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Chemical stimulation on the hydraulic properties of artificially fractured granite for enhanced geothermal system

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ABSTRACT

Hydraulic fracturing is often conducted to create artificial fractures as flow paths in Hot Dry Rock (HDR) geothermal reservoirs. However, the fractures could be closed due to the high geo-stress conditions, resulting in low efficiency of geothermal productivity. Hence, maintaining a high hydraulic permeability of the created fractures is a key point for the success of Enhanced Geothermal Systems (EGS).

In this study, chemical stimulation was carried out to improve the hydraulic properties of fractured granite. The effects on the hydraulic properties of two sets of samples were examined by laboratory flowing tests. Results show that chemical stimulation solution with mixture of 12%HCl+5%HF improved efficiently permeability. The permeability was increased by four orders of magnitudes with an optimized reaction time. The mud acid was found to react fast with minerals such as feldspars and biotite, but rather inactive with quartz as revealed by the microscopic structure and ionic detection of the fluid and rocks. Thereby, the quartz particles can be used as fracturing proppant to support opening of aperture. The findings obtained from this study indicated that a hydraulic fractured granite based HDR geothermal reservoir can be effectively improved by chemical stimulation.

1. Introduction

In the past few decades, geothermal energy has been developed rapidly due to its attractive advantages of cleanness, renewability and environmental friendliness [1,2]. Geothermal energy systems can be simply categorised into shallow geothermal energy systems ($\leq$400 m depth) and deep geothermal energy systems (>400 m depth). Hot Dry Rock (HDR) is a typical type of deep geothermal energy usually refers to intact rock with extremely low permeability, within a depth of more than 3 km [3] and temperature ranges from 150 to 650 °C [4]. HDR geothermal reservoir is often hydraulically fractured to exploit deep geothermal energy by a technology which is called Enhanced Geothermal System (EGS) [5,6]. EGS works under the coupling of Thermal-Hydraulic-Mechanical-Chemical (THMC). Despite the achievable benefits in hydraulic fracturing, the method induces often earthquakes and the created fractures are easily closed due to the high geo-stress [7,8]. Therefore, more and more alternative strategies such as thermal and chemical stimulation were introduced. Chemical stimulation is considered to be an alternative solution not only for increasing hydraulic properties but also for improving the connectivity of the fracture networks [9,10].

Chemical stimulation was first applied in oil and gas reservoirs to improve productivity. The principle for the chemical stimulation is to dissolve minerals on the fracture surface to extend the size of fissures or fractures, leading to improving of fissures connectivity reservoir [10,11]. In the 1980s, the chemical stimulation technique has been used to improve the permeability for magmatic and metamorphic rocks [12,13]. The first application of chemical stimulation on HDR was the Fenton Hill EGS project in the USA, Na_2CO_3 mix with NaOH solution as chemical agents was injected into the metamorphic rock based HDR reservoir. However, the permeability was not improved significantly due to the lack of the fracture networks in reservoir [14,15]. In the Soultz EGS project in France, the chemical agent with a mixture of 12%HF+3%HCl was injected into the granite based HDR reservoir, and productivity of the reservoir was increased effectively [16–19]. The success of the Soultz EGS project was due to study of the chemical agents and specific

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reservoirs characters after Fenton Hill EGS project. In the Grog Schonebeck EGS project in Germany, the hydraulic fracturing was coupled with matrix acidizing, the output flow rate of the well was increased by 5.5–6.2 times for the volcanic rocks and siliciclastics based HDR reservoir [20]. The above mentioned field experiments proved that chemical stimulation could improve effectively the productivity of EGS reservoir.

On the other hand, many works have been done in order to understand the mechanism of chemical stimulation. Huo [21] established the nonlinear elastic constitutive equation of the corroded rock base on the fact that calcium carbonate ($CaCO_3$) is dissolved and the pore is expanded in the calcareous cementations sandstone subjected to hydrochloric acid attack. Xu et al. [22,23] used the TOUGHREACT software to simulate the stimulation process and the results verified that the high pH solution with chelating agents could improve the porosity and permeability of the reservoir effectively. Portier [24] developed a model for evaluation of chemical stimulation based on the experiences from the Soultz EGS project. Na [25] numerically studied the chemical stimulation of the EGS reservoir in Songliao Basin in northern China using CO_2 and the results indicated that the increase of porosity of fractured channel is mainly caused by calcite dissolution. Dempsey [26] simulated the effect of CO_2 and brine injection reservoirs. It was concluded that reducing uncertainty associated with CO_2 injection and brine production in heterogeneous formations.

Many studies have been conducted on chemical stimulation to improve the hydraulic conductivity through laboratory tests. Sheng et al. [27] studied the hydraulic characteristic of rock fractures under coupled HMC conditions. The permeability of the rock was improved by carbonate solution. Yang et al. [28] revealed the mineral dissolution velocity of the contact surface controlling the flow characteristics under acid condition. However, the precipitation of minerals plays a vital role in the change of hydraulic permeability by the treatment with alkaline solution. Na et al. [29] and Wu et al. [30] investigated the interaction between the mud acid and the thermal reservoir through laboratory experiments. The permeability of the volcanic rock sample was raised by adopting chemical solutions with high flow rate. The analysis showed that the increasing of permeability was mainly caused by the dissolution of K-feldspar and albite. Zhou et al. [31] studied the reaction between CO_2 and granite HDR reservoir through the test and concluded that pure water dissolved greater amount of minerals than $scCO_2$-rich geofluids, especially for those Si-containing minerals. Furthermore, treatment of harmful constituents, e.g. fluoride ions, in the flowback fluid after chemical stimulation was also investigated by considering environmental protection [32,33]. It is indicated that the possible environmental contamination can be avoided by adapting current treatment techniques [34].

The aforementioned publications indicated that chemical stimulation is very useful in improving the permeability of geothermal reservoirs. However, the stimulation effectiveness depends not only on the chemical mechanism but also by the reservoir's characteristic for each site. In order to achieve an efficient stimulation effect, chemical agent types, reaction temperature and time need to be optimized for instructing a practical application of EGS projects. By considering these existing problems, this paper aims to investigate the influences of chemical stimulation on hydraulic properties of two sets of fractured granite samples collected from Gonghe Basin of Qinghai province in China [35]. First, mud acids with different mixture ratios of HF and HCl were used as chemical agents to stimulate the fractured granite samples. The chemical agent effect was estimated by considering hydraulic properties which were examined by permeability tests. Then, the dose and reaction time for the chemical agents were optimized. Finally, mechanism of the chemical reaction was studied based on ions detection of the fluid and microstructure observations.

2. Materials and study methodology

2.1. Geological setting

The study area is located in the Gonghe basin in Qinghai province of China, with an average altitude of 3000 m. The Gonghe basin is surrounded by mountains with NWW longitudinal direction and the total area of the basin is around 1380 km^2. Four deep boreholes were drilled by the Hydrogeological, Engineering and Environmental Geological Survey of Qinghai Province with cooperation of China University of Geosciences (Wuhan). It was detected by one of borehole with a borehole depth of 2927 m, a temperature of 183 °C and a geothermal gradient of 6.8°C/100 m. A granite based HDR geothermal reservoir within depth of 2500 m is predicted based on the measured temperature and thermal gradient. This is the first time when the existence of explorable HDR resource was confirmed in China. The granite samples were collected on the drilling site for the subsequent laboratory tests in this work.

2.2. Sample preparation

Thermal conductivity and fissure rate of the collected samples are first determined in laboratory. Thermal properties are tested by a portable device (ISOMET 2114, Applied Precision Co. Ltd.). In order to measure thermal properties, the cylindrically shaped rock samples were prepared with a diameter greater than 60 mm. The surface were smoothed and polished in order to fit the measuring requirements by adopting a surface probe sensor. Then, water absorption tests were conducted to determine the fissure rate. The obtained physical parameters are listed in Table 1. Furthermore, mineral components of the selected samples were determined by X-Ray Fluorescence (XRF) experiments, X-Ray diffraction (XRD) experiments and thin section identification test. According to XRF data, the chemical compositions include SiO_2 (67.5%), Al_2O (15.3%),

Table 1
Thermo-physical properties of the prepared rock samples.

Set		No.	Weight dry (g)	Fissure rate (%)	Thermal conductivity (W/m·K)	Specific heat (MJ/m^3·K)	Surface area (cm^2)
One	Rough surface	#1	510.06	0.81	2.09	2.08	270.84
		#2	500.79	1.03	2.35	2.10	338.90
		#3	481.45	1.63	2.28	2.13	247.98
		#4	507.80	0.65	2.27	2.12	250.92
		#5	507.35	1.24	2.27	2.09	445.74
		#6	500.38	0.60	2.37	2.08	358.26
Two	Smooth surface	#7	466.46	0.86	2.44	1.47	96.22
		#8	461.57	0.84	2.28	1.80	96.04