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Experimental study of thermal-crack characteristics on hot dry rock impacted by liquid nitrogen jet

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ABSTRACT

Liquid nitrogen jet fracturing is a novel stimulation technology, which is expected to be suitable for hot dry rock (HDR) reservoirs. Due to the large temperature difference between hot rock and cryogenic fluid, a great number of thermal cracks would be created during fracturing process, which is conductive to improve the penetration capacity of formation. In this study, a set of experiments were conducted to investigate the characteristics of thermal cracks. In these experiments, granite specimens with temperatures ranging from 200 °C to 300 °C were impacted by the low-pressure liquid nitrogen jet. The complexity and connectivity of cracks were quantitatively analyzed by a fractal method. The permeability and ultrasonic velocity of the granite specimens were tested in order to evaluate the damage conditions caused by thermal stress. Additionally, scanning electron microscope was adopted to analyze the microscopic characteristics of the thermal cracks. The results show that the heating process has a slight effect on thermal-crack generation compared with the liquid-nitrogen impact. The cracks mainly concentrate in the region near the impingement surface, due to the large temperature gradient there. The impacted rock breaks as the effects of tensile stress and shear stress. With an increase of initial rock temperature, the number of thermal cracks increases, and a more complex crack-network is formed in each specimen. Transient pulse evaluation and ultrasonic velocity measurements indicate that the impact of liquid nitrogen jet can improve the permeability and cause the damage of hot rock noticeably. This study demonstrates the important effect of thermal stress on crack generation during liquid nitrogen jet fracturing for HDR reservoirs, and the results shed light on the exploitation of HDR energy.

1. Introduction

Hot dry rock (HDR), as an abundant, clear and wide-spread energy, has been considered as one of the most potential renewable resources in the future (Caulk et al., 2016; Shi et al., 2018). It was reported that the total HDR heats stored within subsurface of 3–10 km depths in the United States and China can reach about 1.4×10^{25} J and 2.52×10^{25} J respectively (Panel, 2006; Wang et al., 2013). The Enhanced Geothermal Systems (EGS) is an efficient means to extract the heat from deep formations, by circulating the working fluid between injection wells and production wells (Grant, 2015). However, the permeability of HDR reservoirs is normally pretty low, making it difficult for fluid to flow in these formations. Therefore, stimulation treatments need to be performed to commercially exploit the HDR resources (Zimmermann and Reinicke, 2010).

Some stimulation methods have been developed to improve the HDR permeability, such as, hydraulic fracturing (Legarth et al., 2005), thermally induced fracturing (Charlez et al., 1996) and chemical stimulation (Nami et al., 2008). At present, hydraulic fracturing is considered as the most effective means, which has been widely applied in oil and gas industry (Gale et al., 2007; Sun et al., 2017). However, the single large fracture is normally generated during hydraulic fracturing, which is not expected in EGS project. In order to increase heat transfer area in formation, the multiple fractures or reticular fractures are set as a target in HDR fracturing process (Zhou et al., 2018). The hydraulic jet fracturing technology by integrating abrasive jet perforating, hydraulic fracturing and hydrodynamic sealing, can achieve the multi-stage fracturing with a lower initiation pressure (Li et al., 2010; Sheng et al., 2013). Nevertheless, this method consumes a large amount of water, and still cannot create the suitable fracture structures in formation for HDR exploitation.

The novel waterless fracturing technology, liquid nitrogen fracturing has been successfully used in some oil and gas wells (Grundmann et al., 1998; McDaniel et al., 1997). Field applications indicate that the

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performance of wells was improved noticeably after the stimulation of liquid nitrogen, and little damage was caused to casing integrity. Researchers also carried out a series of laboratory experiments and numerical simulations to investigate the feasibility of liquid nitrogen as a fracturing fluid. The experiment by Cha et al. (2014) shows that huge thermal stresses are generated in rock surrounding the wellbore during cryogenic fluid fracturing. Theses stresses are mainly in the form of tensile stress, which would promote the generation and extension of cracks in formation. Zhang et al. (2018b) built a 3D model to analyze the heat transfer and thermal-stress distribution in bottom-hole rock during liquid nitrogen fracturing process. The simulation results support the view of Cha et al. (2014), and show that the tensile stress induced by rapid cooling far exceeds the tensile strength of common rocks. Cai et al. (2015) evaluated the thermal effect of liquid nitrogen on coal damage by laboratory experiment. Their study indicates that coal permeability increases by 48.89%–93.55% because of liquid nitrogen super-cooling. The research by Perkins and Gonzalez (1985) shows that the secondary cracks generated by thermal effect are perpendicular to the main cracks, which are beneficial to form a complex fracture structure in formation. Considering the unique low-temperature characteristic, Zhang et al. (2018a) proposed to use liquid nitrogen to fracture the HDR reservoirs. In fracturing operation, the liquid nitrogen is injected into formation with high pressure and large displacement firstly, to create a single or several large cracks. Then, the reservoir is impacted by the liquid nitrogen with a low flow rate for a long time. The cryogenic fluid would enter into the existing cracks and create new thermal cracks in formation. The expected fractures pattern in liquid nitrogen fracturing for HDR reservoir is shown as Fig. 1.

However, liquid nitrogen lacks of adequate viscosity to carry proppant flowing in reservoir (Rudenko and Schubnikow, 1968). Raising flow rate may improve the proppant carrying ability of working fluid (Gupta and Bobier, 1998), whereas this method would put a huge burden on pumps and pipelines as well. To adapt the low viscosity of liquid nitrogen, ultra-light weight proppants can be used in fracturing operation (Kendrick et al., 2015). In addition, some researches even show that fracturing with cryogenic fluid could rely on self-propping means to keep artificial fracture open (McDaniel et al., 1997). Nevertheless, whether the cracks generated in cryogenic fluid fracturing can meet the demands of fluid flow in reservoir, need to be further investigated.

Researchers have employed diverse methods to evaluate the properties change of fractured rock. Kim and Kemeny (2009) investigated the influence of thermal impact on the rock mechanical properties by supersonic wave velocity and tensile strength tests. Cai et al. (2014) used the methods of scanning electron microscope (SEM) and nuclear magnetic resonance to evaluate the rock damage cooled by liquid nitrogen. Based on the experiments, the crack-structure changes and the

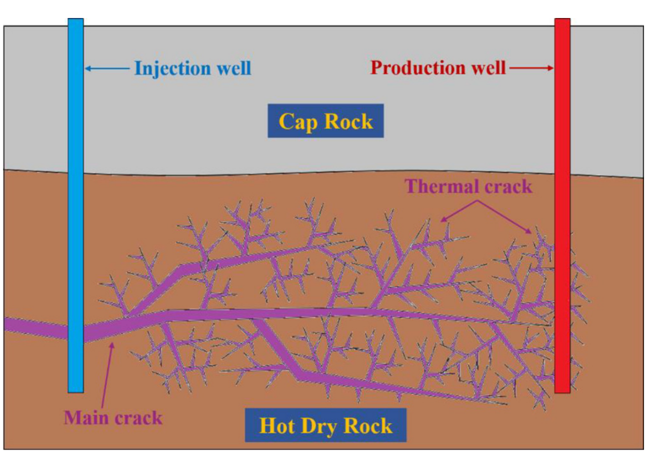

Fig. 1. Schematic diagram of fracture mode in liquid nitrogen fracturing.

micro-fissure distribution can be characterized. The pressure-decay tests was employed by Cha et al. (2018) to measure the permeability change of rock specimen treated by liquid nitrogen. For fracturing cracks, the fractal method is one of the most useful means to quantitatively describe the complexity and connectivity. Researches (Liu et al., 2016; Roy et al., 2007) show that the permeability as well as the porosity of fractured rock has a good correlation with the fractal dimension.

In the process of HDR fracturing with liquid nitrogen, the thermal cracks would play a vital role to improve the formation permeability and connectivity. This study carried out a set of experiments to investigate the cracks induced by thermal stress. In experiment, the hot granite rocks were impacted by the low-pressure liquid nitrogen jet. The distribution of thermal cracks was analyzed by a fractal method. The permeability and ultrasound velocity were measured to evaluate the effect of liquid nitrogen jet on hot rock. The microscopic features of thermal cracks were presented by SEM observation.

2. Experiment design

2.1. Granite specimens

In this experiment, the granite rock is selected as the impacted specimen, which is common for HDR reservoirs. Our previous research (Zhang et al., 2018a) shows that the specimen size has a vital influence on the generation of thermal cracks in rock when impacted by liquid nitrogen jet. Since the limitation of laboratory conditions, the specimen boundaries cannot be effectively fixed in experiment, which affects the thermal-stress distribution noticeably. The previous experiments indicate that there are few thermal cracks generated on specimen (150 × 150 × 100 mm) with temperature below 300 °C. Increasing the size of specimen can reduce the effect of free-boundary. In this study, the rectangular specimen with size of 200 × 200 × 100 mm is adopted in impingement experiment. No obvious natural fractures exist on the surfaces of granite specimen, and other physical properties are shown in Table 1.

2.2. Experimental equipment

The purpose of this study is to investigate the characteristics of thermal cracks. Therefore, the low-pressure liquid nitrogen jet is employed in impingement experiment, in which the effect of liquid pressure on hot rock is small. The cracks in specimens are mainly created by the impact of thermal stresses.

The schematic diagram of experimental setup used to form low-pressure liquid nitrogen jet is shown as Fig. 2. It contains three parts, the gas cylinder, self-pressurization storage tank and fixed bracket. The liquid nitrogen is provided by the self-pressurization tank, which can pressurize the fluid up to 3.45 MPa by vaporizer. However, the pressure in self-pressurization tank is not stable because of the low evaporation rate in heating coil. Therefore, the high-pressure gas cylinder is adopted to maintain pressure stability in tank. The fixed bracket is used to fix the nozzle and adjust the injection standoff distance in this experiment. Due to the low acting force of liquid nitrogen jet and heavy weight of specimen, the rock need not to be fixed during experiment.

The rock permeability was measured by the high-pressure gas

Table 1
Physical properties of granite specimen.

Rock properties	Values
Density	2640 kg/m^3
Young's modulus	26.47 GPa
Poisson ratio	0.1050
Uniaxial tensile strength	4.210 MPa
Uniaxial compressive strength	84.47 MPa