Research Article

How to Seal Hydraulic Fracturing Boreholes in the Large-Size HDR Rocks under HTHP Conditions

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The hydraulic fracturing (HF) is a key technique to enhance the permeability and heat production of hot-dry-rock (HDR) geothermal reservoirs. Normally, laboratory HF tests should be preconducted to understand the HF characteristics of HDR samples. However, in the laboratory test, sealing failure between boreholes and injection pipes always limits the experimental efficiency and data accuracy, especially for the HF tests under high-temperature and high-pressure (HTHP) conditions. Traditional sealing methods, such as rubber and cement sealing, are easy to be failed because of their poor load and/or thermal bear performance under HTHP conditions. Therefore, in this study, we proposed a novel HTHP seal by using wedge-buckled copper components and steel rings. The sealing efficiency was verified by successfully conducting the HF tests of HDR rocks with a dimension of φ200 × 400 mm under various high temperatures ranging from 100°C to 400°C. As expected, the unfavorable factors such as HTHP and high injection pressure could be turned into favorable ones during the introduced seal method. By this investigation, we expect to provide some sealing solutions for researchers when conducting HF tests under HTHP environments.

1. Introduction

Geothermal energy is a kind of renewable energy that is generated and stored in Earth’s crust. A vast store of HDR geothermal energy is contained within hot but essentially dry and impervious crystalline basement rocks, founded in almost everywhere deep beneath Earth’s surface. However, the abundant hot-dry-rock (HDR) geothermal resources are still not well developed due to the extremely harsh environments such as the high temperature (could be above 400°C), low permeability, and the deep burial (normally 3~10 km) of target reservoirs. In the HDR projects, the most important consideration for heat extraction of HDR is to build the Enhanced/Engineered Geothermal System (EGS) by using hydraulic fracturing (HF) technique [1, 2], thus establishing an effective network pathway to enhance the injection fluid flowing and heat extracting [3, 4]. Generally, the HF characteristics of the target HDR rocks should be preunderstood in the laboratory before the in-site HF stimulation of HDR reservoirs. However, a key limitation for laboratory HF tests is that the fluid leak-off or seal failure between casing pipe and rock borehole always occurs, especially for these tests under high-temperature and high-pressure (HTHP) conditions. Therefore, developing a new
seal that could be suitable for the HTHP environments is vital to optimizing the in situ stimulation of HDR resources.

Packer is a key tool to stepping fracturing and injection production for separated pay formation of geothermal wells. In the aspect of sealing materials, cement, rubber, and epoxy resin are usually employed [5–8]. These traditional sealing materials are easy to be failed under HTHP conditions, especially at a high temperature of over 150°C. For example, the cement is prone to be thermally cracked under HTHP conditions, and the rubber and epoxy resin materials tend to be softened under HTHP conditions. In recent years, with the increase of drilling depth, especially the HDR geothermal well which could be 3 km in depth, high temperature working wells have become the new normal state. A large number of packers have failed or even ruptured due to high temperature working conditions, which seriously affected the normal development of geothermal energy.

Dong et al. [9] investigated the high-temperature sealing behavior of packer rubber tube based on thermal aging experiments, revealing that the sealing performance and load bearing performance of the packer rubber tube are greatly weakened in the range of 130°C–150°C. They recommended that the initial limit load range in the high temperature (<150°C) well is 68–76 kN. Previous studies also introduced two types of in situ sealing devices, i.e., friction type and hydraulic expansion type [10]. The friction type is sealed by the lateral expansion of the rubber and the friction of the borehole, and the hydraulic expansion type contains a rubber expansion tube. Similarly, these sealing methods are easy to be failed under HTHP conditions.

Currently used sealing systems for geothermal wells, based exclusively on Portland cement systems, are not designed to withstand extreme temperatures going beyond the critical point of the reservoir fluid [11]. Cement materials have the disadvantage of shrinkage and cracking, which leads to the failure of sealing [12]. Furthermore, not only the phenomenon of strength retrogression but also the thermal expansion and shrinkage at high temperatures as well as thermal cyclic loading cause challenges to the binding matrix of the Portland-based sealing systems. Zhai et al. [13] developed a composite sealing material with excellent expansion performance, but the material strength decreases significantly, thereby affecting the sealing effect. Therefore, traditional sealing materials and techniques are no longer applicable under HTHP conditions.

In the aspect of HTHP triaxial test systems, several apparatuses were tried to conduct coupled thermo-hydro-mechanical (THM) tests of rocks. But the maximum temperature in the existing apparatus can hardly exceed 400°C. For example, the US DOE’s National Energy Technology Laboratory developed the ultradepth drilling simulator which was designed to operate at 205 MPa pressure and 250°C [14]. Kumari et al. introduced a high-temperature and high-pressure triaxial test apparatus in the Deep Earth Energy Laboratory at Monash University [15]. This apparatus is capable of injecting fluid up to 165 MPa, with maximum confining pressures of 137 MPa, maximum axial loading up to 1000 kN, and temperature up to 300°C. Zhao et al. [16] developed an XPS-20 MN test machine to study rock mechanical behavior under HTHP environments, and the maximum normal stress, confining stresses and temperature on rock specimen are 318 MPa, 250 MPa, and 600°C [17, 18].

Recently, we solved the sealing problems of the drilled boreholes for the XPS-20 MN test machine when conducting the HF test of HDR rocks under HTHP conditions. In this study, we first introduced the new HTHP sealing method. Afterward, its sealing efficiency was verified by successfully conducting the HF test of large-size samples under the HT (above 400°C) and HP conditions.

2. Methodology

2.1. Sealing Assemblies and Mechanisms. The proposed HTHP seal is a type of wedge-shaped metal buckle with coupled cap and pedestal. As shown in Figure 1, the cap and pedestal can be well paired to form a set of seals. Copper material is employed to manufacture this seal in considering its excellent ductility and thermal expansion characteristics. This ductile material could easily fill the uneven surface of the rock borehole or pipe once be forced or heated. Furthermore, the thermal expansion effect of copper could further enhance the sealing during the heating of HDR.

The sealing mainly consists of four parts. One is the pre-tighten sealing by mechanical compressing or hammering of seal ends, which is an initial sealing. The second sealing is a kind of passive sealing by loading the large-size granite sample. In this scenario, loading would induce the shrinkage of sample thus further compressing the seals. The third passive sealing scenario is the thermal expansion sealing of copper during heating samples. It is known that all the seals, rocks, and fracturing pipes would be thermally expanded under high temperatures. Because of the large expansion coefficient of copper, the ends and faces of seals would be further stressed. The last sealing is achieved during high-pressure water injecting process. The injected high-pressure water would squeeze the pedestal from below, causing the cap and pedestal buckles to be stressed. Therefore, by using this sealing method, many negative factors would be converted into favorable ones, such as high temperatures, high confining loadings, and high injection pressures. These are also the keys to overcoming the failures of traditional sealing methods under HTHP conditions.

2.2. Sealing Procedures. There are two assembling methods when using this seal technique: the single sealing for small size samples (i.e., φ50 × 100 mm, traditional dimension) (Figure 2(a)) and the series-connected sealing for large-size samples (i.e., φ200 × 400 mm, 300 × 300 × 300 mm³, 1000 × 1000 × 1000 mm³) (Figure 2(b)). Generally, for small size samples under HF test, samples would be fully cracked after the initial HF period. Crack propagation process could be hardly obtained by continuously injecting water. That is to say, after the water injection pressure increasing to the initial HF value, it is difficult to be increased again due to the hydraulically generated cracks have penetrated samples (i.e., leaking off).

However, in the in situ HF test, crack propagation occurs not only in the initial stage of hydraulic fracturing but also in
the stage of continuously injection of fluids (i.e., multiple injecting and cracking). In the laboratory, researchers are more inclined to conduct HF experiments on larger-sized rocks to reveal this multicracking effects. According to our knowledge, the large-size sample can only reach to 1 m in cubic due to the limitation of test equipment. Since the propagating directions of HF cracks are uncertain, it could be further expanded along the drilling well. Therefore, it is necessary to adopt a multistage sealing method. Because once employing a single sealing, the liquid may flow out after the initial HF cracks induced and exceeded the seal. Therefore, the purpose of proposing the series-connected seals is to provide a full-length sealing or partial sealing of large-size rock samples. In this method, the multiple hydraulic fracturing characteristics of large-size HDR rocks could be revealed.

For multiple sets of seals, as shown in Figures 2(b) and 2(c), a certain length of metal segmented pipe or steel rings could be placed between each seal to save sealing materials. The purpose of installing the spacing ring is to save seal materials. The ring length should be determined by considering the size of samples. In this study, the length of steel rings is empirically determined as 30 mm for φ200 × 400 mm granite sample. It is suggested to adopt the full-length sealing method to ensure the sealing efficiency. Therefore, for the large-size granite samples in this study, the series-connected structures are preferred.

The experimental procedures using the proposed seal to conduct HF test under HTHP conditions are as follows: (1) drill a water-injecting borehole in granite samples. (2) Put an injection pipe into the borehole. (3) Install a seal and steel ring at the bottom borehole, and then apply a certain pretighten force through a steel casing to achieve the initial sealing. (3) Repeat procedure (2) to serially install steel rings and seals to achieve the full-length borehole sealing. (4) Put the prepared sample in a loading vessel, and then load the axial and lateral stresses. (5) Heat sample to a target high temperature, and keep the sample at the target temperature for over two hours to ensure that the temperature is evenly distributed. (6) Inject water into the hole until the sample is fully hydraulically fractured.
3. Applications and Verifications

3.1. Samples and Test Machine. The Luhui granite samples (φ200 × 400 mm) that resourced from an open-pit mine in Shandong province (China) were employed to conduct the HF tests under HTHP conditions (Figure 3). A borehole with a dimension of φ18 mm × 250 mm was drilled to install the proposed seals and injection pipes. The prepared sample was then installed into the HTHP vessel, and the constant axial and confining stresses are both applied as 25 MPa. Afterward, the loaded sample was heated at a rate of 5°C/h to the target temperatures (i.e., 100°C, 200°C, 300°C, and 400°C in this study). After reaching the target temperature and being maintained for over 2 hours, the water injection procedures could be initiated.

The XPS-20 MN test machine was employed to conduct the HF tests of granite samples under HTHP conditions [19]. Both the axial and confining maximum loads of this test machine are up to 10000 kN. Correspondingly, the maximum axial and confining stresses of the φ200 mm × 400 mm sample are 318 MPa and 250 MPa, respectively. The maximum water injection pressure is 250 MPa, and the maximum heating temperature is up to 600°C. Figure 4 shows the picture of the test machine and the schematic of the sample in the HTHP vessel, which can be referred to Zhao et al. [16] for more details [19].

3.2. Hydraulic Fracturing Pressures. Figure 5 shows the injection pressure versus time curves for granite samples at 100°C, 200°C, 300°C, and 400°C. The initial HF pressures at 100°C and 200°C are 47.7 MPa and 43.2 MPa, respectively. This indicates that high temperature (100–200°C) has little effect on the initial HF pressures. However, with the increase in temperature, the initial HF pressure drops to 24.6 MPa at 300°C and 15.3 MPa at 400°C, which decreases by 48% and 68% compared to that at 100°C, respectively. Therefore, it can be concluded that the temperature within 200°C has little effect on the crack initiation of granite, while after the temperature exceeds 200°C, a higher temperature always implies a more likely initial HF in HDR rocks. Similarly, Kumari et al. [15] studied the effect of temperature on hydraulic fracturing of Harcourt and Strathbogie granite samples (φ50 × 100 mm) over a range of temperatures from room temperature to 300°C. They found that the initial HF pressure linearly decreased with increasing temperature.

Expectedly, the multiple hydraulic fracturing characteristics of HDR were well demonstrated in the injection pressure versus time curves. Specifically, after the granite being initially cracked (i.e., after the initial hydraulic fracturing pressure), the repeated increases and drops in water pressure were successfully obtained. This enlightens that HF fractures in samples would be further developed or propagated with the continuous water injection after the initial cracking. These findings also imply that the series-connected sealing was successfully achieved.

3.3. Fracture Shapes after HF Tests. Figure 6 presents the fractures of the HDR samples after water injection at high temperatures, in which the red region was colored by a dye conveyed by HF fluids. At 100°C, there are two pairs of symmetrical fractures, dividing the sample into four parts. This shows that a high degree of randomness of hydraulic fractures could be distributed at a relatively low temperature under isostatic confining stress conditions. At 200°C, 300°C, and 400°C, only a main hydraulic fracture is revealed, dividing the sample into two pieces. Due to the injected water is in red color, the dye distribution implies the hydraulic-induced fractures in rock, while the noncolored fractures are further deformed by the applied axial and/or confining loading failure. That is to say, under the effects of hydraulic fracturing, primary fractures open via hydraulic pressure, and there is an obvious red color on these fracture surfaces.
Figure 4: The XPS-20 MN test machine. (a) Pictures of the test machine; (b) HTHP vessel; (c) installation of rock in the vessel.

Figure 5: Hydraulic fracturing pressure versus time curves at different high temperatures. (a) 100°C; (b) 200°C; (c) 300°C; (d) 400°C.
As a result, the applied loading further extends the fracture. It should be noted that the upper and lower ends of the HF fractures are not colored, especially at 200°C and 300°C, which indicates that samples are well sealed by the series-connected sealing.

4. Conclusions

In this study, a wedge-shaped sealing was proposed to seal rock boreholes in the HF tests of HDR rocks under HTHP conditions. The sealing efficiency was verified by successfully conducting the HF experiments. In this sealing technique, high temperatures, high loading stresses and high water injection pressure are all favorable factors for sealing. Furthermore, cooper material with good ductility, thermal expansion, and thermal conductivity is preferred to manufacture the seal components. Specifically, when using the large-size geothermal rock sample to conduct the HF tests under HTHP conditions, the series-connected seal method is suggested. This would be more conducive to avoid single-seal failure.

Data Availability

All data required for this research is included in the paper.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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