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Experimental investigation of quenching effect on mechanical, microstructural and flow characteristics of reservoir rocks: Thermal stimulation method for geothermal energy extraction

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ABSTRACT

Thermal stimulation method can be effectively utilized to enhance the flow performance in the tight porous media with an induced thermal shock. This approach can be applied to many deep geo-engineering applications including geothermal energy extraction. In this regard, understanding the flow-mechanical behaviour of reservoir rock during and after thermal stimulation is necessary for safe and effective stimulation process. The aim of this study is, therefore to investigate the quenching effect on mechanical and flow behaviour of Australian Strathbogie granite by conducting a series of micro and macro-experiments. Experiments were conducted by profiling the micro-structure of rock with CT scanning, microscopic imaging and, quantifying the thermally induced damage due to quenching treatment. In order to understand mechanical response of rock due to quenching, strength tests were conducted under the unconfined condition, and the corresponding fracture propagation patterns were investigated using an acoustic emission (AE) system. In addition, flow performance of thermally treated rock was studied under a wide range of coupled high temperature and high-pressure conditions (temperatures 20–300 °C, confining pressure up to 45 MPa and injection pressure up to 40 MPa), simulating different geothermal temperatures and depths. According to the findings, thermal treatment resulted in around 70% of reduction of strength and elastic properties respectively due to the thermally induced damage caused by induction of both inter and intra-crystalline cracks. Further, increased porosity and crack density significantly enhanced the permeability of the rock compared to the intact rock (from approximately $1 \times 10^{-19}\,m^2$ to $6 \times 10^{-15}\,m^2$ under 10 MPa confining pressure). However with the increasing of normal stresses, permeability decreased non-linearly and further, increasing temperature resulted in significant reductions in permeability of granite (approximately 95% of reduction from room temperature to 300 °C) due to the thermally induced volumetric expansion which leads to enhancement of interlock effect.

1. Introduction

With the ever-growing population and the increased energy demand, the necessity on exploring new energy resources has been counted by scientists and industries. Among a number of renewable energy resources, enhanced geothermal systems (EGS) have been identified as an environmentally friendly energy resources over conventional fossil fuels however their technical feasibility and commercial viability need to be further studied. These systems are located in deep geological formations (depth around 2–4 km), under elevated geothermal gradients (temperatures around 100–300 °C), particularly with crystalline rock formations with ultra-low permeability characteristics and little amount of stored fluid (Breede et al., 2013). EGS is created by drilling a well into the hot dry rock formation and injecting a fluid under high pressure to open up its natural fractures. This process is recognized as the reservoir stimulation because with the absence of a porous medium, it is important to enhance the fluid circulation of the reservoir with an artificially created fracture network. Once a proper hydraulic connection is developed, the heated fluid is pumped out to the surface through one or more production wells drilled in the reservoir zone and with this thermal

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energy steam turbines are operated to generate electricity (Barla, 2017; Tester et al., 2006). Reservoir stimulation is one of a critical aspect throughout the lifespan of any low permeable reservoir and number of reservoir stimulation techniques are adopted in the field including hydraulic stimulation, chemical stimulation and thermal stimulation (O'Sullivan et al., 2001). Considering geothermal reservoirs which experience continuous thermal stresses due to injection of cold fluid into the hot rock mass, thermal stimulation can be identified as an important reservoir enhancement technique to create permeable fractures by induced thermal gradients.

A number of geothermal fields have successfully employed this technique (Clearwater et al., 2015; Flores-Armenta and Tovar-Aguado, 2008; Flores et al., 2005; Kitao et al., 1990) by injecting fluids colder than the hot reservoir rock with a period of thermal recovery between each injection scenario. Intermittent cold water injection has resulted in thermal cracking as a result of the induced thermal shock which causes open up new fluid channels or widening new channels resulting enhancement of reservoir permeability. As a result of thermally induced fractures, due to the increased permeability and effective flow area, the heat transfer process which is mainly governed through heat storage, advection, diffusion, and conduction processes is accelerated (Zhao, 2014). This can result in enhancement of both production temperature and production flow rate resulting increased production rates in the geothermal reservoir. It has been reported that thermal stress fracturing is more efficient once the temperature difference between the rock formation and the injected fluid is sufficiently higher ($<200\,^{\circ}$C) which causes the failure in the rock formation (Kitao et al., 1990).

Although thermal stimulation method has been employed for the underperforming geothermal wells to enhance near-wellbore permeability, thermal stress fracturing might not be the single physical mechanism that results in permeability enhancement. It has been suggested that thermal cracking followed by fluid injection can result in re-opening sealed fractures, dilating the open up fractures (Olsson and Barton, 2001) and further, cleaning out debris and fine particles from the open up fractures or dissolution of fracture filling minerals (Polak et al., 2004) can result in permeability enhancement. On the other hand, as a result of thermally induced volumetric expansion (Barton, 2007) or precipitation of minerals (Yasuhara et al., 2011) on open up fractures, reservoir permeability can be decreased as well. However, depending on the rock type, mineralogy, grain size distribution and stress condition, the amount of thermal damage is different and further, mechanical, thermal and chemical attributes that result in permeability enhancement or reduction of geothermal reservoirs through thermal stimulation is poorly understood to date (Bai et al., 2012; Flores et al., 2005; Kitao et al., 1990).

Understanding the thermally induced damage provides essential knowledge on not only geothermal fields but also nuclear storage, coal gasification projects and oil and gas fields (Egboga et al., 2017; Nair et al., 2016; Uribe-Patiño et al., 2017). Temperature field of these systems can change either naturally or anthropogenically resulting thermal cracking and induced permeability enhancement. In this regards, replication of thermal stimulation technique in the controlled laboratory environment provides basic insights on the physical and mechanical alteration of the rock mass. A number of studies have been conducted to investigate the mechanical and flow performance of different rocks upon thermal damage at laboratory scale. It has been identified that thermally induced cracks along the rock body result in degradation of strength (Kumari et al., 2017a; Shao et al., 2015; Singh et al., 2015; Zhao et al., 2017), attenuation of acoustic and velocity waves (Lee and Rathnaweera, 2016; Nara et al., 2011) and, enhancement of the flow performance of the rock (Chaki et al., 2008; Siratovich et al., 2015). Flow performance of these fracture networks depends on elevated pressures and temperature depending on the depth of the rock formation as well as increased differential stress (pressure gradient) (Izadi and Elsworth, 2015; Nara et al., 2011). Although many studies have been focused on transport properties of fractured rock under room temperature conditions, only a few studies have been captured the thermo-mechanical response (Blaisonneau et al., 2016; Guo et al., 2017). Further, most of the studies have been considered flow performance of the mechanically induced fractures (Polak et al., 2003; Yasuhara et al., 2011) and only a few studies have been focused on the flow performance of the thermally induced fractures (Chaki et al., 2008; Siratovich et al., 2015). However, in the former study, the flow through experiments conducted upon thermally treated samples under room temperature conditions, while the latter study considered only one experimental condition (325 °C, 20 MPa vessel pressure, and 145 ml/min injection pressure).

Due to the limitations of the appropriate advanced instrumentation, none of the studies has been captured the flow performance of thermally treated rock under a wide range of coupled high-temperature and high-pressure conditions to date. Further, there is a distinct lack of the information on understanding the mechanism and quantification of thermally induced cracks. Therefore it is expected that present study would provide basic insights to understand the thermally induced damage with quantification of macroscopic and microscopic fractures followed by the flow performance of the stimulated rock specimen under various stress and temperature conditions. The findings of the present study mainly can be employed during reservoir stimulation and production process of geothermal reservoirs and other deep geological applications. Further, considering the hydro-thermo-mechanical behaviour of the fractures coupled models are being developed in terms of numerical, theoretical and empirical point of view (Liu et al., 2006; Zhao et al., 2014). However, due to the limitations of the comprehensive experimental data, validation of them is far from being realized. Therefore, the present research work would be beneficial for such future research activities also.

2. Crack formation and propagation process during quenching

When a significant thermal gradient occurs along an anisotropic body, different minerals of the rock expand in different amounts resulting in a thermal shock. Apart from the mismatched thermal expansion coefficients of the minerals, heterogeneous thermal gradients and exceedance of threshold temperature of each mineralogical constituents, thermal damage can occur (Heard, 1989). However, anisotropic thermal expansion of the different minerals has been identified as one of the primary mechanisms upon thermal cracking.(Fredrich and Wong, 1986; Johnson et al., 1978). The amount of mineral expansion depends on several parameters including the thermal gradient, thermal expansion coefficient of each mineral and the stress state (Geraud, 1994). As a result of a temperature gradient, new cracks may form between the grains (inter-granular cracks) or within the grain (intra-granular cracks). Further, pre-existing cracks can widen, propagate or close depending on the stress and the temperature state as a result of thermal damage or thermally induced volumetric expansion (Homand-Etienne and Houpert, 1989; Yang et al., 2017).

Heat transfer process plays a critical role in this crack formation and propagation process. According to Wong and Brace (1979), when the internal stress of rock mass exceeds the crack closure pressure with increasing temperature, thermal cracks are initiated.

$$\sigma = E\Delta\alpha\Delta \mathrm{T} \tag{1}$$

where, E, $\Delta\alpha$, ΔT is the matrix Young's modulus, the difference of thermal expansion coefficient of distinct mineral and temperature difference, respectively. During the quenching process, due to the sudden injection of cold water, the rock mass experience an instant, extremely high-temperature change. This can result in the initiation of a significant number of thermal cracks in the rock matrix.

According to the theories of classical fracture mechanics, once the crack extension force F, exceeds the energy required for crack growth, crack propagation occurs. In brittle materials, the energy required for crack propagation is equal to the surface energy to form the new free surface (Irwin, 1968). Therefore the critical energy to propagate thermally induced cracks has been assumed as,