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Research of high-temperature diverting fracturing technology for EGS projects

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ABSTRACT

Diverting fracturing technology plays an important role in EGS multi-stage stimulation which is essential to achieve project commercialization. High-temperature diverter needs to be developed especially for formations beyond 200 ℃. In this paper, two series of newly developed high-temperature diverters, ENNDA-200 and ENNDA-250, used for 200 ℃ and 250 ℃ formation stimulation respectively were introduced. Both feature excellent properties in terms of temperature resistance, degradability and mechanical properties. An optimized mixture of diverters of different particle sizes for diverting fracturing has been researched with a proprietary plugging performance evaluation equipment. A plugging fracturing experiment was conducted using a granite sample containing a pre-made crack loaded on a uniaxial stress device at room temperature. The test results showed the diverters were capable of sealing cracks and diverting fracturing energy to create a new fracture. Furthermore, several plugging experiments were carried out on a true tri-axial mechanical device to test diverter performance in 250°C granite sample under high-stress condition, which have verified that the ENNDA-250 diverter could not only plug fractures in ~250°C environment but also remain effective within 48 hours. These tests validated the new-developed diverter meet the requirement of diverting fracturing technique for EGS projects.

1. INTRODUCTION

The rapid consumption of fossil energy and environmental pollution are among the most urgent challenges facing mankind and many countries are taking steps to promote the transition of the energy mix to low-carbon and sustainable energy. Compared with other energy resources, geothermal resource has advantage of being abundant and stable, clean and renewable, offering a feasible alternative and attracting a number of far-sighted investors. Among them, ENN Science and Technology Development Company (ENN) invested in R&D of deep geothermal energy since 2018.

In order to extract the geothermal energy from hot dry rock (HDR) formation, the concept of enhanced geothermal system (EGS) has been proposed, and afterwards a large number of engineering demonstration projects have been carried out worldwide (Stephen I. Karner. 2005, Jefferson W. Tester et al., 2006; Donald W. Brown et al., 2012)

In short, an EGS usually consists of one injection well, one or two production well(s), and a high-permeability fracture network artificially created in HDR formation connecting production and injection wells. One of the most critical technologies on EGS reservoir creation is hydraulic fracturing.

Bullhead fracturing is commonly used in EGS projects (Stephen I. Karner. 2005, E. Schill, et al. 2017, Jefferson W. et al., 2006, Robert Hogarth and Heinz-Gerd Holl, 2017), yet it is difficult to create more than one fracture in formation and zonal isolation tools fitting for EGS stimulation in HTHP environment is not mature enough to generate high output, which explains why EGS projects are not yet commercialized.

To commercialize EGS, segmented fracturing technology must be used (Jefferson W. et al., 2006,). Although there are many multi-stage fracturing techniques that have been widely used in the oil and gas field, most of them cannot be directly applied to EGS formations because most of the isolation tools required are mechanical tools containing plastic seal materials, whose elongation at break decreases rapidly as the temperature increases (Zhong, A. (2016)). The elongation at break in rubber and many polymeric materials decreases from 110% to 35% as the temperature increases from 70 to 350 °F, while the target formation temperature for EGS is generally higher than 350 °F (Jefferson W. et al, 2006).

Many existing EGS projects in the world, such as Fenton Hill, Cooper Basin, FORGE, etc., have tested fracturing with zonal isolation tools such as bridge plugs and packers, but most of them have failed (Donald W. Brown, 2012, Robert Hogarth and Heinz-Gerd Holl. 2017). The FORGE project well 58-32, with a static bottom hole temperature of 199 °C, underwent a series of small-scale fracturing tests from April to May 2019, using five bridge plugs and packers in total, three of which failed during the tests (Joseph Moore, John McLennan, et al., 2020).

Diverting fracturing is a segmental fracturing technique that relies on using diverter (also known as temporary plugging agent) rather than mechanical tools to temporarily plug previously created fracture and divert fracture fluid to open new fractures along the downhole (Guillermo Gutierrez, et al., 2015, G. Glasbergen, B. et al., 2006). These types of diverters are usually made of degradable materials. For EGS usually target at HDR formations of 180°C or above, this technology can reduce operating risks and cost of reservoir construction, since no mechanical tools are needed.

The performance requirements of diverter used in EGS multi-stage fracturing have some common points compared with oil and gas formation fracturing, such as high temperature resistance, self-degradation, low density, and compatibility with stimulation fluids, etc. However EGS multi-stage fracturing requires a longer temperature resistance time of the diverter, and a standard EGS fracturing process usually lasts for 2-5 days, which requires the temperature resistance of the diverter to last for at least 2-5 days, during which the fracture sealing ability cannot be lost; whereas the similar process in oil and gas industry usually lasts for several hours.

It has been reported that AltaRock Company in the United States used TZIM diverter in NWG55-29 well to conduct staged fracturing in 2013 (Susan Petty,Yini Nordin,William Glassley,et al.. 2013). The NWG55-29 well is 3067 meters deep, with the bottom hole temperature of 331 °C. The fracturing was divided into three segments with diverter applied twice during operation, which proved the diverter to be effective.

ENN is developing various key technologies with an aim to extract geothermal energy from deep formations by means of EGS. Since 2018, we have embarked on a focused effort to develop degradable diverter that can be used at temperature of 200°C or above, for it is not yet available on the market.

2. DEVELOPMENT OF DEGRADABLE DIVERTER

2.1. Synthesis of diverter

A research route was adopted to develop diverter for formations above 200°C, with the purpose of finding at least two base materials to synthesize diverter. One of them has a higher temperature resistance than the other, and by adjusting the ratio of the two base materials, we can synthesize the diverters applicable in different temperature formations (160-250°C).

Through a large number of indoor experiments, two polymers were selected as base materials, which are temporarily named as Polymer-A and Polymer-B. The diverter was synthesized by twin-screw extrusion process, and the diverter masterbatch was produced by feeding, melting, shearing and mixing, discharging and pelletizing processes at appropriate temperatures with different ratios of base materials A and B. The masterbatch was then tested for temperature resistance, mechanical properties and degradation properties, etc.

By adjusting base material's types, ratio, and process parameters, different diverter masterbatches can be synthesized. Through repeated experiments, we finally obtained the diverter formulations suitable for fracturing 200°C and 250°C formations (see Table 1).

Table 1. Synthetic formula for diverters

Formation Temperature	Formula	Notes
200 °C	Polymer-A(90%) +Polymer-B(10%)	The base materials are named as A and B due to the company's confidential policies.
250 °C	Polymer-A(20%) + Polymer-B(80%)	

2.2. Granulation

The masterbatch cannot be used directly in field fracturing or indoor plugging experiments, and needs to be processed into granules of different sizes. A cryogenic crusher can be applied for granulation. After crushed, the diverter particles of different sizes were obtained through sieving, the final products are shown in Figure 1 and Figure 2.

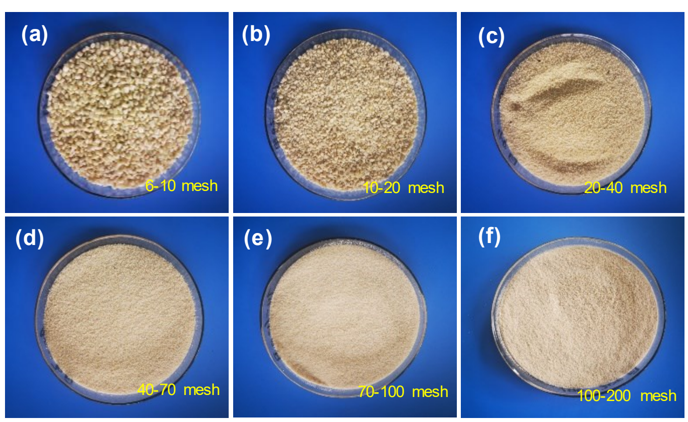

Fig.1. ENNDA-200 diverter of different sizes

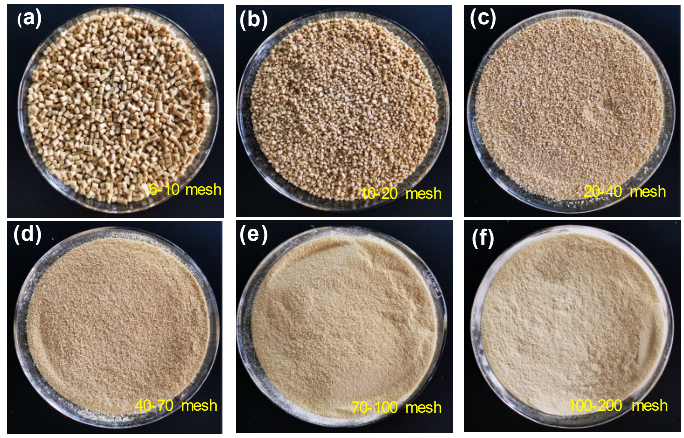

Fig.2. ENNDA-250 diverter of different sizes

2.3. Performance tests

2.3.1. Product specifications

Table 2. Properties of ENNDA-200 and ENNDA-250 diverters

Diverter	ENNDA-200	ENNDA-250
Application Temperature (°C)	200	250
Temperature Resistance (day)	2~5	2~5
Degradability	100%	100%
Specific Gravity	~1.15	~1.24
Compressive Strength (Mpa)	>80	>150
Particle Size (mesh)	6~200	6~200
Compatibility	The diverters are non-toxic and compatible with various stimulation fluid and formation fluid.	

2.3.2. Temperature resistance

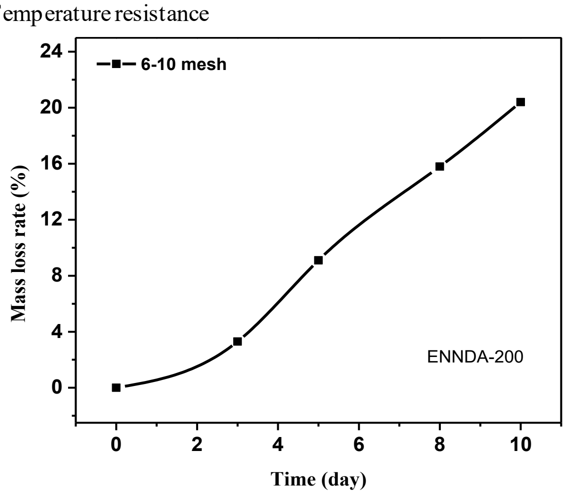

Fig.3. Temperature resistance of ENNDA-200

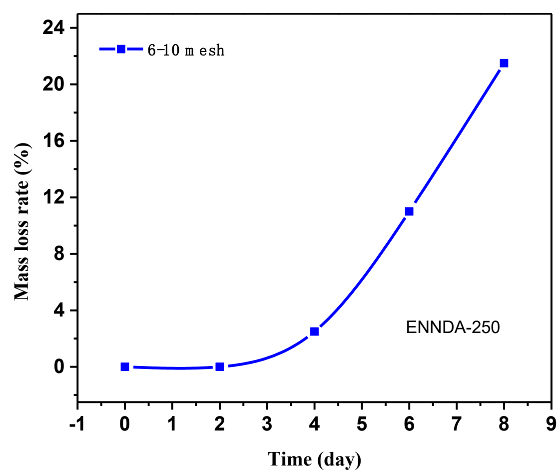

Fig.4. Temperature resistance of ENNDA-250

2.3.3. Degradability

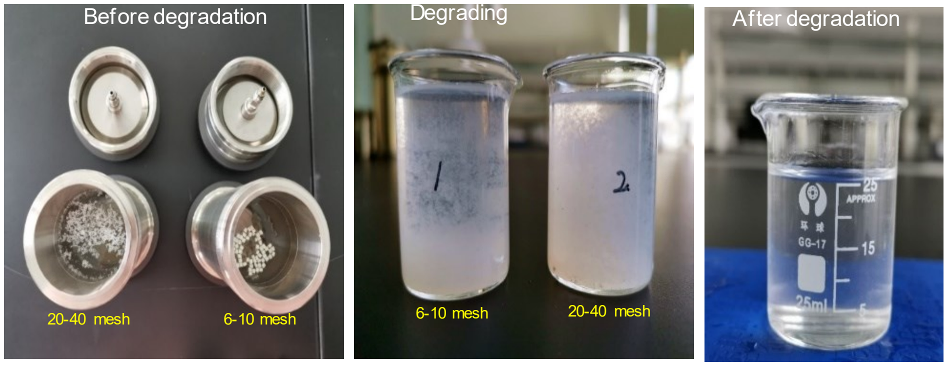

Fig.5. ENNDA-200 degradation tests

2.3.4. Mechanical Strength

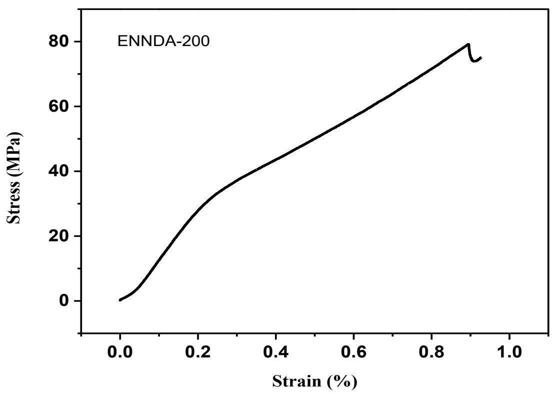

Fig.6. Test curve of the ENNDA-200 mechanical properties

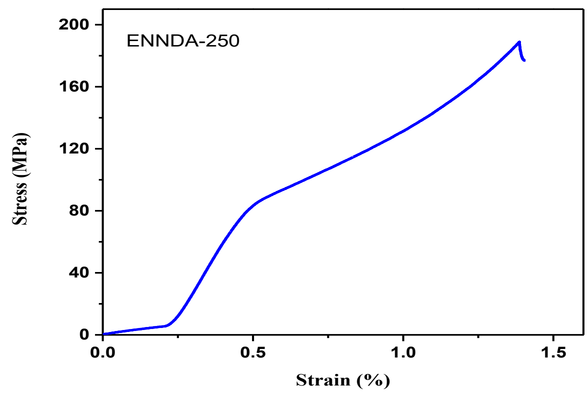

Fig.7. Test curve of the ENNDA-250 mechanical properties

2.4. Mixture optimization of diverters of different particle sizes

Although the diverter has been processed into 6~200 mesh particles, a random combination of diverter particle sizes cannot guarantee effective plugging. For different crack widths, it is necessary to use diverters of suitable particle size combinations.

ENN designed and assembled an experimental device to evaluate the plugging performance of the diverters of various particle sizes, which can simulate the process of temporary plugging and fracturing. This device is shown in figure 8.

Fig.8. Experimental device for evaluating plugging performance

A series of orthogonal experiments has been conducted on this device, a final formula for diverter particles combination is shown in Table 3.

Table 3. Final formula of diverter particles combination

	6~10 mesh	10~20 mesh	20 ~40 mesh	40 ~ 70 mesh	70 ~ 100 mesh	100 ~ 200 mesh
Mass percentage	20%	20%	15%	15%	15%	15%

3. PLUGGING EXPERIMENT IN GRANITE SAMPLE

Since the developed diverter will eventually be used in the real fracturing process, it is necessary to verify its plugging ability in laboratory before put it into use in field.

3.1. Criteria for effective plugging

The Nolte's pressure analysis method is widely accepted and used in the academic and engineering communities of hydraulic fracturing, where the double logarithmic slope of the pump pressure versus time curve, i.e., a Nolte slope equal to or greater than 1, can be used as a criterion for whether a screenout has happened (K. G. Nolte. 1988). In this paper, it can be used as a criterion for whether a diverter is effective based on same principle..

3.2. Experiment preparation

3.2.1. Rock sample preparation

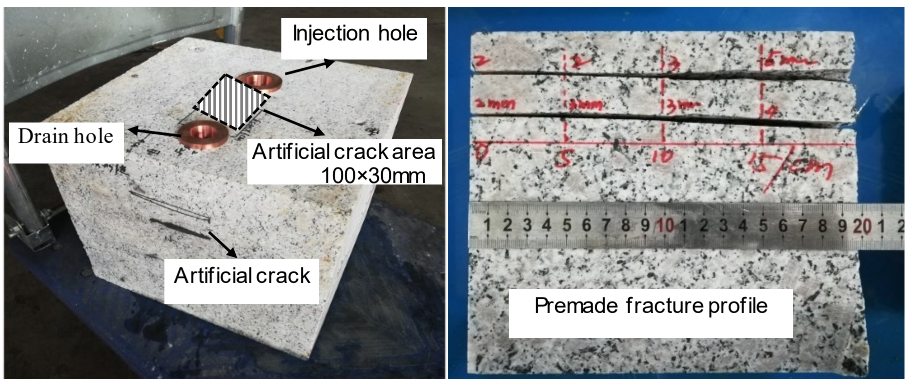

Fig.9. Granite sample (left) and pre-made crack created by hydro-jet (right)

The rock sample was a 300 mm x 300 mm x 300 mm cubic granite excavated from Penglai county in Shandong Province, China. A wedge-shaped slit was prefabricated in the granite sample by hydro-jetting process at location of 150 mm height, the slit was 230 mm deep and 100 mm long from side view, its width varied from 2 mm at rock surface to 10 mm at the other end and the exit of the slit was sealed with glue which could withstand high temperature up to 300 °C. (See fig. 9).

Two boreholes (φ20 mm) with one inlet and one outlet were designed on the rock sample, with the injection hole drilled to a depth of 15 cm and the discharge hole drilled to a depth of 10 cm. Both the injection and discharge holes were drilled through the prefabricated fracture to simulate a EGS.

Due to the height of the artificial fracture was 10 cm, there was a 5 cm length injection hole below the fracture surface which was particularly designed as a pocket for collecting extra diverter to avoid drilling hole blocked during experiments.

3.2.2. Fracture fluid

Polyacrylamide (PAM) solution with 2% concentration and 47.5 mPa.s apparent viscosity was selected as fracturing fluid in the following experiment. 200 g ENNDA-250 diverter was mixed with 1 liter of 2% PAM solution. (see Fig.10)

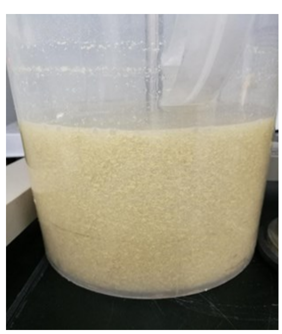

Fig. 10. Mixture of diverter and PAM solution

3.3. Uniaxial diverting fracturing experiment at ambient temperature

The purpose of uniaxial diverting fracturing experiment is to verify whether the diverter mixture can effectively seal an existing crack and divert fracture fluid to create a new fracture.

3.3.1. Experiment procedure

The processed granite specimen was placed on the uniaxial compression device, the pump, pipeline, granite rock sample, and a storage tank (to store the diverter-carried fracturing fluid) were connected, and then the uniaxial press was started to compress and seal the rock sample with a vertical pressure of 15 tons (1.67 Mpa). Once ready, the temporary plugging and fracturing experiment was started. (See Fig.11)

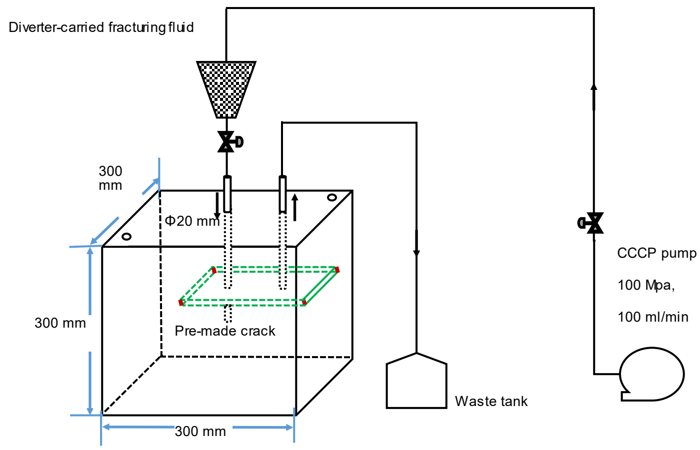

Fig. 11. Process diagram of plugging and fracturing test at ambient temperature

We started the constant flow rate pump (also known as CCCP pump) to inject the diverter-carried fracturing fluid into the granite specimen at a flow rate of 100 mL/min and recorded the pump pressure and flow rate. After the diverter sealed the fracture, we continued pumping until the rock sample was fractured. At the end of the experiment, the pumping volume of the diverter-carried fracturing fluid was 573 ml.

In the experiment, although the granite rock sample was fractured, its appearance remained intact and was not completely broken down. To visually examine the effect of plugging and fracturing, a static crushing technique with fluorescence display (Zheng wenzhong, Li ruisen et al. 2020) was used. Its process is to inject static crushing agent (consisting of calcium oxide, cement, gypsum and water reducer, etc.) and fluorescence agent into the rock sample, and after 3~5 days, the rock sample was completely broken down along the formed fracture due to the expansion of the crushing agent, and the fluorescence agent would help to identify the fracture surface formed by diverting fracturing.

3.3.2. Data analysis

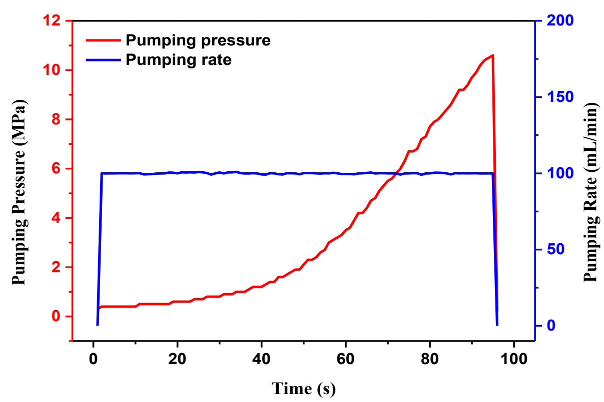

Fig. 12. Pumping curve of uniaxial plugging experiment at ambient temperature

The pumping pressure shown in figure 12 rose rapidly as the diverter entering pre-made fracture in rock sample. When pressure reached 10.6 Mpa, the rock broke. According to Nolte's fracturing pressure analysis, the double logarithm of net pressure versus time was 6.13, far beyond 1, which theoretically proved that the plugging was successful.

A compressed diverter cake in the drilling borehole is clearly visible in figure 13 (a) after the pipeline was disassembled, which indicated that the plugging is successful; in addition, the rock sample was split into two pieces after static fracturing, see Fig. 13(b), and it could be seen from the split rock sample that a new fracture was formed, and it was consistent with the maximum stress direction (vertical stress), while the pre-made fracture was a horizontal fracture, which indicated the flow of fluid has been reoriented to create a new fracture.

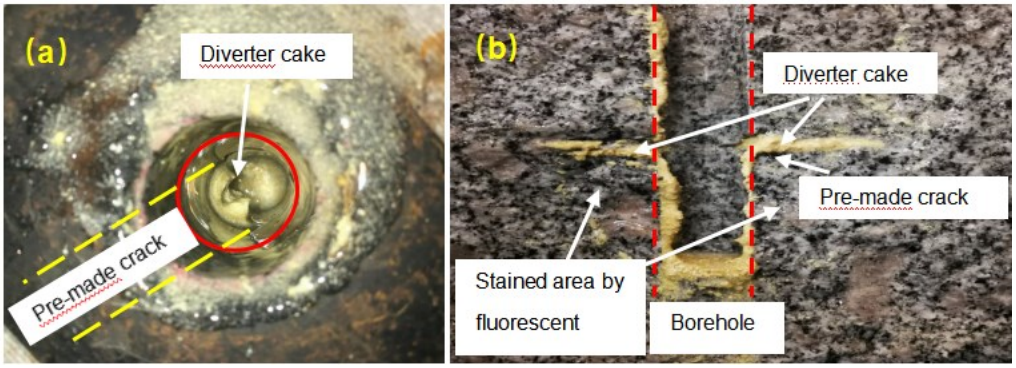

Fig. 13. Photos of granite sample before and after static crushing

3.4. Fracture Plugging Experiments in 250 °C Granite on a True Tri-axial Mechanical Device

3.4.1. Experiment procedure

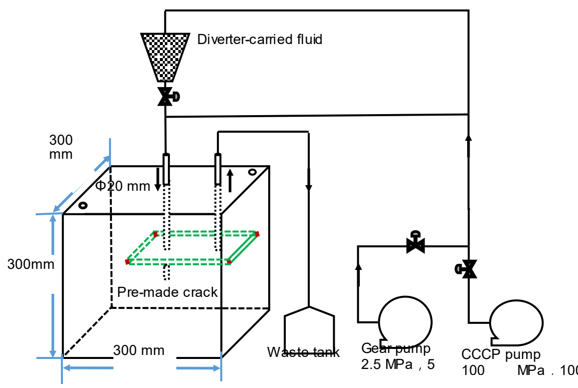

Fig. 14. Schematic diagram of plugging experiment in 250°C granite sample

The schematic diagram of plugging experiments in 250 °C granite sample is shown in figure 14.

(1) Connect the granite sample, pump, diverter-carried fracturing fluid tank and pipeline according to the layout shown in Figure 14.

(2) Apply triaxial stress δX/δY/δZ=20/20/20 MPa to the rock sample with a loading rate of 10 kN/s.

(3) Heat the rock to 250 °C at a rate of 20 °C/h.

(4) Increase the pipeline pressure to 2 Mpa for leak test, and the pressure shall not drop within 5 minutes.

(5) The first phase of the experiment --- initial plugging. Pump the diverter-carried fracturing fluid at 100 mL/min with a CCCP pump (constant flow rate and constant pressure pump) and stop pumping once pressure was greater than 5 Mpa.

(6) The second phase of the experiment--- maintaining plugging for 48 hours at low rate. Keep the temperature of the rock sample at 250°C, and pump clean water at 10 mL/min to maintain plugging of diverter cake.

(7) The third phase of the experiment - testing the plugging capacity after 48 hours. Start the gear pump to pump clean water at 3.5 L/min (20 Hz) to test the availability of the plug in the fracture.

(8) Stop the experiment, cool down the temperature, remove the pipeline, take out the rock sample and observe the plugging effect.

(9) Conduct rock static crushing experiment.

3.4.2. Data analysis

The temperature of granite sample of whole experiment is shown in Figure 15.

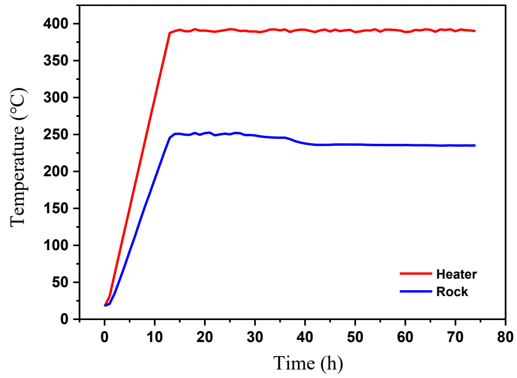

Fig. 15. Temperature of the granite sample

After the diverter entered the fracture, the pump pressure increased rapidly. In order to avoid the rock sample being fractured and affecting subsequent experiments, the pump was stopped immediately when the pressure rose to 5 Mpa, and the second stage test was started.

The total volume of pumped diverter-carried fracturing fluid was 1417 ml. The double logarithmic slope of Nolte pressure analysis in figure 16 is 1.82, indicating the plugging is effective.

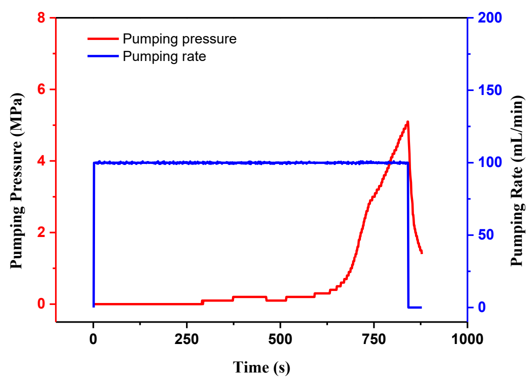

Fig. 16. Pumping pressure and flowrate of initial plugging experiment (250°C granite sample)

In the real temporary plugging and fracturing process, after the previous fracture is temporarily plugged, a new fracture is being created. During the extension of the new fracture, the diverter cake at previous fracture may bear pressure at both ends, and the previous fracture will continue to be pressurized in the high temperature environment, so there may be a bit of leakage through the diverter cake to the deep fracture. This experiment is designed to continue pumping at a discharge rate of 2~10 ml/min for 48 h after the initial plugging to simulate this process. See figure 17.

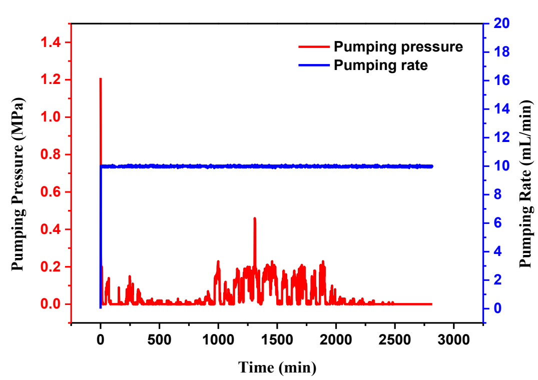

Fig. 17. Pump pressure and flow rate during stage of maintaining pumping for 48 hours

The diverting fracturing process requires that the diverter in the previous fracture cannot lose the plugging performance during the fracturing process of the latter fracture stage. Generally, it takes more than 2 days for EGS to create a fracture, so the blocking performance of diverter needs to be retested after 48 hours of initial plugging.

Figure 18 shows the post 48 hours blocking performance of ENNDA-250 in a 250°C granite sample.

When pumped at 3.5 L/min, pressure rose to 5.7 Mpa immediately and double logarithmic slope of Nolte in this test was 1.41, which showed the plugging of diverter cake was still effective.

Figure 18 also showed two more pressure tests carried out subsequently, and the corresponding pressures were 5.1 Mpa and 4.8 Mpa respectively, which also proved the plugging cake remained effective.

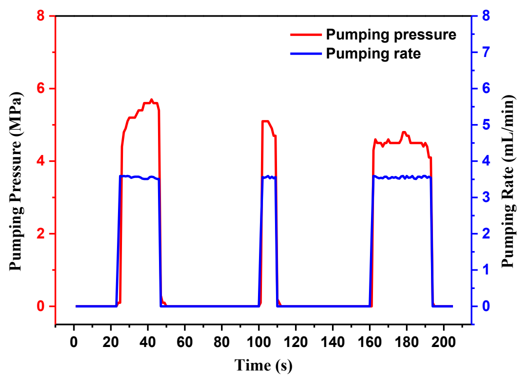

Fig.18. Tests of the diverter cake blocking ability after 48h

In order to visually check the fracture plugging, static crushing experiments were conducted after the rock sample was unloaded at the end of the experiment on the true tri-axial device. As seen in the figure 19(a), a piece of diverter cake was formed in pre-made fracture and extruded into borehole, and a small amount of diverter particles could be seen at bottom of the borehole. Figure 19 (b) exhibits the formed diverter cake in pre-made crack after a static crushing, the diverter cake was tightly self-assembled by particles of different sizes during pumping, which proved the bridge-blocking theory of particles is correct.

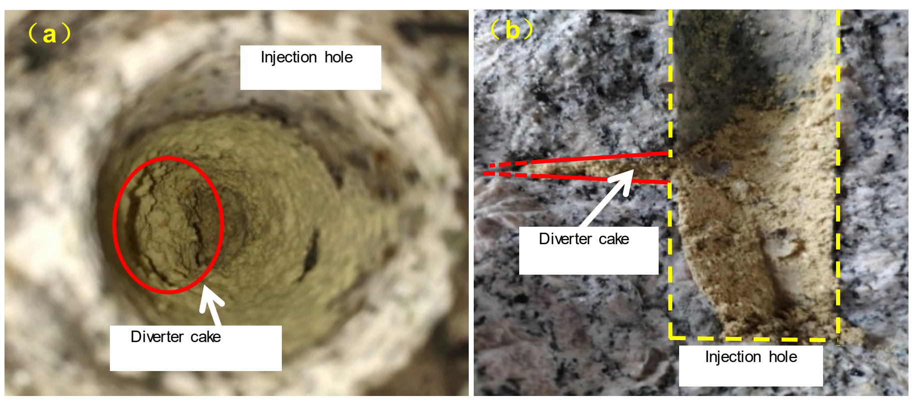

Fig. 19. Photos of fracture blockage in the 250 °C test before and after static crushing

According to the parameters and process of experiment 3.3, we conducted three repeated experiment, and all of them obtained results similar to the first experiment, which validated the reproducibility of the experiment and the reliability of the results.

Based on above mentioned experimental researches, it is proved that the ENNDA-250 diverter can meet the requirement of diverting fracturing in 250°C formation.

4. CONCLUSIONS

(1) Multi-stage fracturing is essential to increase production flow rate and realize commercialization of an EGS. Diverting fracturing method is an important technology for staged fracturing in high temperature formations.

(2) Over the past two years, ENN has developed two series of diverters (ENNDA-200 and ENNDA-250) for 200°C and 250°C formations stimulation. Performance tests such as temperature resistance, self-degradation, and mechanical strength showed that the overall performance of the temporary plugging material meets the requirements of hydraulic fracturing.

(3) We came up with an optimized combination of the diverter particle sizes for HDR fracturing based on a proprietary plugging performance evaluation equipment.

(4) A diverting fracturing experiment was conducted using a granite sample on a uniaxial compressive device. When the diverter entered a pre-made fracture, the pump pressure rose rapidly, and the rock sample was fractured when the pressure reached 10.6Mpa.

The presence of "diverter cakes" could be seen directly from the unloaded rock sample borehole, and the static crushing test proved the effective sealing of the fracture and creation of new fractures.

(5) Furthermore, several plugging experiments were carried out on the true tri-axial rock mechanical device to test the diverter in 250 °C granite samples. An initial plugging pressure of 5 Mpa was obtained. After keeping a constant temperature at 250 °C for 48 h, a plugging pressure of 5.7 Mpa was obtained. Repeatable tests validated the newly developed ENNDA-250 diverter meets the requirement of diverting fracturing technique in 250°C formation for more than 48 hours.

(6) The next step is to carry out on-site tests of diverting technology for EGS reservoir creation by using the developed diverter.

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