Temperature-dependent factors on hydraulic fracturing of hot dry rock (HDR): An experimental investigation

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Abstract: Hot dry rock (HDR) is rich in geothermal energy and renewable and does not cause pollution; therefore, it has attracted considerable research attention. Previous studies have extensively discussed the process of HDR hydraulic fracturing based on the crack initiation mechanism, initiation pressure, and crack propagation law. However, the temperature-dependent factors (thermal damage and thermal shock) affecting the HDR hydraulic fracturing process have not been specifically discussed. Therefore, HDR hydraulic fracturing tests with different sample temperatures and injection rates were designed in this study. Further, various factors affecting the hydraulic fracturing related to temperature, including the thermal damage, thermal shock, and injection rate, were analyzed. The test results indicate that under the condition of variable temperature parameters, thermal damage and thermal shock caused the initiation pressure of the reservoir to decrease with the increasing temperature. The degree of weakening increased with the increasing temperature. After fracturing, the initial fracture in HDR continued to expand under the action of thermal shock and residual pressure, and the fracture expansion scale increased with the increasing temperature. Under the condition of variable fracturing parameters, microfractures with large areas were more likely to form when fracturing occurred at a lower injection rate, which is beneficial to improve the heat exchange efficiency of the reservoir and avoid short circuits. These research results provide a scientific explanation for the influencing factors of HDR hydraulic fracturing and offer geological and engineering guidance for optimizing the hydraulic fracturing in an enhanced geothermal system.

1. Introduction

Geothermal energy is the only type of renewable energy that can ensure the stable operation of the power grid, and the geothermal resources endowed by hot dry rock (HDR) are tens of thousands of times greater than the traditional hydrothermal geothermal resources [1, 2]. Therefore, to complete China’s energy revolution, the country must rely on the power generated using HDR. Currently, a set of HDR development technology represented by an enhanced geothermal system (EGS) has been derived from oil and gas exploitation. Therefore, engineers often use the theory and methods of oil and gas reservoir fracturing to design fracturing construction schemes for HDR reservoirs; however, the influence of the high-temperature environment unique to HDR on the fracturing processes is often ignored [3].

The manner in which the high temperature affects the rock mechanics are divided into thermal damage and thermal shock. Rock is a dual-porosity medium containing water; part of the water is
freely present in pores or fissures (free water), whereas the other part is bound in the rock minerals (bound water). Under high temperatures, the mechanical properties of rocks are mainly dependent on the density and morphology of pores or cracks and the changes in the moisture content of the rocks. During the early period of heating, free water forms vapor and escapes from the rock fractures, resulting in increasing initial pores or cracks and thermal damage to the rock [4, 5]. As the temperature increases, the crystal water in the rock minerals decomposes thermally and escapes, thereby forming more pores. Moreover, thermal cracks are formed across the particle boundary and gradually expand into a network owing to the different thermal expansion coefficients of various mineral particles in the rock, considerably decreasing the rock strength [6-8]. When the temperature is increased to a certain value, the rock is almost completely dehydrated. At this point, the development of thermal expansion and thermal cracking in the mineral particles decelerates, and the strength of rock is mainly dependent on the changes in mineral composition [9, 10]. The mechanism of thermal shock in rocks differs significantly from that of thermal damage. When a high-temperature rock is rapidly cooled, different temperature gradients can be observed from the inside to the outside. Therefore, strong thermal stress is instantly generated in this unstable temperature field, causing rock fracture via thermal shock. During the process of HDR hydraulic fracturing, thermal shock is caused by the rapid cooling of the high-temperature rock by the fracturing fluid, and the initial cracks expand further under this action [11, 12]. Many experimental investigations have investigated the thermal damage and the thermal shock caused by HDR fracturing. The experimental studies that have investigated the effects of thermal damage on the physical properties of granite indicate that thermal damage considerably affects the evolution of permeability, porosity, and p-wave velocity. With an increase in temperature, the permeability and porosity generally increase and the p-wave velocity decreases [13-16]. Mechanical tests have shown that the compressive strength, tensile strength, and elastic modulus of granite are inversely related to temperature [17-21]. The acoustic emission and the stress–strain curves show that the failure mode of the granite specimen is converted from brittle fracture to quasi-brittle shear fracture and finally to ductile fracture as the temperature increases [22-24]. Several thermal shock experiments have been conducted to study the thermal shock effect of high-temperature rock during rapid cooling. The results of a test conducted using the Brazilian disc (BD) method on high-temperature granite samples cooled at different cooling rates revealed that the tensile strength and p-wave velocity were inversely proportional to the heating temperature and cooling rate of the sample [25, 26]. The experimental study on the fracture characteristics of granite after the application of alternate cooling and heating showed that the fracture toughness gradually decreased with an increase in the cooling rate and cycle number and that the thermal shock effect was conducive to crack generation [27, 28]. Because HDR is rapidly cooled during fracturing, thermal damage and thermal shock play key roles during the HDR hydraulic fracturing process. Although extensive previous research has been conducted, the influencing factors of HDR hydraulic fracturing relative to thermal damage and thermal shock have rarely been reported. In this study, two sets of hydraulic fracturing experiments using HDR are designed in which the temperature and fracturing parameters are considered to be independent variables, respectively. Finally, from geological and engineering perspectives, the temperature-dependent factors affecting the HDR hydraulic fracturing, specifically the thermal damage and thermal shock, are analyzed.

2. Test sample and test device

2.1. Sample description

HDR, particularly Mesozoic mesoacid granite, is an important geothermal resource [29, 30]. Therefore, the rock material selected in this study is the Mesozoic granite obtained from Changsha, Hunan Province. These granite blocks are light gray and medium-grained and are highly uniform in texture, density (2.82 g/cm³), and compressive strength (134 MPa). The rock mineralogy was analyzed using X-ray diffraction. As shown in figure 1, the granite mainly comprises quartz (47.63%), feldspar
(39.14%), mica (7.43%), and montmorillonite (5.8%).

![X-ray diffraction pattern of granite at room temperature.](image)

**Figure 1.** X-ray diffraction patterns of granite at room temperature.

The tests conducted in this study include the Brazilian split test and the real-time high-temperature true triaxial hydraulic fracturing test. According to the requirements of the Brazilian split test recommended by the International Society for Rock Mechanics (ISRM) [31], the samples were processed into BD samples with a diameter of 50 mm and an aspect ratio of 0.5. The hydraulic fracturing test sample was a 100 mm × 100 mm × 100 mm cube with a surface tolerance of ±0.5 mm and perpendicularity of ±1°; samples with higher homogeneity were preferred. To reduce the sample heterogeneity, all the samples were obtained from the same rock block and were measured based on the p-wave velocity using the ZD18 integrated wave velocity tester prior to the experiments. In this study, samples with similar p-wave velocities were selected, including 21 BD samples and 10 cubic rock samples.

### 2.2. Test device

The Brazilian split test was conducted using the MTS universal material tester. The hydraulic fracturing test was conducted using a triaxial electrohydraulic servo mutagenesis test system developed by Central South University, which enabled the hydraulic fracturing tests to be conducted under a high-temperature underground true triaxial stress environment in real time. As shown in figure 2, the true triaxial test system comprised loading frames in the X- and Z-directions, a loading vehicle in the Y-direction, a heating furnace, a rigid tension rod, an infrared thermographer, and a control software that functioned as a three-way system involving independent rigid loading with a maximum horizontal stress of 200 MPa and real-time high-temperature heating at a maximum temperature of 800 °C. Before the hydraulic fracturing test, as shown in figure 3, a hydraulic head was added at the top of the sample using the true triaxial electrohydraulic servo mutagenesis test system. This enabled the test system to develop into a high-temperature and high-pressure sealing system with a maximum water injection rate of 15 ml/min. Subsequently, the real-time high-temperature true triaxial hydraulic fracturing test was conducted.
3. Test procedure
In this study, simulated tests for HDR hydraulic fracturing were conducted in two ways. In the first method, the heating temperatures of the samples were considered to be independent variables, including the samples subjected to Brazilian split test with different heating temperatures. In the second method, the injection-rate fracturing parameter was considered to be the independent variable. The complete test procedures occur during the following three stages: (1) sample preparation, (2) hydraulic fracturing, (3) and postfracturing treatment. The specific processes used in each of these stages are described in the same order in which they were applied. It is worth noting that owing to changes in the mechanical properties of the rock under high temperatures and pressures, physical simulation tests of HDR hydraulic fracturing must be conducted under the actual temperature and stress environments. Because the actual ground stress is large in the laboratory, a similar ratio was
used to reduce the stress for hydraulic fracturing.

### 3.1. Hydraulic fracturing tests at different temperatures

The tensile strength of granite is affected by high temperatures [32]. According to the calculation formula of the rock fracture pressure, the tensile strength of the rock affects the magnitude of the fracture pressure [33]. Therefore, before performing hydraulic fracturing tests on rocks at different temperatures, Brazilian split tests were conducted on the rock samples to obtain the theoretical fracture pressure of the samples at different temperatures.

#### 3.1.1 Brazilian split test

The BD samples and the hydraulic fracturing cube samples were obtained from the same granite block; therefore, they have the same p-wave velocity. In the Brazilian split test, seven sets of BD samples were provided, among which one was obtained at room temperature and six were treated at 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C. Each group contained three samples heated in a servo-controlled electric furnace at a rate of 2 °C/min. Once the temperature in the furnace reached the specified value, it was held for 2 h to uniformly heat the entire sample. The sample was then cooled to room temperature at a rate of 2 °C/min to avoid thermal shock during cooling. After the sample preparation was completed, the Brazilian split test was conducted using the MTS universal material tester at a loading rate of 0.06 mm/min. As shown in figure 4, the loaded sample contained an alloy wire on and under the center of the sample to avoid eccentric loading.

![Figure 4. Photograph and schematic of the Brazilian test loading.](image)

#### 3.1.2. Hydraulic fracturing tests with variable temperatures

Sample preparation: This stage generally includes the following steps. (1) The cubic rock sample is drilled with a hole depth of 50 mm and an aperture of 10 mm. (2) The sample is wrapped with a copper foil and placed in the three-dimensional loading chamber of the hydraulic fracturing test system. (3) The six rock samples are heated to 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C at a heating rate of 2 °C/min. After reaching the target temperature, the temperature is maintained for 2 h. (4) True triaxial stress loading is performed on all cube samples, in which the loading rate is maintained at 0.5 MPa/s; the final sample stress state is vertical stress at 60 MPa, and the two horizontal stresses are both 25 MPa. Hydraulic fracturing: The sample begins to fracture after reaching the HDR condition. Then, the following specific steps are applied. (1) The hydraulic head sleeve is installed into the sample hole, and the corresponding epoxy resin grout is distributed and left for at least 24 h for curing. (2) Prestimulation is conducted by water injection, wherein the pore pressure is maintained at 2 MPa to evaluate the initial permeability of the reservoir and to check for leakage in the hydraulic pipeline. (3) Hydraulic fracturing stimulation tests are conducted on rock samples with different temperatures at an injection rate of 2 ml/min. (4) The injection pressure is monitored. When the pressure reaches the peak point, the water injection is stopped. Thus, the fracturing ends.
Postfracturing treatment: The following steps are performed after hydraulic fracturing. (1) The true triaxial stress is released. (2) The sample temperature is reduced to room temperature at a rate of 2 °C/min. (3) The rock sample is slowly ejected from the loading chamber using an auxiliary hydraulic jack and pressure plate system. (4) The rock sample is checked. Through these steps, minimal secondary damage can be achieved with respect to the sample and the residual stress caused by the elastic deformation of the tester can be overcome.

3.2. Hydraulic fracturing tests with different injection rates
The sample preparation stage of the hydraulic fracturing test at different injection rates conducted in this study followed the aforementioned steps. Except for heating the three samples to the same temperature of 400 °C in the second part of the test preparation phase, the steps were similar to the previously described steps associated with hydraulic fracturing. In the fracturing stage, after the hydraulic head casing is fixed and pre-pressurized to check for leakage in the hydraulic pipeline, three rock samples with the same temperature of 400 °C were hydraulically injected at injection rates of 0.05, 2, and 10 ml/min. The fracturing ended after reaching the peak pressure in the hole. The postfracturing treatment stage was completely consistent with the hydraulic fracturing tests conducted at different temperatures.

4. Results and discussion

4.1. Temperature-dependent tensile strength
The tensile strengths of samples with different heating temperatures were measured using the MTS universal material tester and were calculated according to the relation between the measured stress and displacement of each sample. The results are summarized in table 1, and the relation between the tensile strength and treatment temperature is shown in figure 5. The average tensile strength of each group of samples is expressed in the form of standard deviation. With an increase in temperature, a clear negative trend was noted in the tensile strengths of all the samples.

| No. | T (°C) | Tensile strength (MPa) | P_T (MPa) | P_M (MPa) | P_T − P_M (MPa) |
|-----|--------|------------------------|-----------|-----------|-----------------|
| 1   | 25     | 14.6                   | 64.6      | 60.9      | 3.7             |
| 2   | 100    | 11.2                   | 61.2      | 52.1      | 9.1             |
| 3   | 200    | 10.5                   | 60.5      | 47.9      | 12.6            |
| 4   | 300    | 8.6                    | 58.6      | 43.6      | 15              |
| 5   | 400    | 7.5                    | 57.5      | 36.7      | 20.8            |
| 6   | 500    | 6.2                    | 56.2      | 30.2      | 26              |
| 7   | 600    | 4.3                    | 54.3      | 26.5      | 27.8            |
Figure 5. Variation in tensile strength with the treatment temperature.

The trend that the tensile strength is dependent on the temperature in this test is consistent with that shown in a previous study [34]. A large and sharp decrease of 23.3% was noted in tensile strength at room temperature to 100 °C. This occurred because the evaporation of the water in the rock resulted in a large number of pores, reducing the cohesion between the mineral particles. Although the tensile strength continued to decrease, the speed decreased by 33% in the temperature range of 100 °C–400 °C because of the microcracks that can be attributed to thermal stress. In the range of 400 °C–600 °C, the tensile strength considerably decreased by 42.7% owing to the α–β quartz phase transformation occurring at approximately 573 °C, which resulted in a large number of cracks in the specimen [35]. Thus, the decrease in tensile strength of the specimen in the Brazilian split test was caused by thermal damage to the rock.

4.2. Hydraulic fracturing at different temperatures
Hydraulic fracturing tests were conducted on seven samples with different temperatures, and the fracturing curve of each sample during fracturing, which shows the relation between time and water pressure in the sample hole, was obtained based on the pressure sensor conversion signal, as shown in figure 6.

Figure 6. Hydraulic data from the hydraulic fracture treatment.
The fracturing curve can be divided into stages of pore pressure maintenance, pressurization, and pressure drop [36]. Furthermore, the fracturing conditions before and after the sample reaches the initiation pressure can be analyzed separately according to the pressurization and pressure drop stages. The hydraulic fracturing initiation pressure of the sample is the pressure corresponding to the peak of the fracturing curve [37]. Therefore, the initiation pressure of the sample at different temperatures can be derived, as shown in figure 6. Figure 7 shows the relation between the initiation pressure and temperature, and the specific data are summarized in table 1. The initiation pressure of the granite sample decreased considerably with the increasing temperature. This indicates that as the temperature and thermal damage increase [38], the samples are more prone to cracking during fracturing. Finally, the initial pressure decreased as the sample temperature increased.

![Figure 7. Variation in the measured initiation pressure with the sample temperature.](image)

Figure 6 shows that the pressure drop rate slowed as the sample temperature increased during the pressure drop phase. This occurred because the high-temperature specimen underwent thermal shock during the hydraulic fracturing process. Under the combined effects of thermal shock and residual pressure, the hydraulic fracturing cracks continue to expand slowly after initiation [39]. Because of the slow growth of the cracks, the pressure in the sample hole drops slowly, and the slower pressure drop rate was related to the wider range of crack propagation. Thus, the effect of thermal shock became increasingly obvious. Therefore, according to the pressure drop stage of each sample fracturing curve, the thermal shock generated by high temperature is beneficial for the initial crack propagation, wherein a higher sample temperature results in a wider initial crack propagation range.

4.3. Theoretical and measured initiation pressure

The measurement of the in situ stress by the hydraulic fracturing method has shown that the magnitude of the in situ stress can be calculated if the initiation pressure and the tensile strength of the rock are known. Conversely, if the magnitude of stress and the tensile strength of the rock are known, the theoretical value of the initiation pressure of hydraulic fracturing can be calculated as follows [40]:

\[ P_T = 3\sigma_h - \sigma_H + T \]  

(1)

where \( P_T \) is the theoretical initiation pressure, \( \sigma_h \) and \( \sigma_H \) are the maximum and minimum horizontal principal stresses, respectively, and \( T \) is the Brazilian tensile strength. Therefore, the theoretical value of the initiation pressure was calculated based on the tensile strength of the sample in this study and the loading stress of the hydraulic fracturing test, as shown in figure 8.
The theoretical and measured initiation pressure ($P_M$) data are summarized in Table 1.

As shown in figure 8, the theoretical initiation pressure is negatively correlated with the sample temperature, which is consistent with the correlation between the measured initiation pressure and temperature. The impact of thermal damage on the initiation pressure is further verified because the decrease in tensile strength is caused by thermal damage. The theoretical and measured values of initiation pressure versus temperature are shown in figure 9. The two types of initiation pressure are negatively correlated with temperature, although the theoretical initiation pressure was significantly larger than the measured initiation pressure at each temperature. This disparity can be explained by the effects of thermal damage and thermal shock. The theoretical initiation pressure was calculated based on the tensile strength of the high-temperature specimen. Because this specimen is not subject to thermal shock, the tensile strength is affected only by thermal damage; thus, the theoretical initiation pressure reflects only the effect of thermal damage. However, in the high-temperature rock hydraulic fracturing test, the sample was subjected to the dual effects of thermal damage and thermal shock under high-temperature and water cooling conditions. Thermal shock is the fundamental reason for the significantly higher theoretical initiation pressure when compared with the measured value. Moreover, the thermal shock reduces the initiation pressure of the high-temperature rock hydraulic fracturing. As shown in figure 9 and table 1, the deviation of the theoretical and measured initiation pressure increases with the increasing temperature, indicating that the thermal shock effect becomes more intense with the increasing temperature.

Figure 8. Variation in the theoretical initiation pressure with the sample temperature.
4.4. Fracturing cracks with different injection rates
Three samples at the same temperature (400 °C) were subjected to the hydraulic fracturing tests at different injection rates of 0.05, 2, and 10 ml/min. Figure 10 shows the photographs of the sample surface after fracturing.

As shown in the figure, after hydraulic fracturing at an injection rate of 10 ml/min, macrofractures with small areas were generated on the sample surface. At an injection rate of 2 ml/min, locally dense microfractures and macrofractures were generated on the sample surface. At an injection rate of 0.05 ml/min, microfractures with large areas could be observed on the sample surface. When the injection rate changed from high to low, the crack geometry of the sample gradually evolved from a small area of macrofractures to a large area of microfractures.

The aforementioned phenomenon can be attributed to the fact that the pressure in the sample hole increases rapidly owing to the high injection rate and exceeds the initiation pressure of the rock,
resulting in the formation of macrofractures with a small area. When the injection rate is low, there is sufficient time for the formation of microfractures on the samples under the action of thermal shock before the pressure in the sample hole reaches the initial pressure. After being filled with the fracturing fluid, the generated microfractures continue to expand under the action of thermal shock and injection pressure and finally form microfractures with a large area.

Thermal storage needs a sufficient amount of heat exchange space after fracturing to ensure a high and stable temperature in the fluid produced in the production well of the HDR reservoir. Therefore, a main channel cannot be present in the thermal reservoir to avoid the rapid flow of water along the main channel, which would considerably reduce the temperature of the produced fluid. When fracturing at a lower injection rate, microfractures with a larger area are formed, which not only provides a larger heat exchange space for the fracturing fluid but also avoids the short circuit phenomenon caused by the main fracture. Therefore, the fracturing effect is better when fracturing at a low injection rate.

5. Conclusion

In this study, HDR hydraulic fracturing tests were conducted at different temperatures and injection rates using a real-time high-temperature triaxial hydraulic fracturing test system, and Brazilian split tests were performed using the MTS universal material tester. According to the test results, the temperature-dependent influencing factors during the HDR hydraulic fracturing process were analyzed based on thermal damage and thermal shock. The conclusions are summarized below, and future research directions are proposed.

1. As the temperature increases, the thermal damage becomes more intense, which reduces the initiation pressure of hydraulic fracturing. Before achieving the initiation pressure, the thermal shock caused by the cooling of the high-temperature sample can reduce the initiation pressure. As the temperature increases, the thermal shock becomes more obvious and the degree of weakening increases. After achieving the initiation pressure, the cracks continue to grow under the action of thermal shock and residual pressure, with higher temperature resulting in a wider expansion range.
2. During the hydraulic fracturing test at a large injection rate of 10 ml/min, HDR tends to form macrofractures with a small area. However, when fracturing at a low injection rate of 0.05 ml/min, HDR will form microfractures with a larger area. These microfractures not only provide a larger heat exchange space but also prevent the short circuit phenomenon caused by macrofractures, resulting in improved fracturing effects.

Because the current formula used to predict the initiation pressure does not consider the thermal shock effect, the theoretical initiation pressure of HDR hydraulic fracturing differs considerably from the measured value. Therefore, establishing an initiation pressure calculation formula by considering the thermal shock effect will be the focus of our future work.

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