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Laboratory Studies of Cryogenic Fracturing on Hot Dry Rock by Cyclic Injection

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ABSTRACT

Hot dry rock (HDR) geothermal energy exploitation is essential to meet the energy demand and achieve low-carbon solutions. Creation of complex fracture networks to enhance the thermodynamic efficiency and heat production in HDR is significant. Here, we presented a new reservoir stimulation concept, i.e. cyclic cryogenic fracturing, based on cyclic soft stimulation (CSS) which is originally put forth to mitigate the seismic events and improve the permeability enhancement process in Enhanced Geothermal System (EGS). In cyclic cryogenic fracturing, liquid nitrogen, an eco-friendly and super-cooling fluid (-196℃ at atmospheric pressure), is proposed to be an alternative fracturing fluid and injected in a cyclic manner, i.e. alternating high-injection-rate and low-injection-rate. Hence, formation rocks will be subjected to cyclic cooling, stress oscillating and fatigue failure, which is expected to improve the stimulated reservoir volume. First, laboratory cyclic cryogenic fracturing tests were conducted on 200°C granite to investigate the fracture initiation/propagation behavior and fracture network morphology. Water fracturing experiments were also conducted as a comparison. Then, X-ray microscope (XRM) and scanning electron microscopy (SEM) in a micro-nano-scale resolution were presented to assist in understanding the cyclic cryogenic fracturing mechanisms. Finally, the implications and potential applications in the EGS field site were discussed. The results demonstrated that cyclic cryogenic fracturing can significantly lower the breakdown pressure and produce more tortuous fracture patterns. Increasing the number of cycles could generate more pronounced complex fracture networks. Besides, microstructure analysis showed that numerous thermal fatigue cracks were formed, which played a role of "fragmentizing the rocks" during fracturing. The key findings of this work are expected to provide a theoretical basis for the development of HDR geothermal resources in an efficient and safe manner.

1. INTRODUCTION

Hot dry rock (HDR) geothermal energy is a kind of renewable and sustainable energy resource that plays a significant role in meeting the energy demand (Armstrong et al., 2016; Breede et al., 2013).The extraction of heat from HDR is difficult because of the extremely low permeability (0.001-0.1 md) and high temperature (180-650 °C)(McClure and Horne, 2014). Hydraulic fracturing is widely used to create complex fracture networks to connect the injection wells and the production wells, which is also called as Enhanced Geothermal System (EGS)(Olasolo et al., 2016). However, to create large heat-exchanging area, large volumes of water are needed and waste-water disposal problems must be faced(EPA, 2016; Yoon et al., 2017). Furthermore, hydraulic fracturing treatment also causes fluid-injection-induced seismicity(Ellsworth, 2013; Pollyea et al., 2019; Scanlon et al., 2017; Schultz et al., 2018). Examples where fluid injection caused large earthquake events in the past include the Cooper Basin EGS site in Australia with a local magnitude of *ML* 3.7 (Baisch et al., 2006), the Basel EGS site in Switzerland with a local magnitude of *ML* 3.4 (Deichmann and Giardini, 2009) and the Pohang EGS site in South Korea with a moment magnitude of M_W 5.5 (Grigoli et al., 2018). Therefore, methods must be taken in order to reduce the magnitudes of fluid-injection-induced seismic events.

Cyclic soft simulation (CSS) was proposed as a new fracturing method to mitigate the induced seismicity, which is also named as fatigue hydraulic fracturing (FHF)(Hofmann et al., 2018a; Zang et al., 2013; Zang et al., 2019). The major purpose of CSS is to balance two conflicting objectives: (1) minimizing fluid-injection-induced seismic hazard and (2) maximizing the hydraulic and thermal performance increase of EGS resulting from hydraulic stimulation treatments (Hofmann et al., 2018a). The essence of the concept is the combination of a cyclic fluid injection scheme with a specified "seismic traffic light system" where certain injection protocols with limited pressures, pressurization rates and injected net volumes must be followed. Cyclic fluid injection scheme means fracturing fluid is injected into the wellbore in a cyclic manner, i.e. alternating high-injection-rate and low-injection-rate, rather than a monotonical injection rate. Consequently, damage accumulates in rocks during cyclic loading and fatigue failure occurs, leading to the decrease of rock strength locally by generating an enlarged fracture damage zone. The recent laboratory and field experiments have investigated the performances of cyclic hydraulic fracturing in terms of breakdown pressure, fracture patterns, and number or magnitudes of the induced seismic events(Hofmann et al., 2019; Hofmann et al., 2018b; Zang et al., 2017; Zhuang et al.). Their results indicated that cyclic hydraulic fracturing can (1) break down the reservoir rocks with lower fluid pressure, (2) generate more complex fracture networks with more branches and relatively smaller fracture apertures and (3) replace the larger seismic events by a cloud of smaller event resulting from an optimized rock fragmentation process as compared to the conventional hydraulic fracturing with monotonic, continuous fluid injection(Zang et al., 2019).

Cryogenic fracturing by using liquid nitrogen (LN_2) as the fracturing fluid has attracted more attentions in EGS development recently (Yang et al., 2020b; Zhang et al., 2020). LN_2 is -196 °C at atmospheric pressure. When LN_2 is injected into the reservoir formation, large temperature difference between the reservoir rocks and fracturing fluid can exert a sharp thermal gradient that induces numerous fractures(Cha et al., 2018). The previous laboratory studies indicated that LN_2 fracturing can lower the breakdown pressure, generate 3-D volumetric fracturing patterns and promote the permeability enhancement (Yang et al., 2020a). Thermal stress plays a significant role in reducing fracture initiation and propagation pressure. Besides, phase transition of LN_2 due to temperature/pressure changing could promote the fracture propagation and network generation. Moreover, by using LN_2 as the fracturing fluid, fresh water usage in EGS stimulation can be saved and waste-water disposal problem can be addressed.

In this paper, we presented a new reservoir stimulation concept in EGS, i.e. cyclic cryogenic fracturing, to complement the advantages of the above two fracturing techniques as a new method. By injecting the cryogenic fracturing fluid in either cyclic injection rate or cyclic injection pressure scheme in HDR formation, rocks will be subjected to cyclic cooling, stress oscillating and fatigue failure, which is expected to further lower the breakdown pressure and improve the stimulated reservoir volume. Previous attempts have investigated the changes of pore structure and rock mechanical properties after LN_2 cyclic cooling (Qin et al., 2016; Wu et al., 2019; Yan et al., 2020). Their results suggested that porosity of the sample, fracture volume, fracture thickness and fracture connectivity increased significantly with the growth of LN_2 cooling cycles. The physical and mechanical properties of granite reduce as the increase of LN_2 cooling cycles. It is also worthy of mention that the deterioration of granite mainly occurs within the initial ten cycles. After about ten cycles, changes in physical and mechanical properties become relatively minor. To test the feasibility of cyclic cryogenic fracturing, we conducted laboratory tri-axial fracturing experiments on high-temperature granites. Fracturing performances of cyclic LN_2 injection were investigated with respect to breakdown pressures and morphology of the resulting fracture networks. Water fracturing tests were also conducted as comparisons. The key findings are expected to provide a theoretical guidance for the development of HDR energy in a clean and safe way.

2. EXPERIMENTAL STUDIES

2.1 Materials

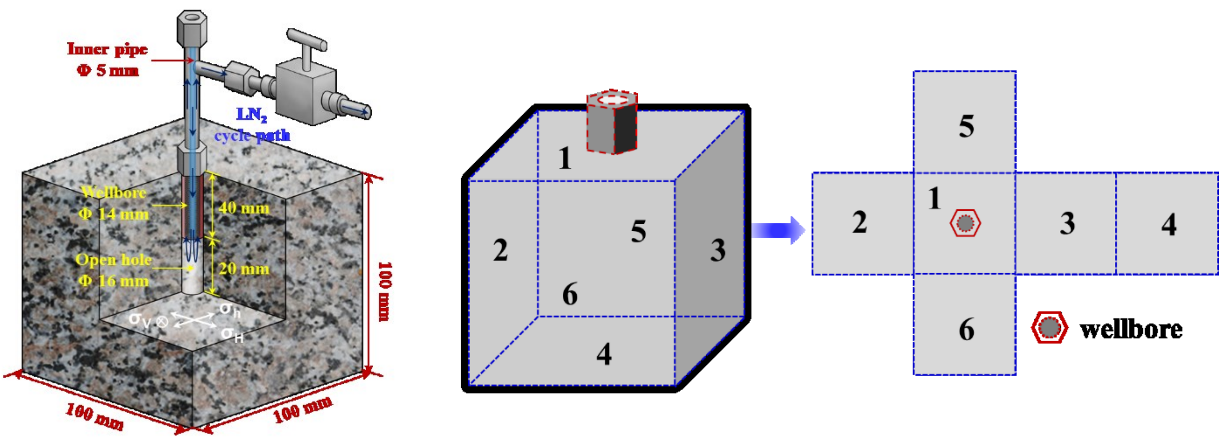
Granite samples were collected from outcrops in Shandong, China. The size of each sample was 100×100×100 mm. The basic geo-mechanical properties and mineral contents of an intact sample can be found in **Table 1** and **Table 2**. The granite specimen was shown in **Figure 1**.

Table 1 Basic geomechanical properties of the granite specimens at room temperature.

Density (g/cm^3)	Young's Modulus (GPa)	Poison's ratio	Cohesive strength (MPa)	Internal friction angle(°)	Tensile strength (MPa)	UCS (MPa)
2.63	39.41	0.28	44.84	48.74	10.02	121.97

Table 2 Mineral contents of the granite samples (%).

Quartz	K-Feldspar	Plagioclase	Dolomite	Siderite	Hornblende	Glauberite	Augite	Iron mica	Clay minerals
14.9	19.1	26.6	2.6	1.0	8.4	4.5	12.2	6.1	4.6



(a) **(b)**

Figure 1: Granite specimens: (a) Size of the specimen and the simulated wellbore. σ_V=overburden pressure; σ_H=maximum horizontal stress; σ_h =minimum horizontal stress; (b) fold-out diagram of the rock sample.

2.2 Experimental setup

Liquid nitrogen (LN_2) fracturing, which is a process under an extremely low-temperature and high-pressure condition, requires rigorous laboratory equipment to accomplish. We developed a new laboratory system for LN_2 fracturing (**Figure 2**). The laboratory system mainly consists of high-pressure LN_2 generation system, true triaxial-loading device and heating system, and data acquisition system. The detailed descriptions of this newly-developed laboratory system for LN_2 fracturing study under true triaxial-loading conditions can be seen in our previous work(Yang et al., 2020a; Yang et al., 2020b). In this work, we used two types of fracturing fluids, namely LN_2 and water. Water-fracturing tests were also conducted on the equipment shown in **Figure 2** and the fluid-injection power was controlled by the MTS servo booster. Then, X-ray microscope (XRM) and scanning electron microscopy (SEM) in a micro-nano-scale resolution were presented to assist in understanding the cyclic cryogenic fracturing mechanisms. The granite sample was cut into slabs of 5 ×5 ×2 mm. The sample surface was sputtered by Ar-ions which produces a smooth and planar cross section. XRM was conducted by using Xradia 520 Versa-Zeiss with a resolution of 0.7 um. SEM tests were conducted on Navigator-100 High-throughput SEM with a resolution of 2.5nm at 3 kV.

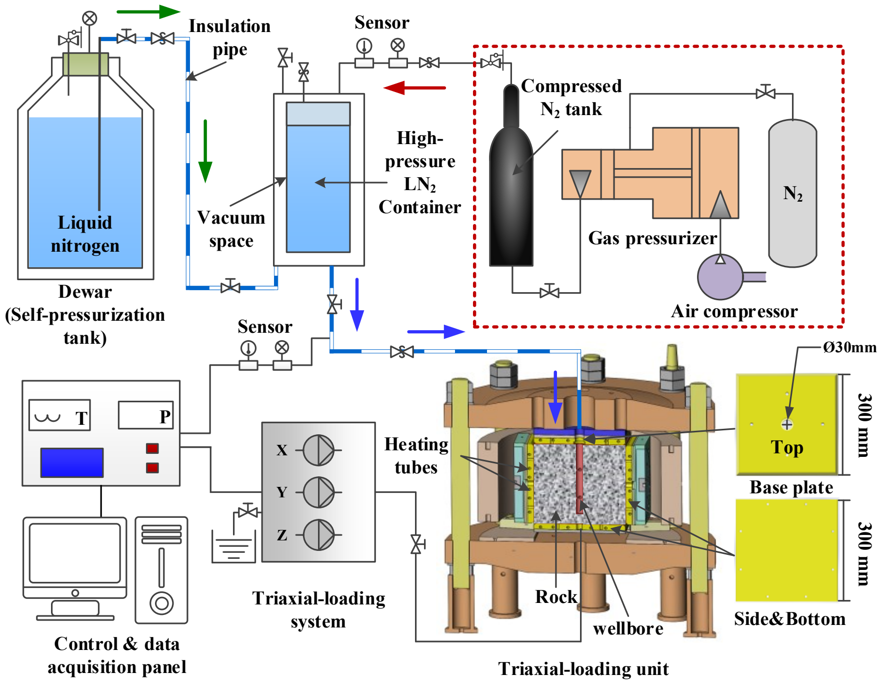
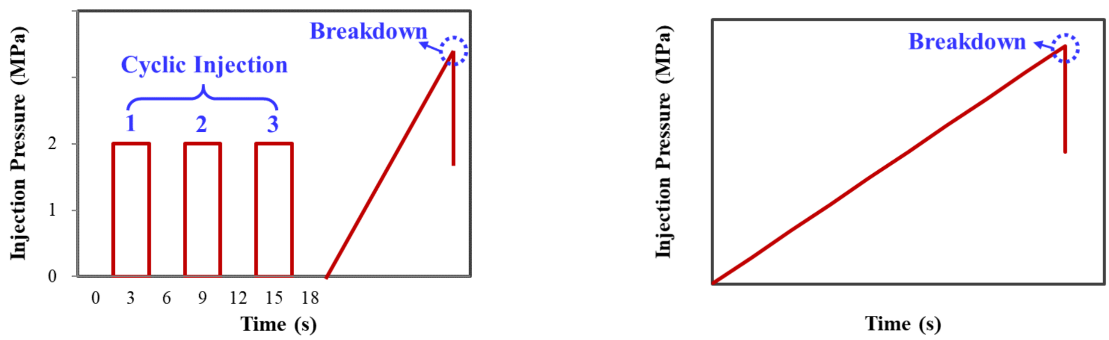


Figure 2: Schematic of the true-triaxial liquid nitrogen fracturing setup

2.3 Experimental procedure and matrix

To achieve cyclic fracturing, we applied cyclic injection pressure in this work. **Figure 3a** shows the cyclic injection manner. The maximum injection pressure in each loading-unloading cycle was below the breakdown pressure. In this work, the injection pressure at each cycle was 2 MPa. After the cyclic treatment, the rock sample was pressurized under a constant pressurization rate until breakdown. As a comparison, **Figure 3b** shows the continuous injection manner where the injection pressure-time curves under a constant pressurization rate until breakdown.



(a) (b)

Figure 3: Two different injection schemes: (a) cyclic fracturing: cyclic injection with low pressure followed by constant pressurization rate until breakdown; (b) conventional fracturing: injection with constant pressurization rate until breakdown.

The experimental design is shown in **Table 3**. Totally, 6 specimens were tested with various cycle times. Based on the geological data from FORGE site (EGI, 2018), the temperature of a potential EGS reservoir is 175-225 °C. Stress magnitudes is σ_h = 13.1 - 14.2 kPa/m, σ_H = 15.4-18.5 kPa/m and σ_V = 25.5 kPa/m. Thus, the horizontal stress difference ratio ($\left(\sigma_H - \sigma_h\right)/\sigma_h$) is within the range of 0.08 to 0.4. In this work, we set the sample initial temperature as 200 °C, and the horizontal stress difference ratio was 0.4 as the base case.

Table 3 Experimental matrix for cyclic liquid nitrogen fracturing on granite

Sample No.	Fracturing fluid	Cycle times	$\sigma_H/\sigma_h/\sigma_V$ (MPa)	Coefficient of horizontal stress difference	Sample temperature (°C)
LN1	Liquid nitrogen	1	10/7/15	0.4	200
LN1	Liquid nitrogen	2	10/7/15	0.4	200
LN1	Liquid nitrogen	3	10/7/15	0.4	200
LN1	Liquid nitrogen	4	10/7/15	0.4	200
LN1	Liquid nitrogen	5	10/7/15	0.4	200
W1	Water	/	10/7/15	0.4	200

3. EXPERIMENTAL RESULTS

3.1 Breakdown pressure

Pressure-time curves were presented to illuminate the fracture initiation behavior under different cyclic conditions in this section (**Figure 4**). It can be found that the rock specimens were fractured with lower breakdown pressure by LN_2 than that by water. Compared **Figure 4a** with **Figure 4f**, under the same applied stress and rock initial temperature conditions, LN_2 returned 36% lower breakdown pressure than water. The possible reason is that thermal stress generated during LN_2 fracturing could induce micro-fractures or cause the pre-existing pores and cracks to be connected, which lowers the breakdown pressure. Furthermore, the rock samples broke down at a lower pressure in cyclic fracturing than in the conventional method and the breakdown pressure decreased when the number of cycles increases (LN5 was an exception with a slightly higher value compared with LN3). Compared **Figure 4a** with **Figure 4d**, the rock breakdown pressure accomplished by four cyclic treatment times was 64% lower than that by single injection and 77% less than that by water fracturing. This indicated that local damage (crack growth) in each injection cycle was generated despite total macro-failure not being achieved. During LN_2 pumping period, the localized internal damage was induced by the coupled hydraulic-thermal stress. Since LN_2 has low fluid viscosity and low interfacial tension, it is easy to infiltrate the rock body once the injection starts, thus opening new microcracks and simultaneously creating connections between the isolated pores and cracks. Our previous research found that there were numerous small-scale cracks and pores distributed around the wellbore during LN_2 injection (Yang et al., 2020b). These mall-scale fracture swarms were not controlled by the in-situ stress, thus made up a thermally-stimulated zone. During shut-in period, LN_2 phase transition into supercritical or even gas state mainly causes the propagation and extension of the existed fractures. Different from cyclic hydraulic fracturing in granite, the alternate thermal exchanging between LN_2 and rock matrix during cyclic loadings can result in more significant thermal fatigue damage. The accumulation of these damages could facilitate the reduction of breakdown pressure. A reduction in breakdown pressure has the benefit of using smaller pumps which makes the treatment safer (Zang et al., 2019).

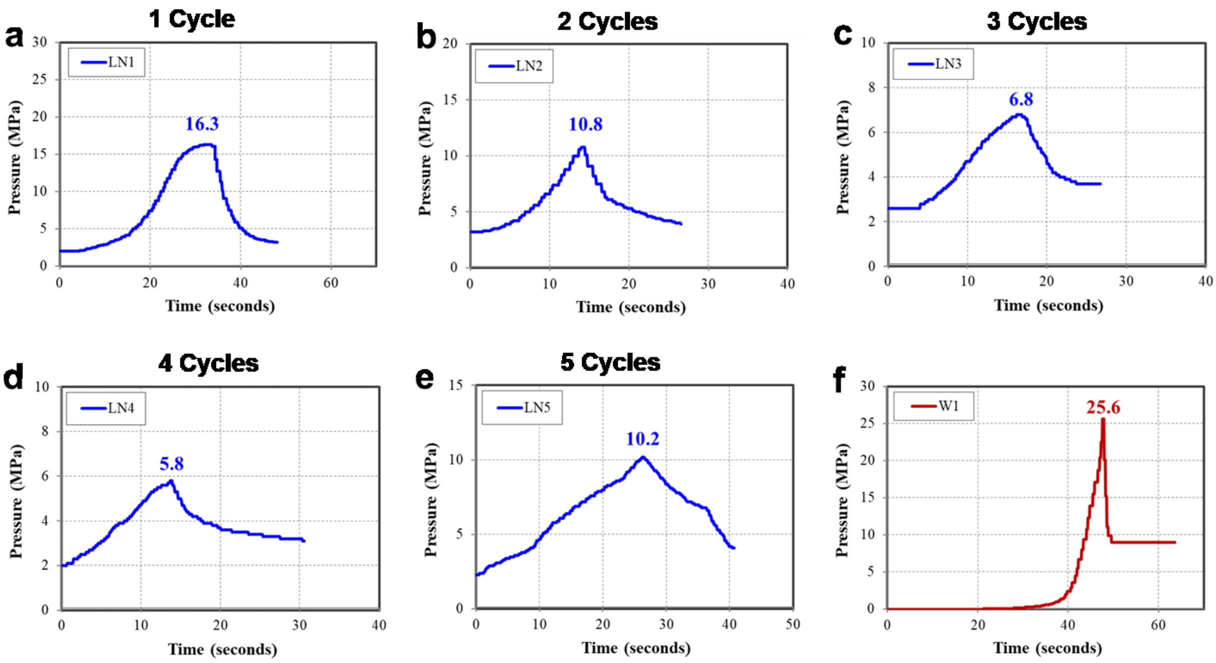


Figure 4: Fracture patterns of granites under different cyclic fracturing conditions.

3.2 Fracture Patterns

To identify the fracture distributions, red-colored water was later injected into the sample without any confining stress until it migrated to the surface along the induced fractures. Fracture patterns for rock samples under different fracturing conditions were shown in **Figure 5**. In water fracturing (**Figure 5f**), one major fracture that perpendicular to the minimum horizontal stress direction was generated, which follows the stress principles. In conventional LN_2 fracturing (**Figure 5a**), two fractures were presented with one major fracture generated perpendicular to the minimum horizontal stress direction. Both of the fracture numbers and fracture lengths increased in the cyclic fracturing, especially LN3 (three cyclic treatment times in **Figure 5c**) and LN5 (five cyclic treatment times in **Figure 5e**). Hence, a larger stimulated reservoir volume can be obtained in the cyclic fracturing. Moreover, fracture tortuosity became more predominantly in LN3 and LN5. This is an important advantage of cyclic fracturing compared with the conventional fracturing method. Because more tortuous flowing conduits can enhance the heat extraction efficiency between the injected fluid and the heated matrix, and also mitigate the early thermal breakthrough during later heat production period (Shi et al., 2019). As discussed above, each cyclic injection event may create small-scale fractures and LN_2 phase-change in each shut-in period could further promote the fractures extension. Consequently, a larger stimulated region in the final macroscopic failure can be obtained.

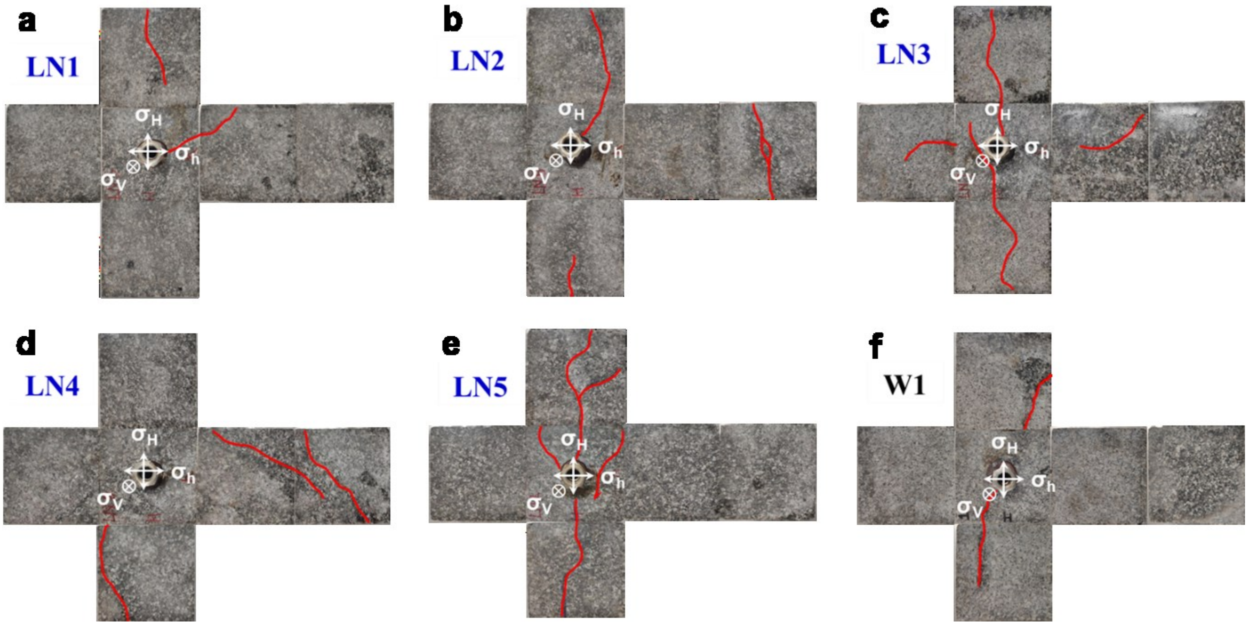


Figure 5: Fracture patterns of granites under different cyclic fracturing conditions

Then, we calculated the fracture conductivities based on the re-injection pressure. The calculation method can be found in our previous work (Yang et al., 2020a). The result can be seen in **Figure 6**. It suggested that the magnitudes of the fracture conductivity produced in LN_2 fracturing were 7-10 times larger than that in water. Moreover, the cyclic injection time has relatively minor influences on the fracture conductivity generated by LN_2. LN3 (three cyclic treatment times) presented the highest fracture conductivity value because of more numbers of fractures generated. Although more complicated fracture patterns appeared on LN5, the fracture conductivity showed approximately the same level with LN1 and LN4. This is because flowrate inside the rock samples is greatly dependent on the fracture aperture and number of flowing conduits (Gringarten et al., 1975). One injection cycle may create a larger fracture aperture in LN1 since the fracture number is less than that on LN5.

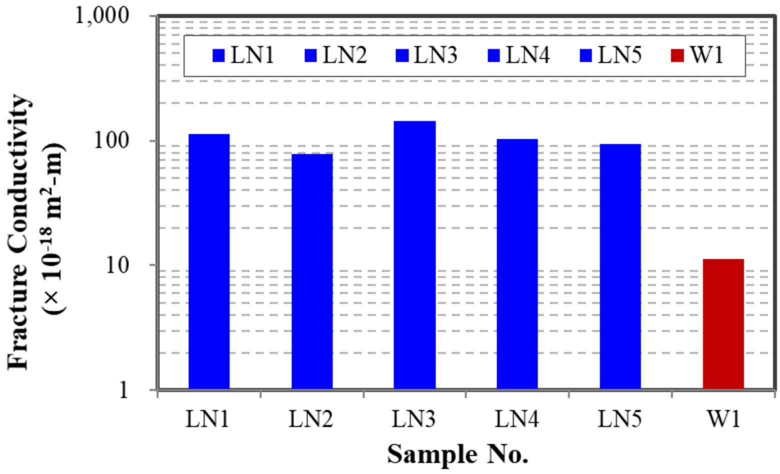


Figure 6: Fracture conductivities of granites under different cyclic fracturing conditions

As discussed above, cyclic LN_2 fracturing has many advantages. It leads to lower breakdown pressure and more complex fracture patterns or a larger stimulated volume. However, it also requires more fracturing fluid volume which is a negative aspect for the development of EGS. There may be an optimal scenario in which a balance between the advantages and disadvantages can be obtained. In this work, three cyclic-injection-times is the optimum scenario since lower fracture breakdown value with complicated fracture patterns and higher fracture conductivities have been obtained. The cyclic-cryogenic-fracturing method has the potential to become a new stimulation method for EGS exploitation after its advantages and disadvantages are quantitatively accounted for, especially when the optimal scenario is designed (Sakhaee-Pour and Agrawal, 2018).

3.3 Micro-cracks evolution during cyclic cryogenic treatment

To further illuminate the micro-cracks evolution during cyclic cryogenic treatment, X-ray microscope (XRM) and scanning electron microscopy (SEM) in a micro-nano-scale resolution were presented here. XRM showed the change of fracture thickness for a granite sample before and after LN_2 cooling (only one cycle was displayed here). SEM illustrated the rock surface change after LN_2 cyclic cooling. The results were shown in **Figure 7** and **Figure 8**.

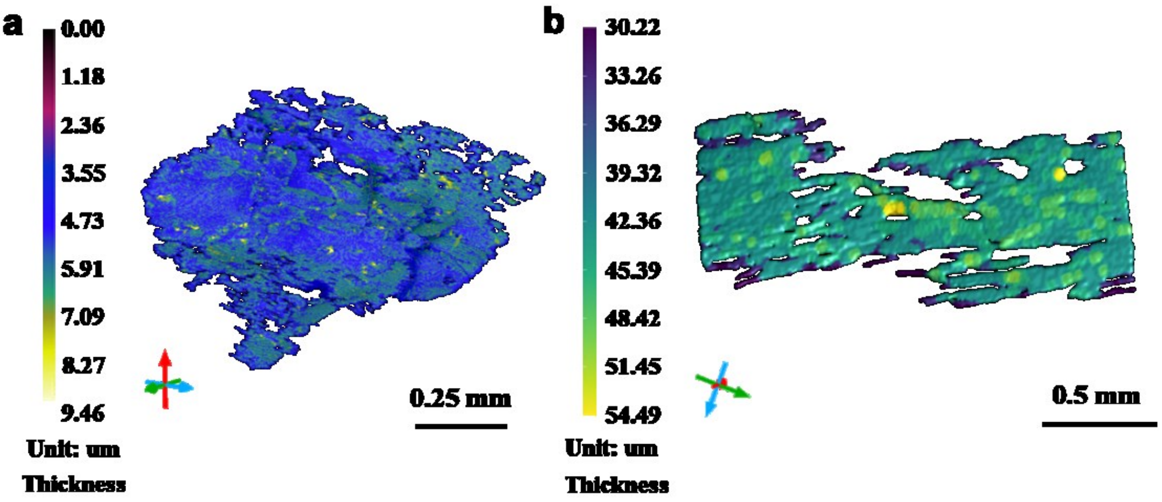


Figure 7: Fracture thickness of a granite sample (a) pre-LN_2-treatment; (b) post-LN_2-treatment

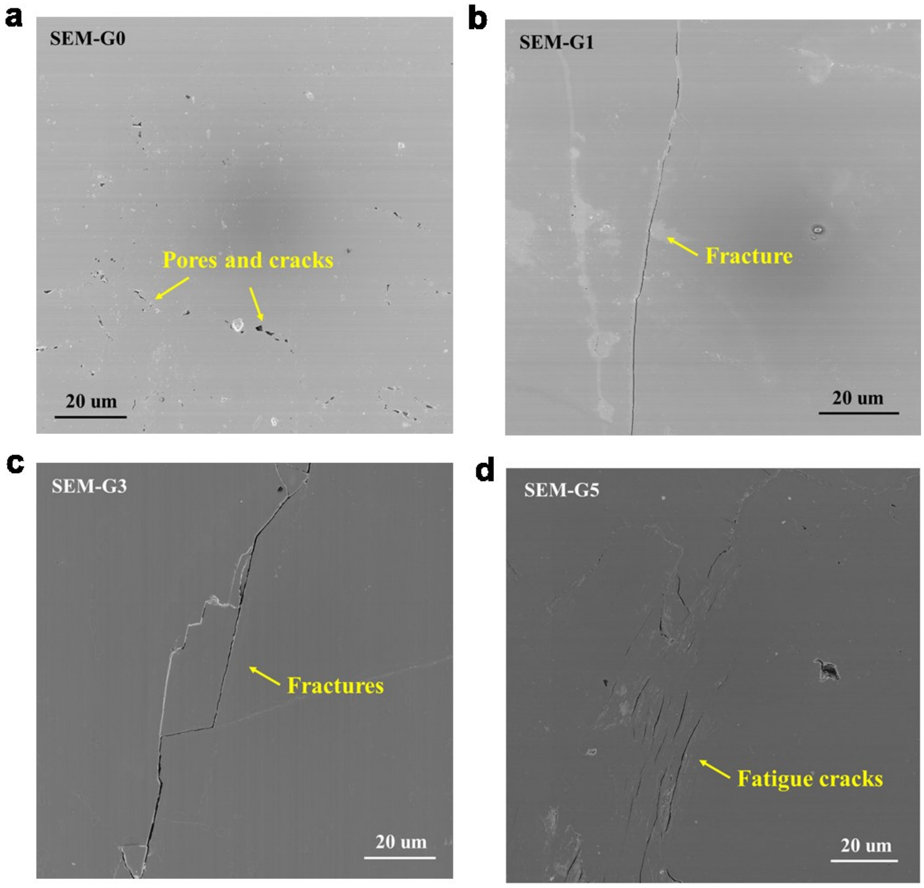


Figure 8: Fracture morphologies at the surface of a granite sample (a) pre-LN_2-treatment; (b) post-LN_2-treatment (1 cycle); (c) post-LN_2-treatment (3 cycles); (d) post-LN_2-treatment (5 cycles)

Figure 7 suggested that fracture thickness for the granite sample has increased significantly after LN_2 cooling. Before LN_2 cooling, most of the fracture thicknesses were between 3 um to 5 um (**Figure 7a**). After LN_2 cooling, most of the fracture thicknesses were between 35 um to 50 um (**Figure 7b**). Hence, the fracture thickness increased approximately ten times after LN_2 treatment, which indicated that the flowing conduits can be aggrandized significantly due to the LN_2 thermal shock. In the original rock, SEM images showed there were some pores and cracks existed but no noticeable fractures appeared (**Figure 8a**). However, the SEM images of post-LN_2-treatment revealed newly-induced fractures. We also found that when the granite sample was subjected to one LN_2 cooling cycle, fractures without branches were generated (**Figure 8b**). When the granite sample was exposed to three LN_2 cooling cycles, branched fractures were created (**Figure 8c**). When the granite sample was treated by five LN_2 cooling cycles, fracture swarms were appeared (**Figure 8d**), which clearly proved that fatigue cracks were produced after five times thermal cyclic loadings (Gludovatz et al., 2014). The number of fractures increased significantly but some of the fracture lengths and apertures might be reduced. The possible reason can be that the thermally induced stress intensified and relaxed periodically during LN_2 cyclic treatment, causing fractures opening and closing periodically. Subsequently, thermal damage was accumulated in the rock sample and rock mechanical strength could be diminished. This might also can explain the above laboratory fracturing observations where sample LN5 have a relatively lower fracture conductivity but more complicated fracture patterns.

Future energy exploitation technologies rely not only on production but also on safe injection of fluid into the subsurface(Hofmann et al., 2019). Cyclic cryogenic fracturing proposed in this work can be a potential effective technique in developing EGS geothermal energy. The following advantages support the idea: (1) LN_2, as a non-contaminating cryogenic fracturing fluid, can save fresh water usage for EGS stimulation which contributes approximately 60%-80% of total upfront water requirements (Clark et al., 2010), and also protect the environment and alleviate the waste-water disposal problem. (2) Due to cyclic hydraulic-thermal loadings, numerous fatigue cracks can be generated, which can lower breakdown pressure compared with conventional continuous injection and cyclic water fracturing, thus decrease the pumping pressure, and possibly mitigate earthquakes(Giardini, 2009). (3) Larger stimulated reservoir region with more tortuous patterns and higher fracture conductivity can be achieved, which could enhance the heat extraction efficiency and also alleviate the early thermal breakthrough during later heat production period. In the future, more works are needed including optimizing the injection schemes and testing for the magnitude frequency distribution of the seismic events.

4. CONCLUSIONS

Cyclic cryogenic fracturing is proposed in this paper as a potential method to increase the EGS stimulation efficiency in a safe and environmentally acceptable manner. Laboratory experiments were conducted to test the fracturing performance of cyclic LN_2 fracturing in terms of breakdown pressure, fracture patterns and fracturing mechanisms. Following conclusions can be drawn:

- Cyclic cryogenic fracturing can reduce the breakdown pressure, with observed 64% lower than continuous injection and 77% less than water fracturing at laboratory. A reduction in breakdown pressure can make the fracturing treatment safer.

- Cyclic cryogenic fracturing has the tendency to create larger stimulated reservoir volume with more tortuous fracture patterns and higher fracture conductivity. The alternate thermal exchanging between LN_2 and rock matrix during cyclic loadings can result in more pronounced thermal fatigue damage compared with cyclic water fracturing. LN_2 phase-change in each shut-in period could further promote the fractures extension.

- Future works are needed to optimize the injection schemes such as number of cycles, injection intervals or duration time, amplitude of injection rate/pressure/pressurization rate, etc. Besides, all the obtained results were based on the laboratory investigation. The merits of cyclic cryogenic fracturing in exploiting deep geothermal energy resources are suggested to be further verified in mine scale or by field tests

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