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Experimental study on hydraulic fracturing of granite under thermal shock

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ABSTRACT

As one of the key technologies for hot dry rock (HDR) geothermal exploitation, artificial reservoir is giant hydraulic fracturing at its core and takes the theory of hydraulic fracturing of rocks under thermo-mechanical coupling as its key scientific problem. With large samples of Shandong grey granite being the experimental subject, this paper conducted hydraulic fracturing experiment under triaxial stress at 20 °C, 100 °C, 200 °C, 300 °C and 400 °C, analyzed the characteristic of water pressure loading curves in the experiment, and found that crack initiation pressure decreased remarkably after 300 °C. In order to verify the factors controlling the influence of temperature on crack initiation, this paper established a strong transient thermal stress model, carried out numerical computation on this model and compared it with the experimental results. The results showed that the cooling effect of fracturing fluid for high temperature borehole can lead to thermal shock phenomenon and cause tensile stress near the borehole surface; the area near the borehole experienced two impact shocks, namely, elastic wave and thermal wave; the mechanism for the effect of temperature on the hydraulic fracturing of granite is not changes of rock mechanical parameters, but the thermal shock generated by the action of fracturing fluid of rock at high temperature.

1. Introduction

One of the key technologies for exploiting geothermal energy, a kind of renewable green energy with great development value, is to conduct giant hydraulic fracturing reconstruction on Enhanced Geothermal Systems (EGS) target reservoir. At present, the stimulation technologies such as hydraulic fracturing and adding chemical agent are not mature (Xie et al., 2014) enough to fully grasp the complete process technologies such as drilling stimulation and fluid circulation test, so they cannot be used to accurately simulate and predict the reservoir fracturing effect.

At present, hydraulic fracturing has been widely used in shale gas exploitation, oil exploitation and in-situ stress measurement, etc. When reservoir is established through hydraulic fracturing, single large fracture is not desired in the project. Instead, multiple fractures or reticular fractures are set as targets in the process of hydraulic fracturing so as to maximize the permeability of low permeability rock layers. A large number of studies have indicated that the viscosity of fracturing fluid, chemical additive and water pressure blasting play an important role in determining the fracturing effect (Kim and Moridis, 2015; Pirzadeh et al., 2015; Huang et al., 2011). Hydraulic loading mode also has an impact on the fracturing effect. For example, with higher loading frequency, the crack initiation pressure is reduced, so the fracture network is more complex, which requires a longer time; on the contrary, with lower loading frequency, the effect is on the opposite (Li et al., 2014). Traditional theories hold that hydraulic fracturing is a very complex seepage-damage problem. Many scholars have introduced fracture mechanics and damage theory to study hydro-fracturing problems. For instance, Shojaei et al. (2014) introduced continuous fracture theory to simulate hydraulic fracturing problems with models.

In terms of the physical properties of hydraulic fracturing, the researchers have studied the crack initiation, propagation and direction change of fractures using true triaxial testing machine. The development and propagation of fractures are not only related to the in-situ stress but also influenced by the occurrence of strata (Dahi-Taleghani and Jon Olson, 2011). Cheng et al. (2015), who studied the possibility of fractures penetrating into the structural plane, concluded that hydraulic fractures were closely related to the occurrence of the discontinuous surface after they connected the discontinuity surface in the 3D reservoirs. Compared with the incline angle of discontinuous surface, the strike angle is the key factor affecting the penetration behavior of hydraulic fractures. After the propagating hydraulic fractures

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penetrate the structural plane, complex fractures intersecting with the natural bedding plane are likely to be formed, and then network fractures are formed after the hydraulic fractures cross the fractured bedding plane (Guo et al., 2014).

Based on the research status at home and abroad, the main research methods of hydraulic fracturing are numerical simulation and physical experiment. Most of the existing physical researches are mainly aimed at low-temperature rocks such as coal and shale; yet, the rock stratum temperature of EGS is generally over 200 °C. Temperature rise changes physical and mechanical properties of the rock (Yin et al., 2015; Xu and Liu, 2000; Zhang et al., 2011), reducing its compressive strength, tensile strength, elastic modulus, etc. to a certain degree. In addition, the large temperature difference between the injected fracturing fluid and the rock body results in the complex thermo-fluid-solid coupling effect between rock and liquid in the fracturing process, which causes intense thermal shock to the rock body and is accompanied by a large scale of thermal rupture of rock (Chaki et al., 2008; Fu et al., 2007). As these problems have an important impact on the fracturing process, the temperature effect in the fracturing process cannot be ignored. However, limited by the experimental equipment, it is difficult to carry out the experiment of hydraulic fracturing of rock at high temperature, so this field rarely reported. Numerical simulations, which can be applied more flexibly, are widely adopted by scholars at home and abroad in the researches on hydraulic fracturing at high temperatures, but it is difficult to really simulate the fracturing process as the simulations are limited by the development of the theoretical model (Davies et al., 2013). Therefore, the lack of related theoretical researches on hydraulic fracturing at high temperature has led to lots of blindness in engineering development. There are many cases of failure, for example, the two cases of hydraulic fracturing failure in Australia introduced by Rahman et al. (2007): it was found that the vertical fractures of the vertical shafts were distorted into horizontal ones in the process of hydraulic fracturing, so that the permeability increase of the rock stratum is not obvious.

In this paper, “triaxial testing machine of servo control for rock mass at the high temperature of 600 °C and the high pressure of 20 MN” (Zhao et al., 2008a) independently developed by China University of Mining and Technology is used to study the hydraulic fracturing of granite from 20 °C to 400 °C in order to get the fracturing pressure and propagation law of the fractures at high temperature.

2. Experimental equipment and methods

2.1. Temperature and pressure loading system

The main performance and technical parameters of the coupled thermo-mechanical loading device “triaxial testing machine of servo control for rock body at the high temperature of 600 °C and the high pressure of 20 MN”: (1) the testing machine uses solid media to transmit confining pressure; axial pressure and lateral pressure are controlled independently; the maximum axis stress is 318 MPa and the maximum confining pressure is 250 MPa; (2) the highest stable heating temperature of the sample is 600 °C; (3) the holding time of axial pressure and lateral pressure is over 360 h; (4) the high-temperature triaxial pressure chamber has a highly precise temperature control function with its sensitivity being no more than ± 0.3%.

2.2. Hydraulic loading system

High pressure water loading system uses the plunger type high pressure water pump whose maximum load pressure is 400 MPa and test precision is at level 0.1. Hydraulic loading has two modes of control, namely, automatic control and manual control. Automatic control refers to the mode that the motor speed is raised automatically at a certain rate during system loading which causes automatic rise of water pressure; manual control refers to the mode that the motor speed is manually adjusted through the general inverter knob to realize water pressure regulation. This experiment adopts automatic control mode. The pump pressure is measured by the pressure sensor at the water inlet pipe, and the resolution is 0.1 MPa. The rate of flow is measured indirectly by using highly precise electronic scale to measure the reduction of water amount in the water tank in the process of water injection and then calculating the flow rate of the injected water, and the resolution is 0.5 mL/s. With the application of centralized control by the software, the hydraulic loading system can automatically collect water pressure and flow rate, and the acquisition frequency of 100 Hz.

2.3. Experimental sample

The sample whose commodity name is “Shandong Grey” and size is φ200 × 400 mm is the grey granite from Pingyi, Shandong Province. The test sample is drilled with a water injection hole that is 18 mm in diameter and 250 mm in depth at the upper end face of the sample; a metal high pressure water injection pipe is buried in the hole; and a fracturing section of 50 mm is set aside at the bottom of the hole. The great strength of granite and high temperature of this experiment determines that the water injection hole cannot be sealed with sealing cement, so this experiment uses copper sealing ring to seal the hole section by section (see Fig. 1).

2.4. Experimental methods

The sample was loaded into the triaxial test machine for rock mass under high temperature and high pressure according to the operation instructions. After both the axial pressure and the side pressure were increased to 25 MPa, the temperature was raised to target temperature by the rate of 10 °C/h. Temperature of the sample was maintained for 2 h after the target temperature was reached to stabilize the internal temperature of the sample. Then, the high pressure pump was started to inject high pressure water into the sample. The motor speed of the water pump was increased by the rate of 2 Hz/s to maintain a steady increase of the water pressure in the sample. A sudden drop of water pressure in the sample at a drop rate of over 1 MPa indicated that a new large fracture appeared in the sample, at which time the high-pressure pump automatically shut down and maintained the pressure.

The water pressure, water flow, axial and lateral pressure of the sample were recorded automatically during the whole testing process.

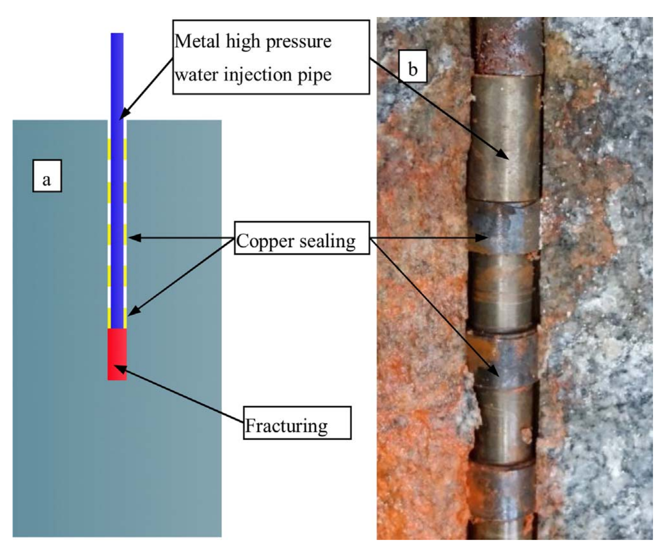

Fig. 1. High pressure water injection pipe and the method of sealing the borehole in the granite.