Laboratory hydraulic fracturing experiments on thermally treated tight sandstone samples under step up incremental loading

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ABSTRACT: This paper aims to investigate the effect of thermal treatment on tight sandstone samples during the hydraulic fracturing process. The sandstone samples were preheated at different temperatures and cooled at the same rate (1 °C / min). Step-up incremental loading opted for all hydraulic fracturing experiments. SEM investigations were done on thin sections of fractured samples to find the fractal dimension and tortuosity. After 300 °C, the samples hydro fractured at higher temperatures and showed lower fractal dimensions than those at lower temperatures. The effect of the heat treatment was also observed in the breakdown pressures as they reduced with the increased temperature. Due to the thermal effects, it was also found that the crack tortuosity increased with an increase in temperature. After 300 °C, the degree of micro cracks and the complexity of the fracture growth network increases.

Keywords: Step up incremental loading, fractal dimension, tortuosity, SEM (Scanning electron microscope) images.

1 INTRODUCTION

Geothermal energy is becoming the promising source of clean energy when compared to fossil fuels and can be efficiently obtained from the engineered /enhanced geothermal system (Axelsson 2010; Martin –Gamboa et al., 2015; Olasalo et al. 2016). Geothermal reservoirs being hot dry in nature and having very low permeability are subjected to hydro fracturing to extract the heat stored in the rock mass via fluid circulation. To enhance the performance and life span of engineered geothermal reservoir, fractures geometry plays an important role (Fu et al. 2016). Conventional hydraulic fracturing could produce the earthquakes of magnitude 5.5 which results in risk to enhanced geothermal reservoirs (EGS) (Kim et al. 2017; Lee et al. 2019). The generation of complex hydraulic fractures was difficult with conventional hydro fracturing (Feng et al. 2014). Previous studies by Zhuang et. al (2020) mentioned that the number of seismic events produced by conventional hydraulic fracturing were more compared to step up incremental loading. The present aim of the study is to generate hydraulic fractures under step up incremental loading and to characterize these hydraulic fractures at different temperatures ranging from 25 °C to 600 °C.

2 EXPERIMENTAL METHOD

In the present study, sandstone samples comprises of 90-95% quartz, 3% feldspar and 1-2% of lithic fragments after XRD analysis. The sandstone samples with dimensions 54 mm diameter and 108 mm length were drilled with central hole diameter of 12 mm with 65 mm length along vertical axis. After that six samples were thermally treated to six different temperature (25 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C) in a programed temperature furnace. The temperature in furnace was programed to increase the temperature by 1°C /min and once the desired temperature was achieved it was maintained for 24 hours. After 24 hours the temperature was decreased by same rate till it reaches to 25 °C, where it was kept there for 2 hours for cooling before retrieving the sample from the temperature furnace. The experimental stages in consist of five parts that is heat treatment of

Figure 1. (a) Temperature furnace (b) Sandstone sampled glued to 20mm length cylindrical tube. (c) Rock triaxial setup (c) Hydro fracturing machine.

drilled sandstone sample, hydraulic fracturing of thermally treated sample epoxy filling in fractured sample, thin section preparation of hydraulically fractured samples and analyzing the thin section through SEM images through Carl Zeiss ultra-field emission microscope. Hydraulic fracturing experiments were done in a triaxial testing machine considering the deviator stress of 25 MPa and 10 MPa confinement in all the tests. Hydraulic fracturing was done by water with step incremental loading of 1MPa increment in each cycle and the hold time for each step was 20 sec. The applied pressurizing rate for all experiments was 1MPa /sec. The current study aims to the application of step up incremental loading during hydraulic fracturing in thermally treated sandstone samples as mention in Figure 1.

3 RESULTS AND DISCUSSIONS

3.1 Breakdown pressure

Hydraulic fracturing experiments were conducted on preheated – sandstone samples, considering step incremental loading and wide range of thermal treatment from 25 °C to 600 °C. Figure 2 explains the typical injection curve for hydraulic fracturing of sample at 25 °C and this type of injection curves follows for all other temperature. The step incremental loading was applied in order to minimize the seismic effects when compared to conventional hydro fracturing.

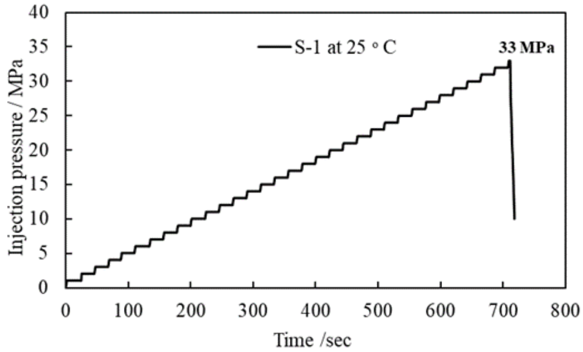

Figure 2. Typical injection curve for step up incremental hydraulic fracturing loading for S-1 sample at 25 °C.

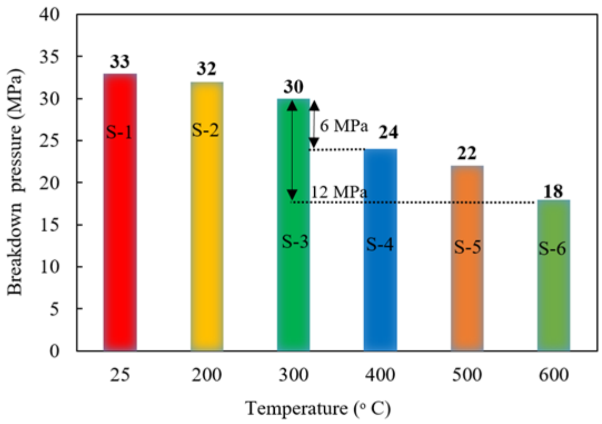

Figure 3. Breakdown pressure variation at different temperatures ranging from 25 °C to 600 °C.

During hydraulic fracturing the breakdown pressure reduces linearly from 25 °C to 300 °C with a very small decrease in breakdown pressure of 3 MPa indicating that the thermal effect was very low. The effect of thermal treatment was dominant in between 300 °C to 400 °C and Figure 3 shows nonlinear reduction in the breakdown pressure from 30 MPa to 24 MPa. The decrease in the breakdown pressure in nonlinear form is generally caused by the activation of micro fractures due to thermal treatment. From 300 °C to 600 °C, it can be seen form Figure 3 that breakdown pressure has decreased which can be correlated with the sharp reduction in tensile strength of the sandstone samples after thermal treatment. Also the increase in micro fractures with increase in temperature was the main reason for the decrease on breakdown pressure.

3.2 Hydraulic Fracture tortuosity

The fracture profile obtained from combination of all fracture images are wavy in nature. The fracture profile give us two resulting length one is normalized fracture length (C_L) and the other one is actual fracture length (C_A). Normalized fracture length is obtained from start of fracture center to end of fracture center whereas the actual fracture length is obtained by ImageJ segmented line tool where the trace of left and right portion of fracture is measured and averaged to obtain the final fracture length. Tortuosity (τ) is defined by the ratio of actual fracture length and normalized fracture length of the fracture and is denoted by the following equation:

$$\tau = \left(\frac{C_A}{C_L}\right) \qquad (1)$$

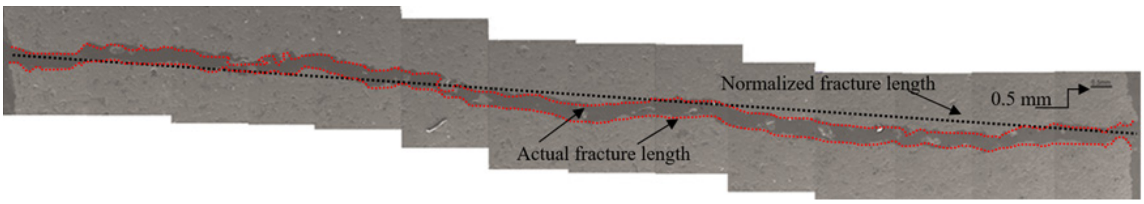

Figure 4. Hydraulic fractured image of sample at 200 °C illustrating actual fracture and normalized fracture length.

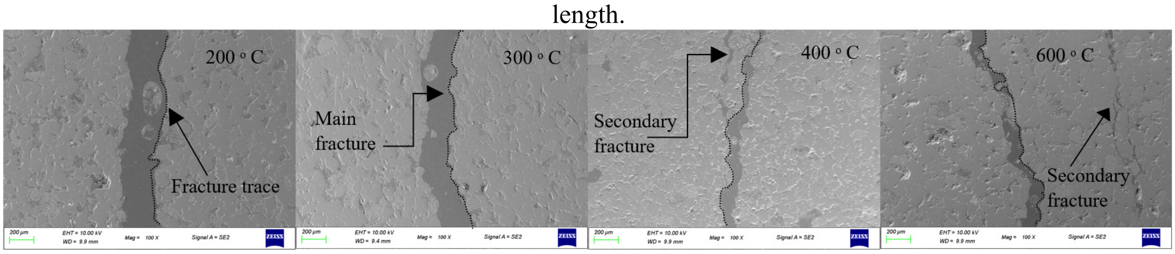

Figure 5. Fractures characteristics at different temperature of 200 °C, 300 °C, 400 °C and 600 °C.

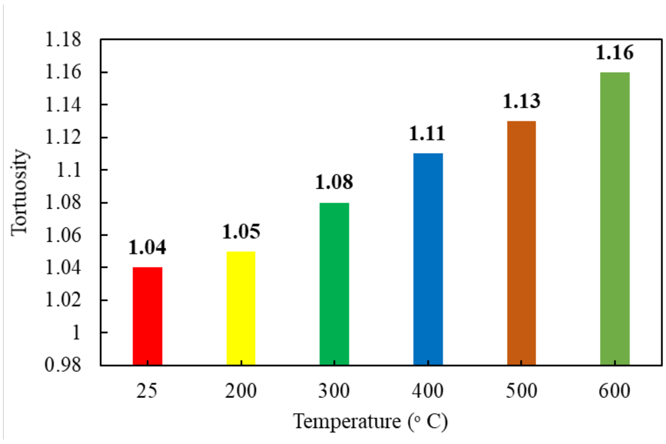

Figure 6. Tortuosity of hydraulic fracture after hydraulic fracturing at different temperatures from 25 °C to 600 °C.

From Figure 5, it was observed that the hydraulic fracture produced in sample at 200 °C was less tortuous when compared to the fractures at 300 °C, 400 °C and 600 °C which shows more tortuous path. The secondary fractures in form of branching appears in the samples at 400 °C, 500 °C and 600 °C and complex fracture network could also be seen in 600 °C treated samples as presented in Figure 5. Figure 6 shows the effect of tortuosity on hydraulic fractures for all the temperatures and it was observed that the tortuosity increment between 25 °C to 200 °C was only 0.96 percent. The hydraulic factures of sample at 200 °C and 300 °C were compared and observation from Figure 6 reveals an increased tortuosity of 2.85 percent. The sudden change in tortuosity at 300 °C is due to the weakening of cementation especially between the quartz grains and more generated micro fractures which changes the direction of fractures abruptly. The tortuosity of hydraulic fractures continued to have a significant increase of 7.40 percent from 300 °C to 600 °C. After 300 °C, the tortuosity of the hydraulic fracture increases which directly enhances the flow friction of hydraulic fracture. Thus overall it could be concluded that tortuosity has a significant effect when there is a change in temperature of the samples.

3.3 Fractal dimension of hydraulically induced fracture

The procedures involved in determining the fractal dimension for SEM image were as follows. (a) First, the image was scaled to the desired dimensions in ImageJ software (TJ Collins (2007)) (b) Image was converted to a grayscale version of itself. (c) The thresholding of the image was done so that only black and white pixel could be obtained. (d) In the next step, the image is transformed into a binary format. (e) ImageJ FracLac tool by Karperien et.al (1993-2003) was utilized in order to carry out the box counting technique. (f) The fractal dimension was calculated using a graph that contained the logarithms of N and S.

The number of boxes is represented by the N value, and the size of each box is represented by the S value. In this particular study, the scaling values for boxes were 2, 4,16, and 64 and they represents the lengths 4.875 µm, 9.75 µm, 39 µm, 156 µm respectively. Thus for estimating the fractal dimension the formula is presented as below by B.B Mandelbrot (1982):

$$D = -\lim_{S \to 0} \left(\frac{LogN}{LogS} \right) \tag{2}$$

Where N is the number of boxes and S is the size of the box. The fractal dimension of each image was calculated by the procedure as described in Figure 7. The maximum and minimum values of fractal dimension of fractures at 200 °C and 600 °C were presented in Figure 8 and Figure 9 respectively. The negative slope obtained from the linear regression analysis provide the fractal dimension of each image. Fractal dimension calculated for hydraulic fractures at different temperatures were mentioned in Table 1. The Table 1 observation reveals that between 25 °C to 200 °C the decrease in fractal dimension was only 1.08 percent.

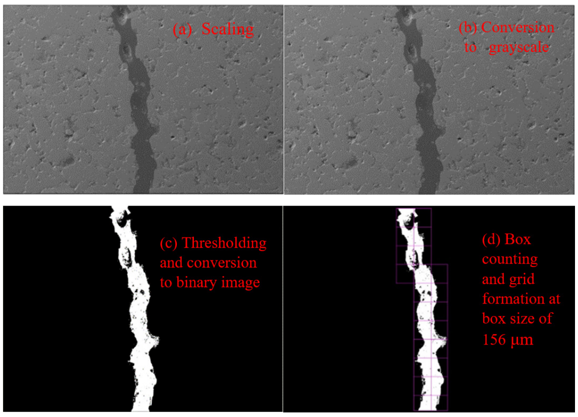

Figure 7. Fractal dimension calculation procedure step by step from figure (a-d).

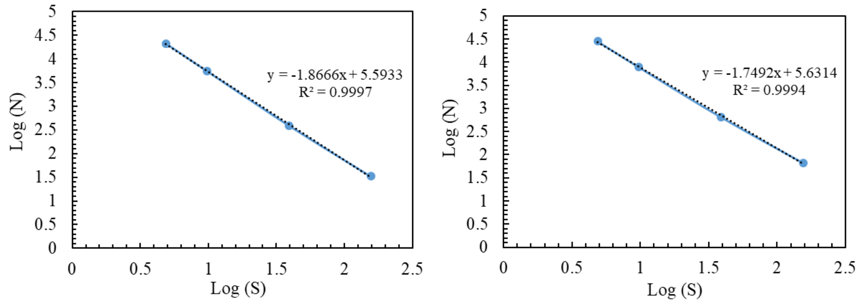

Figure 8. Graphical representation between Log (N) and Log(S) representing highest (1.86) and lowest value (1.74) of fractal dimension for S-2 sample at 200 °C.

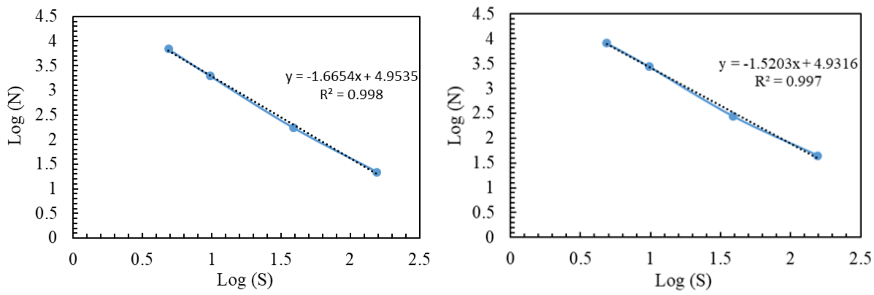

Figure 9. Graphical representation between Log (N) and Log(S) representing highest (1.66) and lowest value (1.52) of fractal dimension for S-6 sample at 600 °C.

Table 1. Fractal dimension of hydraulic fractures at different temperatures.

Sample number	Temperature (°C)	Fractal dimension range	Average Fractal dimension
S-1	25	1.86 - 1.78	1.84
S-2	200	1.86 - 1.74	1.82
S-3	300	1.82 - 1.71	1.77
S-4	400	1.75 - 1.67	1.71
S-5	500	1.72 - 1.64	1.66
S-6	600	1.66 - 1.52	1.60

The maximum decrease of 3.38 percent in average fractal dimension was observed between 300 °C and 400 °C. Overall the fractal dimension has significantly changed after 200 °C and showed a decreasing trend with the increase of temperature. Fractal dimension decrease could also be attributed to the decrease of aperture width of hydraulic fractures with increase in temperature especially after 300 °C. The maximum change in fractal dimension range was observed in fractures produced at 600 ° C, which could be also an indicator that fractures were more complex. The minimum difference in change of fractal dimension range was observed in S-1 at 25 °C indicating fracture were very less complex and straight.

4 CONCLUSIONS

The effect of thermal treatment and step incremental loading on hydraulic fracturing process was discussed by analyzing the characteristics of breakdown pressure, tortuosity and fractal dimension Of hydraulic fractures. The conclusions made during this study are as follows:

(1). The activation of micro fractures at 300 °C was the resulting factor in decrease of breakdown pressure nonlinearly from 30 MPa at 300 °C to 24 MPa at 400 °C. Breakdown pressure variation between 25 °C to 300 °C was significantly less and the effect of thermal treatment was very less.

(2). Tortuosity of the hydraulic fractures at initial temperature between 25 °C to 200 °C changed very less. Between 200 °C and 300 °C, the tortuosity increased to 2.85 percent and also the decrease in fracture aperture was observed. After 300 °C the fracture aperture continued to decrease whereas the tortuosity increases significantly to 600 °C.

(3) After 300 °C the fracture were more complex and secondary fractures along the main fractures were also observed. The maximum complex fractures were observed at 600 °C.

(4). Averaged Fractal dimension of the fractures between 200 °C and 300 °C was decreased by 2.74 percent. The maximum decrease of 3.38 percent of average fractal dimension was observed between 300 °C and 400 °C. The maximum change in fractal dimension range was observed in fractures produced at 600 ° C .Thus it could be concluded that fractal dimension decreases with the effect of increased thermal treatment.

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