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Investigation on the damage of high-temperature shale subjected to liquid nitrogen cooling

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ABSTRACT

Cryogenic nitrogen fracturing can provide a new insight into the stimulation of deep shale gas reservoirs. In order to investigate the physical and mechanical behaviors of high-temperature shales (298–533 K) subjected to LN_2 cooling, we tested the permeability, P-wave velocity and uniaxial compressive strength (UCS) of shale specimens. In the experiment, two cooling ways were used and compared: cooling by LN_2 immersion and cooling in air naturally. The scanning electron microscope (SEM) was employed to observe the micro-structural changes after cooling. To determine the effect of cooling rate on the rock damage, we conducted a transient 3D thermo-mechanical simulation using ABAQUS. The experimental results indicate that LN_2 cooling induces significant damage in shales. At any given shale temperature, the enhancement of permeability and reductions of UCS and P-wave velocity after LN_2 cooling are greater than those after air cooling. Differences in the physical and mechanical properties between two cooling groups become more significant with shale temperature rising. LN_2 cooling can create obvious cracks on the surface of shales, and size and number of these cracks increase as temperature rises. According to the SEM observation, most of the cooling induced cracks are inter-granular cracks which are mainly attributed to the mismatch of thermal properties between particles. The simulation results indicate that the cooling rate has a positive impact on the thermal stress. Faster cooling rate generates higher tensile stress in the exterior region of rocks, which helps intensify the deterioration of the rocks.

1. Introduction

Unconventional natural gas plays an important role in meeting the demand for energy and reducing the global CO_2 emissions (Gregory et al., 2011; Vedachalam et al., 2015). It contains four main categories, including shale gas, coalbed methane, tight gas and gas hydrates (Wang et al., 2014). Among them, shale gas is the fastest growing source, and will provide the largest contribution to the growth of total natural gas production in the future (Vidic et al., 2013). Shale gas is the natural gas trapped in the tight shale formations with extremely low porosity and permeability. Hydraulic fracturing is an essential technology in the economic exploration of shale gas, which involves in creating artificial fractures with sufficient permeability. However, the conventional massive hydraulic fracturing is increasingly criticized recently due to the risks such as water consumption, environmental contaminations and formation damage (Stringfellow et al., 2017; Shrestha et al., 2017; Xu et al., 2016; Zhou et al., 2016).

To address these issues, several waterless fracturing technologies, such as CO_2 fracturing, LNG fracturing, etc., have been proposed and applied in the field (Wang et al., 2012, 2016a; Middleton et al., 2015; Qin et al., 2017). Liquid nitrogen fracturing is one of such technologies, and was first reported by Mcdaniel et al. (1997) and Grundmann et al. (1998) in 1990s. In this technology, liquid nitrogen (LN_2) is used as a substitute for the conventional water-based fracturing fluid (Cai et al., 2016a). The super-cold LN_2 can induce thermal stress by cooling the formation rocks and relax the in situ hoop stress (Charlez et al., 1996). If the hoop stress reduces below the injection pressure, a fracture will be generated and propagated. Moreover, LN_2 cooling can deteriorate mechanical properties of rocks and lift the pressure by expansion. These two effects further facilitate the fracture initiation and help form longer fractures in the reservoir (Cai et al., 2016a; Wu et al., 2018). The fact that LN_2 cooling facilitates fracture initiation has already been proved by Cha et al. (2014) and Alqatahni et al. (2016) via laboratory tests. They conducted a series of cryogenic fracturing experiments on concrete, sandstone and shale samples. Their results show that the breakdown pressure dropped up to nearly 40%. Besides, the LN_2 cooling can even induce many secondary fractures perpendicular to the main fracture. The secondary cracks grow and connect with each other, and

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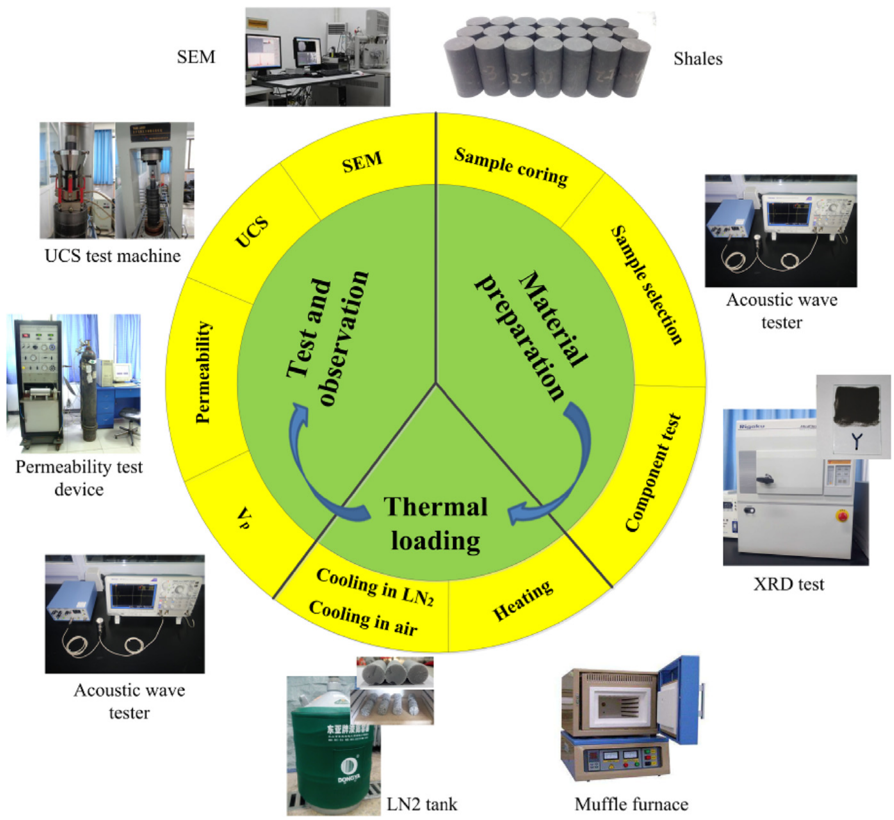

Fig. 1. Experimental procedures and equipment.

thus enhance the reservoir permeability significantly.

Liquid nitrogen fracturing technology can even be applied in hot dry rock geothermal (HDR), which is the most abundant geothermal resource. Temperature of HDR varies from 150 °C to 500 °C at depth of 5–6 km. Large temperature difference between liquid nitrogen and rock may induce more significant damage in formation and enhance the stimulation efficiency of geothermal reservoir dramatically. It is estimated that energy content of HDR is 300 times greater than the fossil fuel resource. Economic development of HDR will contribute a lot to the world energy supply, and simultaneously reduce global carbon dioxide emissions.

Temperature changes have a great impact on the physical and mechanical behaviors of rocks. Most previous literature are focused on the effect of heating, but only few priors investigated on rock deterioration induced by cooling. Actually both heating and cooling treatments can create cracks in rocks, reduce elastic modulus, enhance permeability and etc. However, magnitude and mechanisms of the rock physical and mechanical responses for heating treatment are quite different from those for cooling treatment. Rock property changes in heating are mainly attributed to the dehydroxylation of losing constitution water and solid mineral expansion (Zhang et al., 2016), while the changes in the cooling treatment are mainly caused by the thermal stress which highly depends on the temperature change rate (Shao et al., 2014; Zhang et al., 2017). During cooling treatment, the thermal stress is usually tensile. The tensile stress induced by rapid cooling, also called thermal shock, can obvious damage the rocks by destroying the cementation in particles and changing the pore structures. Kim et al. (2014) investigated the effect of rapid thermal cooling on rock mechanical properties. The specimens (igneous, sedimentary, and metamorphic rocks) were first heated to different temperatures, and then cooled rapidly with a fan. Significant changes in mechanical properties were observed. Besides ventilation cooling, water bath cooling is also a common rapid cooling method. Shao et al. (2014) investigated the effect of water bath cooling on the mechanical behavior of heated granites. The results indicated that the uniaxial compressive strength (UCS) of granites cooled in water did not drop a lot until the rock temperature reached to 400 °C. Wang et al., 2016b, 2017 carried out dynamic mechanical experiments on the red sandstone subjected to repeated thermal shock. Water bath was also used in their experiments to cool the hot sandstone rapidly, and a significant deterioration of strength was found after treatment. In the aspect of liquid nitrogen cooling, Cai et al., 2014, 2015, 2016a, 2016b have conducted a series of experimental investigations. He tested the permeability and UCS of coal samples before and after liquid nitrogen cooling. The results show that the permeability was improved up to 93.55%, and the UCS was decreased by 33.74%. In order to reveal the mechanisms of rock damage after liquid nitrogen cooling, the scanning electron microscope (SEM) and nuclear magnetic resonance (NMR) were adopted. He found that liquid nitrogen cooling could generate new micro-cracks and expand the pre-existing cracks in rock samples. However, previous studies about LN_2 cooling induced damage are mainly focused on the room-temperature rocks. The physical and mechanical responses of high-temperature rocks are quite different from those of room-temperature rocks. With the rapid development of natural gas in deep shale, it is becoming more and more necessary to find out the influence of LN_2 cooling on the high-temperature shale in deep formations to further apply liquid nitrogen fracturing technology in deep shale stimulations.

In present paper, we mainly aim to investigate the damage characteristics of high-temperature shales subjected to LN_2 cooling. The permeability, P-wave velocity and UCS were tested and analyzed. We also adopted the SEM to observe the changes of pore structures and micro-cracks. Finally, a transient thermo-mechanical coupling analysis was conducted to reveal the damage mechanisms and provide some explanations for the experimental results. Results in our experiment are expected to provide some new insights into the stimulation of high-temperature reservoirs such as deep shale gas reservoirs and even geothermal reservoirs.