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Experimental research on rock fracture failure characteristics under liquid nitrogen cooling conditions

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A B S T R A C T

As liquid nitrogen is injected into a wellbore as fracturing fluid, it can rapidly absorb heat from warmer rock and generate cryogenic condition in downhole region. This will alter the physical conditions of reservoir rocks and further affect rock failure characteristics. To investigate rock fracture failure characteristics under liquid nitrogen cooling conditions, the fracture features of four types of sandstones and one type of marble were tested on original samples (the sample without any treatment) and cryogenic samples (the samples just taken out from the liquid nitrogen), respectively. The differences between original samples and cryogenic samples in load-displacement curves, fracture toughness, energy evolution and the crack density of ruptured samples were compared and analyzed. The results showed that at elastic deformation stage, cryogenic samples presented less plastic deformation and more obvious brittle failure characteristics than original ones. The average fracture toughness of cryogenic samples was 10.47%–158.33% greater than that of original ones, indicating that the mechanical strength of rocks used were enhanced under cooling conditions. When the samples ruptured, the cryogenic ones were required to absorb more energy and reserve more elastic energy. In general, the fracture degree of cryogenic samples was higher than that of original ones. As the samples were entirely fractured, the crack density of cryogenic samples was about 536.67% at most larger than that of original ones. This indicated that under liquid nitrogen cooling conditions, the stimulation reservoir volume is expected to be improved during fracturing. This work could provide a reference to the research on the mechanical properties and fracture failure of rock during liquid nitrogen fracturing.

Introduction

Over past few decades, hydraulic fracturing has played a significant role in oil and gas stimulation [1,2]. However, this technology faces many challenges because of its heavy dependence on water [3,4]. The water used in hydraulic fracturing can generate the issues of water blocking and water sensitivity as it makes contact with formation rock [5,6]. Consequently, the performance of stimulation will be impaired. To solve this problem, the idea of liquid nitrogen fracturing was proposed [7–9]. Fortunately, field trials have proved that it is feasible to use liquid nitrogen as a fracturing fluid [10,11]. In field application of liquid nitrogen fracturing, liquid nitrogen and nitrogen gas are injected through tubing pipe and tubing-casing annulus. Additionally, vaporizers are installed on the wellhead to realize the vaporization of liquid nitrogen. The key procedures of this technology can be described as follows [10,11]: in the beginning, nitrogen gas is injected to pressure up the wellbore until a stable annulus pressure is produced. Secondly, liquid nitrogen is injected into the wellbore through tubing pipe. Meanwhile, nitrogen gas is still pumped to create fractures in formation rock. As artificial fractures are created, the liquid nitrogen injected through the tubing pipe can reduce the temperate of the walls of fractures and further generate thermal fractures. Thirdly, as the procedure of liquid nitrogen injection is finished, nitrogen gas is pumped through tubing pipe to replace the residual liquid nitrogen inside the tubing pipe. When the temperature of tubing pipe recovers to greater than zero, the water can be injected into the formation. As the water contacts with cryogenic formation, it will freeze into ice to seal artificial fractures. Fourthly, the pipes and wellhead are heated by the nitrogen gas. Fifthly, the well is shut in and pressure curves are monitored for about 15 min. The above fracturing procedures have been applied in a few wells. So

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it can be seen that fracturing with liquid nitrogen are feasible and efficient.

As it offers excellent compatibility with reservoir fluids and is waterless, liquid nitrogen does not produce the problems of both formation damage and water consumption. As a result, the technical and environmental issues of conventional hydraulic fracturing are overcome. In addition, liquid nitrogen is an extremely cold fluid, which can rapidly absorb heat from the warmer formation rock as it is pumped into the wellbore. Due to the sharp decrease in the temperature of formation rock, the physical properties of rock are expected to be altered. Thus, the most obvious feature of liquid nitrogen fracturing is the super-cryogenic characteristic of the fluid, which leads to the rock suffering greater damage compared with conventional fracturing technologies. In addition, the thermal stress was also proved to be beneficial for the stimulation performance of reservoir [12]. However, before liquid nitrogen fracturing can be widely adopted in, many fundamental and technical problems should be solved, such as the alteration of rock mechanical properties due to liquid nitrogen cooling and the efficient multistage fracturing method.

With respect to the former issue, much fundamental research has been conducted. McDaniel et al. [10] found that a coal sample was separated into smaller cuboidal fragments as it was submerged into liquid nitrogen. This finding validated the feasibility of rock cracking with liquid nitrogen. Subsequently, successful field trials suggested that liquid nitrogen can be safely injected into a moderate-depth formation as a fracturing fluid [10,11]. Ren et al. [13] measured the ultrasonic wave velocity of coal samples before and after liquid nitrogen cooling. The results indicated that the micro-cracks inside the sample expanded, which led to the decrease in wave velocity. To investigate the effect of liquid nitrogen cooling on rock pore structure and failure characteristics, Cai et al. [14,15] examined the pore structure damage and cracking effect induced by liquid nitrogen cooling by means of scanning electron microscopy (SEM), nuclear magnetic resonance (NMR), acoustic emission (AE) testing, uniaxial compression, *etc.* These findings showed that cooling with liquid nitrogen could promote the expansion of inter-grain micro-fissures, enhance the connectivity of pore structure, improve the extent of brittle failure, and weaken the mechanical strength of rocks. Cha et al. [3,16] researched the crack distribution characteristics on rock surfaces and the micro-crack expansion features attributed to liquid nitrogen cooling using self-designed experimental apparatus. They found that liquid nitrogen cooling can promote the creation and propagation of micro-cracks inside the rock. Based on freeze-thaw cycling tests with liquid nitrogen, Li et al. [17] indicated that the micro-fissure width of a coal sample increased with the growth of temperature difference and water saturation. Zhai et al. [18] and Qin et al. [19,20] performed laboratory tests to research the effect of liquid nitrogen freeze-thaw on the pore structure and mechanical properties of coal sample. Their results showed that liquid nitrogen freeze-thaw cycles can induce the damage in the pore structure and the increase in the permeability of the coal. As a result, the effective, and total, porosities increased while the strength, elastic moduli, and wave velocity decreased due to freezing with cyclic liquid nitrogen injection.

Previous research has proved that liquid nitrogen cooling can induce the rock pore structure damage and alter the mechanical properties. However, these studies mainly focused on the changes in physical properties after the rock was cooled or frozen with liquid nitrogen. As is known, reservoir rock always comes into contact with the liquid nitrogen during fracturing treatment. The formation is fractured due to the coupling effect of cryogenic temperatures and high pressure of the liquid nitrogen. In other words, the formation rock is damaged and fractured under the cooling conditions during entire liquid nitrogen fracturing process. Thus, it is also worthwhile to investigate the changes in rock mechanical properties and fracturing characteristics in a cooling state. In this study, five different rocks (four types of sandstones and one type of marble) were processed into disks with central cracks. An axial load was applied to each original sample (the sample without any treatment) and cryogenic sample (the sample just removed from the liquid nitrogen) to drive them to be fractured. Based on the experimental results, the fracture failure characteristics, fracture toughness, energy evolution, and fracturing degree of cryogenic samples were analysed by comparing them with original ones. The results could help to understand the changes in rock mechanical properties under liquid nitrogen cooling conditions.

Experimental procedures

Samples

Five types of rocks (four types of sandstones and one type of marble) were used in the experiments and six rock samples were drilled from each type of rock. Finally, a total of 30 samples were prepared. As shown in Fig. 1, each sample was processed into a disk with a central crack. The diameter and thickness of the disk were 100 mm and 30 mm respectively. The length of the central crack was approximately 25 mm. In order to distinguish the samples conveniently, four different types of sandstones were labelled sandstone 1$^{\#}$, sandstone 2$^{\#}$, sandstone 3$^{\#}$, and sandstone 4$^{\#}$. Each sample was numbered in the form of "*X*-*Y*", where the "*X*" was related to the rock type and the "*Y*" represented the sample number. The sandstones 1$^{\#}$–4$^{\#}$ were marked with the numbers of "1–4", and the marble was assigned number "5". For example, the six samples of sandstone 1$^{\#}$ were labelled: 1–1$^{\#}$, 1–2$^{\#}$, 1–3$^{\#}$, 1–4$^{\#}$, 1–5$^{\#}$, and 1–6$^{\#}$. The samples of other types of rocks were also labelled in a similar manner. Partial samples are shown in Fig. 2.

Experimental methods

During the experiment, the samples labelled X-1$^{\#}$-X-3$^{\#}$ were submerged in liquid nitrogen for sufficient cooling. As these samples were removed from the liquid nitrogen, uniaxial compression tests were immediately conducted to measure their deformation and failure characteristics. The uniaxial compression testes were also performed on the samples labelled X-4$^{\#}$–X-6$^{\#}$. For the purpose of expressing clearly, those samples just removed from the liquid nitrogen were called "cryogenic samples", and others were called "original samples". As shown in Fig. 3, the loading direction was

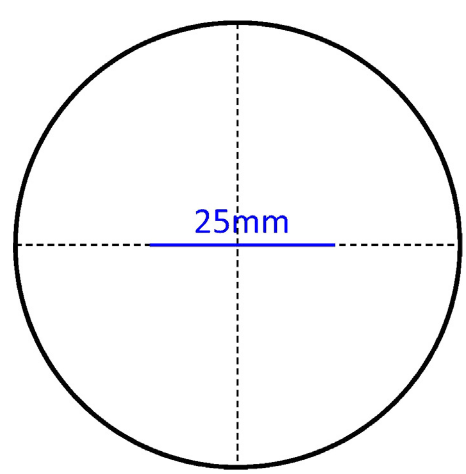

Fig. 1. Schematic diagram of a rock sample.