely to be damaged by external fluids and solid particles. During hydraulic fracturing, the high-pressure fluid mainly promotes the expansion of major fractures, but is ineffective in increasing the fracture density (Enayatpour et al., 2013), which is unfavorable for the improvement of the stimulation reservoir volume (SRV) of coal (Settari et al., 2012). As a result, fractured CBM wells often fail to perform satisfactorily. Hydraulic fracturing consumes a large amount of water and has the potential to pollute underground and surface water resources (Boudet et al., 2014; Jackson et al., 2013), which further restricts its large-scale application in arid areas.

With the rapid development of the oil and gas exploration and production technology, liquid nitrogen has been successfully applied as a fracturing fluid since the 1990s (Mcdaniel et al., 1997; Grundmann et al., 1998). Liquid nitrogen is expected to improve the fracturing performance of unconventional gas, such as shale gas (Rassenfoss, 2013). Liquid nitrogen is tasteless, colorless, and inert and does not have an aqueous phase. Thus, reservoir damage and environmental pollution issues can be avoided effectively. Liquid nitrogen can significantly reduce the temperature of rock when it comes in contact with the hot reservoir because of its extremely cryogenic characteristic (approximately −195.56 °C to −180.44 °C). In this case, significant thermal stress inside the rock will be induced, which can promote the extension of initial cracks and even produce new cracks (Kim and Kemeny, 2009; Cai et al., 2014). During fracturing, cooling effect can contribute to the generation of microfractures orthogonal to the major fracture plane to help prop the fracture open and improve the fracture density (Mcdaniel et al.,

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1997; Tran et al., 2012). The key point of current technology for CBM fracturing is how to reopen the natural fractures (i.e., butt and face cleats), thereby forming the fracture network that connects the artificial and natural fractures (Settari et al., 2012; Cipolla et al., 2009). Therefore, investigating the cracking characteristics of coal due to liquid nitrogen cooling is important to reveal the coal fracturing mechanism during liquid nitrogen fracturing and to provide theoretical guidance for the application of liquid nitrogen fracturing technology for CBM.

Mcdaniel et al. (1997) observed that the coal samples separated into small pieces when submerged in liquid nitrogen. Audible cracking sounds were heard when the coal samples were warmed again. Grundmann et al. (1998) conducted theoretical calculations and determined that microfractures orthogonal to the major fracture plane are generated by the cracking effect of liquid nitrogen cooling. Ren et al. (2013) established a thermal stress model to analyze the effect of liquid nitrogen cooling on coal matrix deformation. Then, they verified the cracking effects of coal attributed to liquid nitrogen cooling by using the ultrasonic method. Cha et al. (2014) developed laboratory setups and simulated the liquid nitrogen fracturing process in the laboratory. They determined that liquid nitrogen cooling can induce evident macrocracks on the rock surface and promote the growth of micro-cracks inside rocks. Zhang et al. (2015) indicated that liquid nitrogen cooling would lead to shrinkage of coal, thereby promoting the propagation of micro-cracks inside coal and the improvement of permeability effectively.

The aforementioned studies mainly focused on the change in rock microstructure. However, only a few investigations focused on rock damage and cracking characteristics, let alone coal. In this study, coal samples were cool-treated with liquid nitrogen to analyze the damage and cracking characteristics due to liquid nitrogen cooling. Then, uniaxial compression tests were conducted on intact (not cool-treated with liquid nitrogen) and cool-treated samples. The energy evolution laws of coal during the loading process were analyzed on the basis of stress and strain. The energy evaluation laws of cool-treated and intact coal samples were also compared to evaluate the damage and cracking characteristics of coal attributed to liquid nitrogen cooling.

2. Energy evolution laws during rock deformation and failure

The energy evolution law is an important and extensively used method in rock mechanical testing and analysis to investigate the rock deformation and failure processes. Compared with the conventional stress–strain method (Martin, 1993), this method investigates the rock failure process from the energy viewpoint, which is closer to the nature of rock failure (Zhang, 2013). According to the mesoscopic mechanics, rock failure is the process of damage evolution, which mainly presents as the development of micro-cracks. With the growth of micro-cracks, the rock needs to absorb external energy to produce new crack surfaces. As such, a part of the energy absorbed by rock will dissipate in the form of crack propagation, which is called dissipated energy. The other part of the energy absorbed by rock will be reserved in the form of elastic deformation, which is called elastic energy. Xie et al. (2005) indicated that the nature of rock failure is the continuous expansion of the initial defects and the deterioration of the mechanical properties because of energy dissipation. For the same type of rock, the energy evolution laws are mainly influenced by the distribution of initial micro-cracks (Zhang, 2013), which affects the process of energy dissipation and leads to different energy dissipation characteristics of rocks. As such, the theoretical foundation of the evaluation of rock damage and cracking characteristics on the basis of the energy evolution laws is achieved.

Many types of energy are involved during the loading process of rock, but are impossible to monitor all of them in the laboratory. In general, elastic energy and dissipated energy are mainly monitored to analyze rock deformation and failure. If the thermal energy exchange between the rock and its surroundings is neglected, then the absorbed energy can be regarded as the sum of the elastic energy and dissipated energy according to first law of thermodynamics.

Given that elastic energy is reversible, the absorbed energy, elastic energy, and dissipated energy can be calculated by using the stress–strain curve of rock. As shown in Fig. 1, the area enclosed by the stress–strain curve and the unloading curve represents the dissipated energy density and the area between the unloading curve and the horizontal axis (shaded part) represents the elastic energy density. The integral area of the stress–strain curve represents the absorbed energy density. The absorbed, elastic, and dissipated energy densities are expressed by the following formulas:

$$U = \int_0^{\varepsilon_i} \sigma \mathrm{d}\varepsilon, \tag{1}$$

$$U^e = \frac{1}{2}\sigma_i \varepsilon_i^2 = \frac{1}{2}\frac{\sigma_i^2}{E_u}, \tag{2}$$

$$U^d = U - U^e, \tag{3}$$

where U is the absorbed energy density; ε is the axial strain; σ is the axial stress; U^e is the elastic energy density; E_u is the unloading elasticity modulus; and U^d is the dissipated energy density.

3. Materials and methods

3.1. Materials

Coal used in the experiments was obtained from Ordos, Inner Mongolia Autonomous Region. All samples were drilled from the same coal block and were processed into cylinders with 25 mm diameter and 50 mm height to minimize the effect of rock heterogeneity on the experimental results. The samples with regular shape and intact structure were selected. The density and

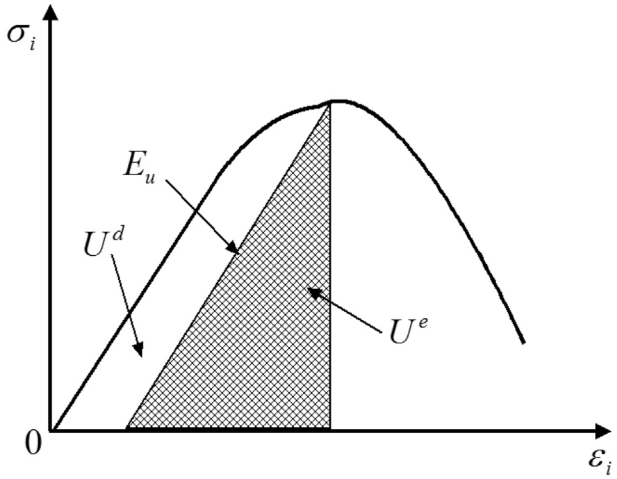

Fig. 1. Relationship between elastic energy and dissipated energy in the stress–strain curve.