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Fracture Network Volume Fracturing Technology in High-temperature Hard Formation of Hot Dry Rock

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Abstract: It is more difficult for a hot dry rock to form a fracture network system than shale due to its special lithology, physical and mechanical properties under high temperature. The essential characteristics, rock mechanics and in-situ stress characteristics of a hot rock mass have been systematically studied by means of laboratory tests and true tri-axial physical simulation. The fracture initiation and propagation characteristics under different geological and engineering conditions are physically simulated, and the main controlling factors for the formation of a complex fracture network are revealed. The technology of low displacement for enhancing thermal cracking, gel fluid for expanding fracture and variable displacement cyclic injection for increasing a fracture network has been applied in the field, and good results have been achieved. Micro-seismic monitoring results demonstrate that complex fractures were formed in the field test, and the stimulation volume for heat exchanging reaches more than 3 million cubic meters. The research results play an important role in the stimulation technology of an enhanced geothermal system (EGS) and realize a breakthrough for power generation.

Key words: hot dry rock, granite, fracture network, natural fractures, thermal cracking, cyclic injection, volume stimulation, Gonghe Basin

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1 Introduction

Hot dry rock (HDR) is a kind of renewable resource buried at depths of 3 km to 10 km underground, where temperatures are 180–650ºC and there is no or only a little fluid (Chen et al. 2019; Hao et al., 2019). The economic development and utilization of this clean energy is of great significance for climate and environmental protection. Granite and granodiorite are common HDRs (Zhai et al., 2014; Liao et al., 2015; Zeng, 2015). In order to convert this kind of resource into energy for heating, cooling or power generation, hydraulic fracturing must be carried out on the hot rock to form an interconnected and huge fracture network system, and then the heat can be replaced by injecting fluid into the fracture network (Frash et al., 2013; Fu et al., 2018). Research on hydraulic fracturing technology of HDR began overseas as early as 1974. Scientists carried out fracturing technology, in the whole process, by using constant small displacement with a large -scale amount of clean water in a few wells (Chen et al., 2019), and made some progress, which promoted grid-connected power generation in some experimental projects, but was far from forming a replicable and practical technical system and technical support (Zhao, 2000; Wan et al., 2008). Domestic research in China started late, and was mainly limited to indoor testing of rock mechanical properties, permeability changes, etc., with a few reports on special research on HDR fracture network fracturing technology (Du et al., 2004; Xi and Zhao, 2010).

Through a State Key R & D project on HDR, we aim to systematically test and analyze rock lithology and physical properties, rock mechanical properties, the difference between two directions of in-situ stress and vertical section under high temperature and confining pressure by using downhole cores and large-scale outcrop rock samples. We also carried out physical simulation to study the fracture initiation and propagation characteristics under different geological and engineering conditions. From this we can recognize the key factors affecting the formation of complex fractures, put forward the fracture network fracturing technology for high temperature hard formation, to design a single well fracturing scheme. We hope to provide a reference for the volume reconstruction of an HDR thermal storage network in China.

2 Study of Characteristics of Hot Dry Rock

Rock lithology and mineral composition, natural fracture characteristics, rock mechanical properties, and horizontal stress differences are the most basic factors affecting the formation of a fracture network in rock. Rock samples were obtained from the Gonghe Basin in northwestern China, which is the first HDR geothermal formation to be developed. The changes of the above parameters have been analyzed by using a downhole granite core in a thermal section (3226–3380 m) of well X1 in the basin, so that the basic characteristics of HDR may be further understood.

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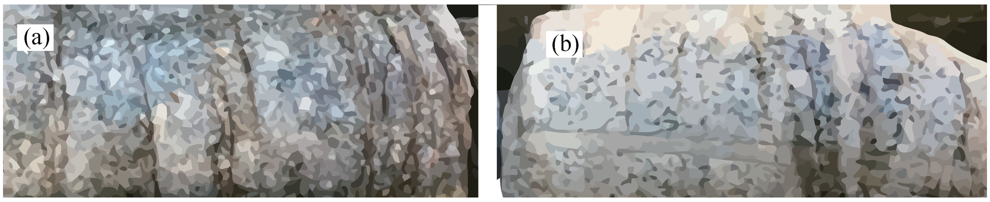

Fig. 1. Horizontal fractures developed in granite core in the thermal reservoir section.

2.1 Mineral composition and pore permeability characteristics

The composition, content, porosity and permeability of the rock were analyzed by X-ray diffraction and the air permeability test. The main lithology is gray medium coarse-grained monzogranite, biotite monzogranite, medium coarse-grained altered granite, etc. The main rock minerals are potash feldspar, plagioclase and quartz, accounting for more than 80% of the total minerals (Table 1). The samples were all drilled from X1 well in Gonghe Basin.

The porosity and permeability are extremely low, with porosity less than 4%, and permeability less than 0.4 mD, and so it belongs to a tight formation.

2.2 Characteristics of natural fractures

The core is a relatively broken cake-shaped cylinder (Fig. 1). Core observation and image logging show that some natural fractures are developed in the thermal reservoir section, mainly horizontal fractures, which are filled with calcite and quartz veins. The distribution of high-angle fractures is relatively low.

2.3 Rock mechanical properties and in-situ stress

The experimental results of uniaxial and triaxial rock mechanics parameters show that the rock is hard, with uniaxial Young's modulus of 31423–33638 MPa and Poisson's ratio of 0.203–0.225. Under confining pressure, Young's modulus is 36933–54142 MPa and Poisson's ratio is 0.25–0.343.

The minimum horizontal principal stress gradient is 0.0214 MPa /m, the maximum horizontal principal stress gradient is 0.0241 MPa/m, and the horizontal two-way geostress difference is 10.8 MPa at a depth of 4000 m. The maximum principal stress is close to the vertical stress.

2.4 Brittle-plastic of sample

The brittle-plastic character of rock is one of the key factors affecting the complexity of the fracture. The stress–strain curve of granite under 100–300ºC and 40 MPa confining pressure (Fig. 2) shows that with the increase in temperature, the stress–strain curve tends to shift gradually to the right, and the slope after the peak clearly decreases, which shows that rock brittleness decreases and plasticity increases. This highlights the plastic characteristics of granite under the condition of underground high temperature.

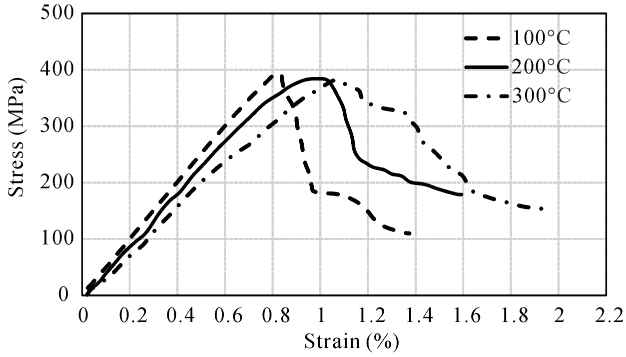

Fig. 2. Stress–strain curves under different temperatures and confining pressures.

The brittleness index of granite is calculated by the rock mineral component method and the rock mechanics parameter calculation method under confining pressure (Chen et al., 2010). The brittleness index of granite calculated by the above two methods were 24.5% and 30.7%, respectively. The brittleness index is low, which also reflects the partial plastic characteristics of the rock.

3 Study of Initiation and Propagation Characteristics of Hydraulic Fracturing in Hot Dry Rock

The target outcrop for rock samples were all in the same geological formation in the Gonghe Basin where dry hot rock wells above 200℃ were found in China. The compressive strength of the rock is about 386 MPa with a Young’s modulus of about 47 MPa.

A true-triaxial hydraulic fracturing test system was applied to simulate the hydraulic fracturing of the HDR geothermal formation in the laboratory. This system has been widely applied for research in the oil and gas industry to monitor and study hydraulic fracture propagation. A true tri-axial hydraulic fracturing test system was specifically modified and designed to meet the requirements of hydraulic fracturing in a realistic rock formation environment at actual reservoir temperatures and pressures. The temperature function includes heating, thermal insulation, temperature control, and thermometry

Table 1 Analysis of results of mineral composition and content

Well no.	Core no.	Quartz (%)	Potash feldspar (%)	Plagioclase (%)	Biotite (%)	Muscovite (%)	Calcite (%)	Chlorite (%)
X1	1	24	40	31	2	1	--	2
	2	25	38	30	1	3	--	3
	3	22	42	28	3	2	2	1
	4	27	35	32	1	3	1	1

parts. The heating part has nine electrical heating rods each with 2000 Watt power. The thermal insulation part is ceramic panels, the thickness of which is calculated to ensure the heating zone can keep a constant temperature up to 250ºC. Six temperature sensors around the sample and a thermoregulator are combined to control temperature.

The heating process for each sample takes 15 to 20 days. Each day, the temperature was only increased by 10ºC and kept at that the temperature for 24 h. This was to ensure that heating was smooth and the temperature increase could not induce any damage in the rock (Zhou et al., 2020).

The geological conditions, such as natural fractures, different two-way horizontal stress differences and temperatures, and engineering conditions, such as injected fluid viscosity, displacement and injection mode, the characteristics of initiation and propagation were studied, and the following conclusions can be reached.

(1) The natural fracture and weak plane in the thermal reservoir are the key factors for forming a complex fracture network (Riahi et al., 2014; Tomac and Gutierrez, 2014). When there is no natural fracture in the rock sample, the fracture pressure is very high and the fracture shape is single; when there are natural fractures in the rock sample, the fracture pressure decreases greatly, and the artificial fractures only extend along the natural fractures, but not into the rock matrix (see Fig. 2). When a dike/dyke (Weak plane with some thickness which might affect the propagation of the hydraulic fracture) is mixed in the rock sample (Fig. 3), a hydraulic fracture is easy to open with a weak plane between the dyke and the rock matrix, which extends along the weak plane.

(2) Engineering measures, such as high temperature difference effect, low displacement and alternative cyclic injection are helpful to form a complex fracture system. The rock sample is heated to 200ºC and then injected with 20ºC clean water. Multiple microfractures crack open before the main fracture breaks during the water injection process, and the fracture pressure is then significantly reduced (see Fig. 4). Under the condition of high displacement, the reservoir fractures extend very rapidly, and single wing fractures appear (Rutqvist et al., 2013). Therefore, it is easy to stimulate and induce the formation of a complex fracture network by alternative cyclic injection at low displacement.

(3) The two-way horizontal stress difference affects the fracture propagation direction and morphology. Under the high stress difference (6 MPa) condition, the hydraulic fracture of the HDR extends along the direction of maximum horizontal principal stress and will not change. The shapes of the hydraulic fractures are simple and it is difficult to form a complex fracture network, and also difficult to connect natural fractures. Under the low stress difference (3 MPa) condition, the fracture morphology is more complex and easy to connect with natural fractures.

(4) The viscosity of the injected fracturing fluid has little effect on the complexity of the fracture. Under the same conditions, the injection of water with a viscosity of 1.0 MPa·s and linear glue with a viscosity of 33.1 MPa·s

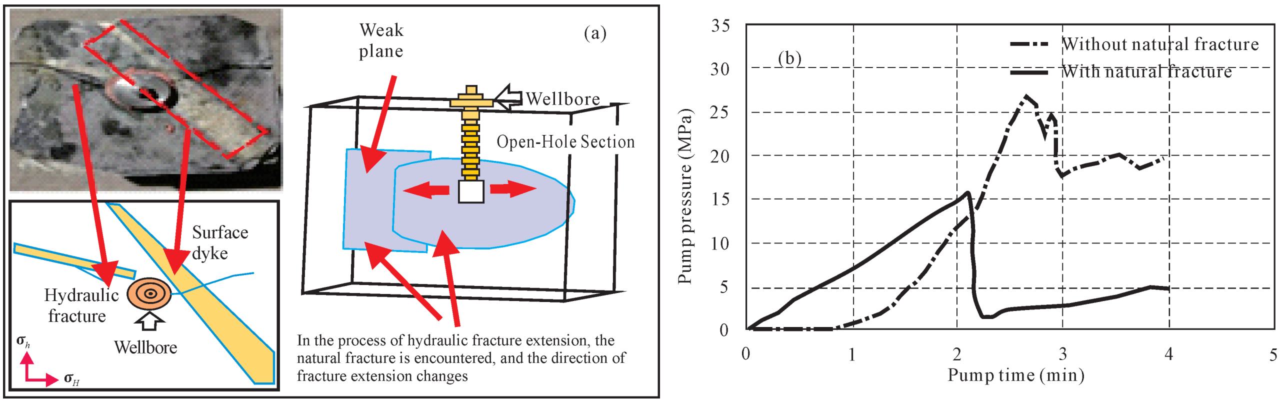

Fig. 3. Hydraulic fracture extension physical picture (a) and injection curve (b).

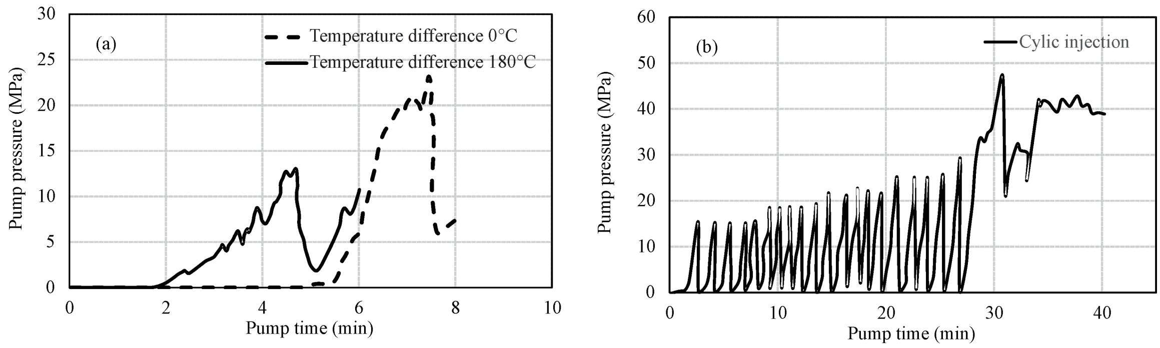

Fig. 4. Effect of temperature difference on fracture initiation pressure (a), and alternative cyclic injection (b) at low displacement on fracture initiation pressure.

into the rock sample has no obvious effect on the fracture morphology.

Physical simulation results show that the formation of a complex fracture network in a thermal reservoir depends on the existence of natural fractures, a temperature difference effect, the liquid injection mode and displacement (Cladouhos et al., 2013). The horizontal stress difference and the viscosity of the injected liquid are secondary factors.

4 Study of Fracture Network Fracturing Technology of Hot Dry Rock

The above research shows that an HDR thermal reservoir is characterized by tight physical properties, partially developed natural fractures, and large horizontal stress differences, which is relatively unfavorable for forming a complex fracture network. Therefore, it is necessary to innovate new fracture network fracturing technology for high temperature and hard formation.

4.1 Fracture network fracturing technology

To form a complex fracture network in a high temperature hard formation and improve the stimulation volume, it is necessary to integrate deeply geology and engineering. Firstly, the fracture development section of a thermal reservoir should be selected as the fracturing section. Secondly, the microfractures produced by thermal fracture should make full use of the temperature difference effect, and then the fracture system should be expanded by using a change of injection mode. In the initial stage of fracturing, a low displacement injection of clean (or slick) water or CO_2 and liquid nitrogen is used to produce the thermal fracture and to form a large number of microfractures. Then water (or slippery water) is injected with constant displacement to expand natural fractures and microfractures. After that, a glue liquid slug is injected to expand the width and height of the crack, to reduce the construction pressure caused by the rock plasticity and narrowness of the fracture, and to ensure a continuous and safe construction. Finally, fresh (or slippery) water is injected by variable displacement circulation to expand the fracture network system, and eventually an artificial heat reservoir with interconnected and huge heat exchange volume is formed.

Table 2 Rock porosity and permeability test results

Core no.	Diameter (cm)	Length (cm)	Porosity (%)	Permeability (mD)
1	2.46	4.94	2.49	0.27
2	2.44	4.86	2.57	0.28
3	2.44	4.94	3.43	0.29
4	2.44	4.90	3.28	0.33
5	2.44	4.95	3.58	0.27
6	2.45	4.87	3.13	0.32
7	2.44	4.90	3.77	0.35
8	2.44	4.94	2.49	0.29
9	2.45	4.85	2.82	0.28

4.2 Optimization design of fracturing treatment parameters

According to the test results of lithology, physical properties, rock mechanics and in-situ stress from the laboratory experiment, the complex fracture model has been established using Mayer software. Parameters such as injection string, treatment displacement, fracturing fluid type and scale were designed, which provides a theoretical basis for the field experiment.

4.2.1 Fracture pressure and gradient prediction

Based on Huang Rongzun's fracture pressure calculation formula (Huang, 1984) that considers the additional stress of thermal fracture, combined with the rock mechanics parameters obtained from laboratory experiments, the bottom hole fracture pressure gradient for the granite matrix at 4000 m depth is 0.025 MPa/m, and the fracture pressure gradient of the fracture development section is 0.023 MPa/m.

4.2.2 Treatment tube and displacement

The wellhead pressure of the natural fracture development section and the matrix section with clean water and slick water at different displacement rates was calculated by considering the fracturing well depth of 4000 m. Under the pressure limit of 70 MPa, the maximum displacement rate of clean water fracturing in matrix section can be up to 2.0 m^3/min, and the treatment displacement rate of slick water can be up to 3.0 m^3/min (see Table 3). The maximum displacement of water fracturing can be up to 3.5 m^3/min in the natural fracture development section and 4.5 m^3/min in the slick water treatment section. Considering the economy and treatment safety, the injection mode of a clean or slick water casing is optimized, and the treatment displacement is controlled within 3.0 m^3/min.

The fracturing fluid should not only be able to open the formation, but also be of low cost and have no influence on the later circulation heat transfer. According to the comprehensive analysis of the thermal fracture and pressure prediction of water injection, the fracturing

Table 3 Rock mechanics parameters under uniaxial and confining pressure

Sample no.	Test conditions		Compression test results				
	Confining pressure (MPa)	Pore pressure (MPa)	Compressive strength (MPa)	Young's modulus (MPa)	Poisson's ratio	Cohesive force (MPa)	Interior friction angle (°)
X1-1-cz1	0	0	82.09	32838	0.206	16.5	48.11
X1-1-sp0	0	0	85.64	33007	0.203		
X1-1-sp45	20	0	178.56	36933	0.25		
X1-1-sp90	40	0	354.07	44910	0.338		
X1-2-cz1	0	0	103.71	33638	0.225	16.0	52.22
X1-2-sp0	0	0	90.23	31423	0.216		
X1-2-sp45	20	0	358.66	47290	0.319		
X1-2-sp90	40	0	430.38	54142	0.343		

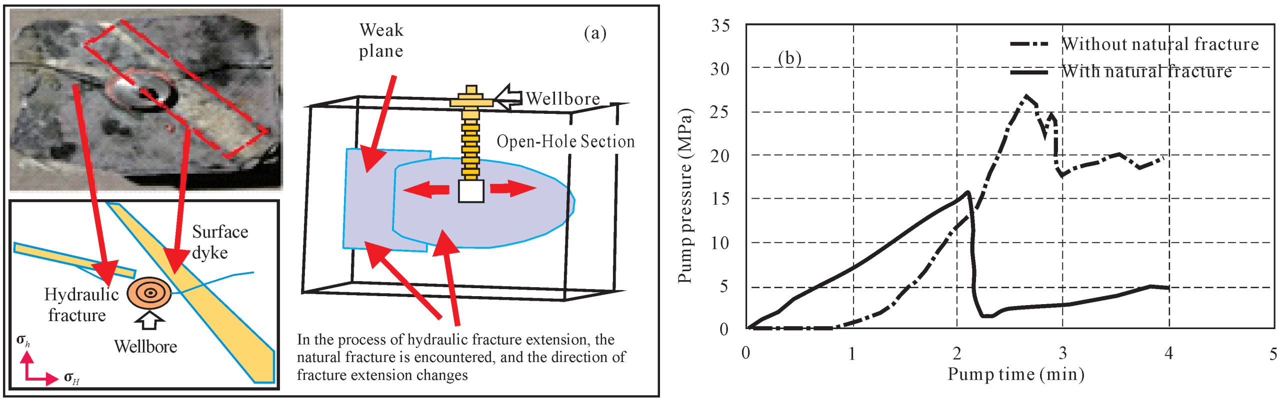

Fig. 5. Fracture creation under large horizontal stress difference (a), and small horizontal stress difference (b).

Table 4 Test results of three-dimensional in-situ stress

Sample no.	In situ stress						
	Stress value corresponding to Kaiser point (MPa)				Three-dimensional principal stress (MPa)		
	Vertical	0°	45°	90°	Vertical stress	Horizontal maximum principal stress	Horizontal minimum principal stress
X1-1	33.32	32.91	20.93	26.23	54.47	54.70	46.74
X1-2	51.8	47.89	29.04	40.65	80.83	77.67	68.94

Table 5 Prediction results of wellhead pressure under different construction displacement

Type of fracturing section	Fracture pressure gradient (MPa/m)	Fluid type	Wellhead pressure (MPa)							
			0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Matrix segment	0.025	Water	66.43	67.49	69.10	71.21	73.79	76.82	80.29	84.18
		Slick water	66.15	66.53	67.11	67.87	68.79	69.89	71.13	72.54
Fracture developmental segment	0.023	Water	58.43	59.49	61.10	63.21	65.79	68.82	72.29	76.18
		Slick water	58.15	58.53	59.11	59.87	60.79	61.89	63.13	67.54

treatment using clean or slick water met the stimulation requirements for 4000 m deep HDR wells.

4.2.4 The scale of fracturing fluid

The results of fracture simulation show that half a length of a fracture is about 252–304 m and the stimulation volume is (10.45–14.92) $\times 10^6$ m^3 when the injection volume is 10000–20000 m^3. Considering the demand of a 500–600 m connection between injection and production wells in HDR, the scale of single well fluid is designed to be 10000–20000 m^3.

5 Field Fracturing Test and Evaluation

Well X1 is an HDR exploration well in a basin. The drilling depth is about 3700 m and the formation temperature is about 200°C. The φ114.3 casing with steel grade P110 and wall thickness of 8.56 mm was used for cementing and completion, leaving about a 200-m granite open hole section as the fracturing section. The fracture in the target section is partially developed. The technology of low displacement thermal fracturing + gel slug expansion + variable displacement circulating water injection was adopted (Chen et al., 2010; Tao et al., 2019; Xie et al., 2020). The operation displacement range is 0.5–3.0 m^3/min, and the operation pressure is 53.2–68.5 MPa. By analyzing the fracturing test curve, the following conclusions are obtained:

(1) the low displacement thermal cracking process is

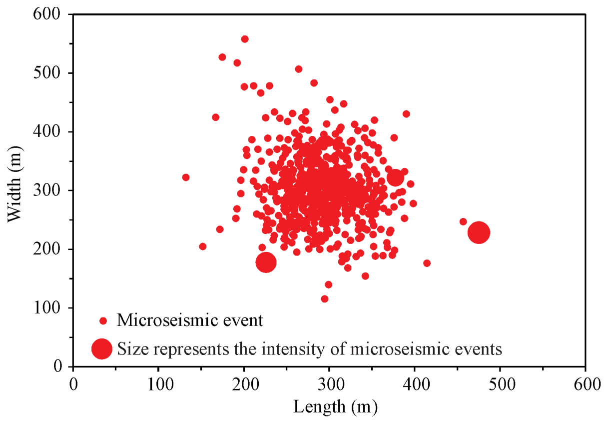

Fig. 6. Micro-seismic events in well X1 during fracturing treatment.

beneficial to the formation of microcracks. A 0.5–0.7–1.0 m^3/min low displacement water injection process was adopted in the initial stage of fracturing, and the treatment pressure was 53.2–65.4 MPa. The treatment curve shows that there are many microfractures (Fig. 4). The pressure drop G-Function analysis curve shows the characteristics of multi-fracture closure. There are more than 1000 micro-seismic events, which are several times more than a conventional sandstone. This process shows that it is feasible to generate and form many microfractures and complicate the fractures by using the temperature difference effect.

(2) The plastic propagation characteristics of fractures are obvious. In the process of constant displacement fracturing, the treatment pressure has been rising, and the plastic expansion characteristics are clear, which is consistent with the indoor core stress–strain test results.

(3) The gel slug helps to expand the fracture width and height. In the process of fracturing, when the gel slug is injected, many obvious fracture points appear on the fracturing operation curve, and the treatment pressure decreases steadily after the gel liquid is injected, which indicates that the gel liquid plays a role in expanding the fracture and reducing the construction pressure. Micro-seismic monitoring shows that the fracture height is well extended.

(4) The technology of low displacement thermal fracturing + gel fluid expansion + variable displacement cyclic injection is basically feasible. The micro-seismic fracture monitoring data in the fracturing test show that the temperature difference effect promotes the formation of complex microfractures, the gel fluid expands the fracture width and height, and the variable displacement cyclic injection expands the stimulation volume.

6 Conclusions and Suggestions

(1) The physical properties of an HDR thermal reservoir are tight, hard but not brittle, and the horizontal stress difference between two directions is large. There are many unfavorable conditions for fracturing forming a complex fracture network, so it is necessary to innovate fracturing technology to realize fracture network stimulation in high temperature and hard formation.

(2) Natural fractures in thermal reservoir, thermal fracture caused by temperature difference and low displacement cyclic injection are the key factors of fracture network fracturing in HDR. The gel slug is helpful to expand the width and height of fracture and increase the volume of reconstruction.

(3) The low displacement thermal fracturing + gel fluid expansion + variable displacement cyclic injection fracturing technology has achieved good field results, forming a complex fracture system and a large stimulation volume, which can be further promoted and applied.

(4) In view of the relatively long thermal reservoir section (hundreds to thousands of meters) of HDR wells, it is necessary to continue studying the staged fracturing method, matching tools and materials at high temperature, to further improve the transformation volume.

(5) Due to the lack of connectivity fracturing, cyclic injection test and power generation test for injection production wells in HDR in China, it is necessary to further improve the fracture network volume stimulation technology based on the connectivity test results.

Based on a State Key R&D project on HDR, the authors have systematically tested and analyzed rock lithology and physical properties, rock mechanical properties, the difference between two directions of in-situ stress and vertical section under high temperature and confining pressure by using downhole cores and large-scale outcrop rock samples. We also carried out physical simulation to study the fracture initiation and propagation characteristics under different geological and engineering conditions, and we recognized the key factors affecting the formation of complex fractures, put forward the fracture network fracturing technology for high temperature hard formation, designed a single well fracturing scheme, and achieved good results after field test application the results of which show a complex fracture system and large stimulation volume. Our study provides a reference for the volume reconstruction of the thermal storage network in HDR in China.

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