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Laboratory studies of hydraulic fracturing by cyclic injection

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ABSTRACT

We assess the possibility of decreasing the breakdown pressure of rock and increasing the damage around hydraulic fracture by using pre-breakdown cyclic injection during hydraulic fracturing under triaxial stress conditions. Unlike the monotonous increase in pressure used in conventional hydraulic fracturing, the fluid is injected in cycles until breakdown. During cyclic injection, the peak pressure of each cycle is increased in an increment of 10% of the reference breakdown pressure. The reference breakdown pressure of the rock is the pressure at which the rocks fails during hydraulic fracturing by conventional injection. To obtain a reference breakdown pressures, specimens of dry and saturated Tennessee sandstone were hydraulically fractured by conventional injection. The decrease in breakdown pressure and increase in damage during cyclic injection is quantitatively compared with the case of conventional hydraulic fracturing. Acoustic emission (AE), fracture permeability, and Scanning Electron Microscope (SEM) images of the fracture surface were used to compare the damage around hydraulic fractures generated by conventional and cyclic injection hydraulic fracturing. Laboratory results indicate that the damage generated around hydraulic fracture by cyclic injection hydraulic fracturing of dry Tennessee sandstone is approximately twice that generated by conventional injection. Also, the breakdown pressure recorded during cyclic injection fracturing of dry Tennessee sandstone is lower and varies more than two standard deviations from that of conventional injection.

1. Introduction

Hydraulic fracturing is a stimulation technique in which injection fluid, a sequence of mixtures, commonly made up of water, chemical additives and proppant, are pressurized in the borehole. Due to pressurization, a fracture is initiated into the formation. Fracture initiation is defined as the initial failure of the rock without fluid ingression. The fracture initiation is followed by breakdown which is the maximum pressure recorded. The breakdown is impacted by the penetration of injected fluid inside the newly created fracture and system compressibility. Thus, a sudden drop in pressure is observed after the breakdown pressure. The created fracture facilitates flow of incoming injected fluid into larger volume of the target formation. In general, the breakdown pressure has to overcome the in-situ stress concentration around the wellbore as well as the tensile strength of the rock. The expression for breakdown pressure for impermeable rock was given Hubbert and Willis[1] as

$$P_{bu} = 3\sigma_h - \sigma_H + T_o - P \tag{1}$$

A modified version of this equation was published by Haimson and Fairhurst[2] to include poroelastic effects:

$$P_{bl} = \frac{3\sigma_h - \sigma_v + T_o - 2\eta P}{2(1-\eta)} \tag{2}$$

where P_{bu} *and* P_{bl} are the upper and lower limits of the breakdown pressure, respectively, T_o is the tensile strength, P is the pore pressure, σ_H and σ_h are the maximum and minimum horizontal principal stresses, respectively, σ_V is the vertical stress, $\eta = \alpha(1-2\nu)/2(1-\nu)$, where α is the Biot coefficient, and ν is Poisson's ratio.[3] A reduction in the tensile strength of the rock will lead to reduction in the breakdown pressure. After the initiation, the fracture propagates creating a process zone around it. In this paper, the process zone is defined as the extent of microcracking in the vicinity of the hydraulic fracture or the extent of damage developed by fracturing and connected to the main hydraulic fracture (Fig. 1). The deliverability of hydrocarbon to a wellbore increases with the increase in the width of the process zone.

Erarslan[4] and Mighani[5] have reported reduction in the tensile strength of the rock by cyclic loading in Brazilian tests. Mighani[5] observed more number of intergranular cracks in the SEM images in rock tested under cyclic loading. If reduction in tensile strength due to cyclic loading occurs by cyclic injection in hydraulic fracturing, it can lead to decrease in the breakdown pressure.

Hulse[6] filed a patent on pre- and/or post-breakdown cyclic injec-

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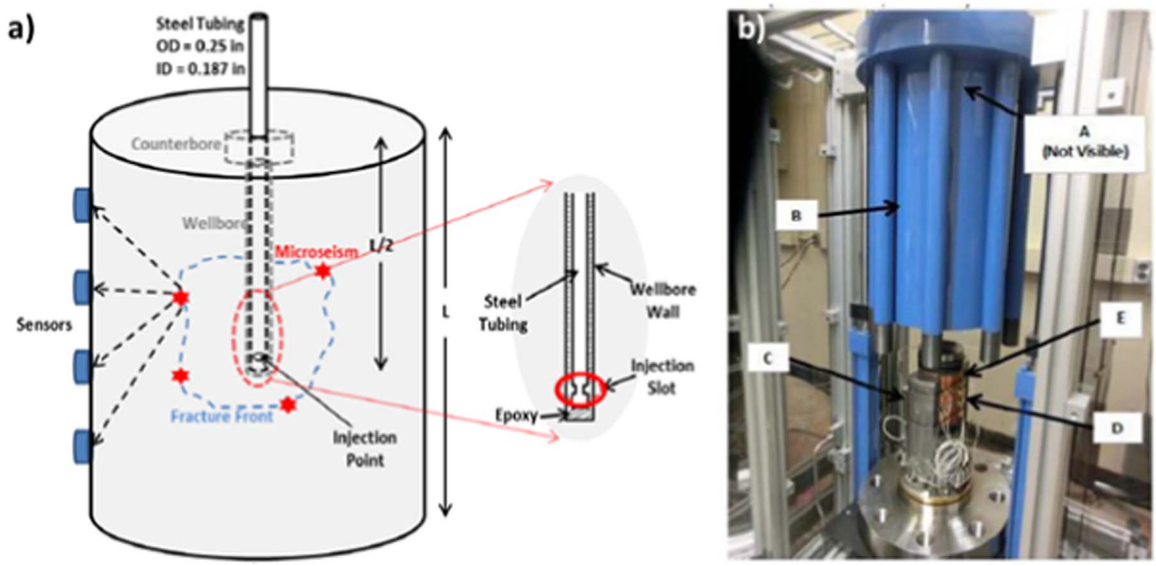

Fig. 1. (a) Schematic of sample completed with steel tubing cemented at the center of the sample; (b) Triaxial loading system (A) axial loading (σ_v) (B) confining vessel (σ_h) (C) flat jacks to apply transverse stress (σ_H) (D) acoustic transducers attached to sample (E) copper jacket covering the sample (transducers attached on it).

tion which improved conventional hydraulic fracturing. He suggested applying a series of pressure shocks before the breakdown pressure to weaken the selected formation and cause a plurality of fractures. The pressure shocks were applied at the wellhead using an air hammer or a piston. They are transmitted to the formation face exposed at the well through colum of liquid present in it. The author observed a 47% increase in productivity compared to conventional hydraulic fracturing in the same formation when the shock method was employed. The combined results of Erarslan,[2] Mighani[5] and Hulse[6] suggest that the pre-breakdown cyclic injection might lead to a decrease in breakdown pressure and an increase in stimulated zone around hydraulic fracture. In this study, an effort has been made to study the effect of pre-breakdown cyclic injection on breakdown pressure and stimulated area around hydraulic fracture. The experiments were performed under triaxial stress conditions. The change in the breakdown pressure and the damage around hydraulic fracture caused by cyclic injection is compared to the results in which samples were conventional hydraulically fractured. Throughout the paper, the term cyclic injection implies pre-breakdown cyclic injection. Hulse,[6] Kiel[7] and Zang et al.[8] have shown the effect of post-breakdown cyclic injection on stimulated zone around hydraulic fracture.

2. Materials and experimental procedure

Fig. 2a show the schematic of the sample used for hydraulic fracturing experiments. The experiments were performed on a cylindrical rock samples of 4 in. in diameter and 5.5 in. in length. A 6.35 mm hole is cored in the center of the cylindrical sample to a depth of 5 mm greater than half of the length. A steel tubing (6.35 mm OD), having holes at 180° apart at 5 mm above the bottom of the pipe, was placed inside the drilled hole and cemented using JB Weld™ epoxy. No perforations are made in the sample. The fluid was injected into the center of the sample through the steel tubing. The tubing holes are aligned with the applied maximum horizontal stress direction. The bottom end of the steel tubing is sealed using the same epoxy before it is cemented inside the drilled hole.

The experimental configuration consists of a triaxial loading system, a hydraulic fluid pumping unit and acoustic emission monitoring and processing system. Fig. 2b shows the triaxial loading system; this is a custom-built load frame, pressure vessel with internal flat jacks; the system was designed and built by New England Research™. The stresses are applied on the sample using an axial loading piston,

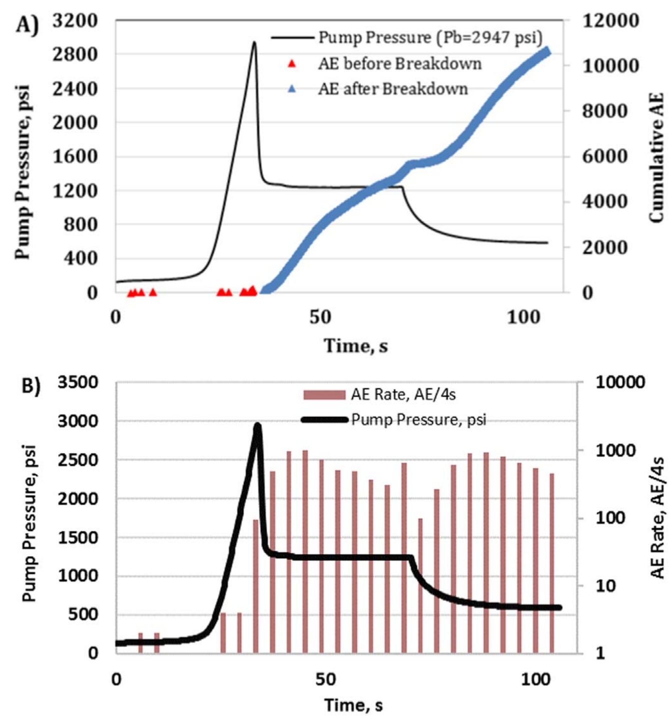

Fig. 2. (A) Pump pressure (black) and pre- and post- breakdown AE (red and blue triangles) as a function of time for dry Tennessee sandstone, hydraulically fractured by conventional injection (Sample-T1); (B) pump pressure (black) and AE rate (pink) as a function of time. The average breakdown pressure of dry Tennessee sandstone is 3007 psi. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

confining fluid and circumferentially mounted flat jacks. The elastic waves emitted during hydraulic fracturing are recorded by a Digital Wave™ system using sixteen piezoelectric sensors (1 MHz). The acoustic wave processing system consist of pre-amplifiers, signal conditioning unit and a data acquisition module. The fluid is pumped into the system using Teledyne Isco 100DX™ pump.

The experiments were carried out on Tennessee sandstone. It has measured porosity and permeability of 6% and 0.007 md at 3000 psi, respectively. The circumferential velocity analysis indicates that the Tennessee sandstone has 3% variation in azimuthal P-wave velocity. It

Table 1
Experiment type, sample state, breakdown pressure and injection fluid, in all the experiments performed on Tennessee sandstone under the stress state of (σ_V)=1500, (σ_H)=3000 psi and (σ_h)=500 psi. The number of cycles in cyclic HF indicate the injection cycles required to break the sample.

Sample	Experiment type	Sample state	Breakdown pressure Pb (psi)	Injection fluid (viscosity in cP)
T1	Conventional HF	Dry	2947	Oil (50)
T1-1	Conventional HF	Dry	3067	Oil (50)
T2	Cyclic HF-8 cycles	Dry	2519	Oil (50)
T9	Conventional HF	Saturated	2060	Oil (50)
T10	Conventional HF	Saturated	2168	Oil (50)
T12	Cyclic HF-10 cycles	Saturated	2062	Oil (50)

contains 60–90% quartz and minor amounts of mixed clays. AE hypocenter locations are determined by the arrival times at the sensors using a weighted least squares procedure. A constant velocity model is used in the procedure. The medium (Tennessee sandstone) velocity while under stress was determined by making measurements between opposing and offset transducers pairs. The time taken by a sound wave to travel between a pair of transducers is recorded using digital oscilloscope. The measured time is used to calculate velocity of the medium. The results of 78 such measurements are averaged to a get a value of the medium.

The experimental conditions of all the cyclic injection experiments are listed in Table 1. The only parameter changed was the number of pre-breakdown injection cycles and saturation of the sample. All six experiments were carried out under the stress state of σ_V=1500, σ_H=3000 psi and σ_h=500 psi at fluid injection rate of 10 ml/min. Vegetable oil (viscosity=50 cP) was used as the fracturing fluid.

3. Results and discussion

3.1. Conventional hydraulic fracturing of dry Tennessee sandstone

The differential stress ($\sigma_H - \sigma_h$) in the experiment was 2500 psi. The breakdown pressure recorded in the experiment was 2947 psi (see Fig. 3). A total of 6539 good events were recorded; however, only 1291 events were located inside the sample. A total of 107 acoustic events were recorded before the breakdown, of which nine could be located (Fig. 4). The AE before the breakdown might be due to pressurization and diffusion of injected fluid into the pore space near the injection zone and local microcracking. Fig. 3 shows that a burst of activity occurs just after the breakdown pressure which might be due to redistribution of stresses near the vicinity of the hydraulic fracture just created. Thereafter, the AE rate decreases gradually during the constant injection period. It again increases near the time when the injection is stopped. This later increase in activity is thought to occur due to failure of asperities along the fracture face as they come together

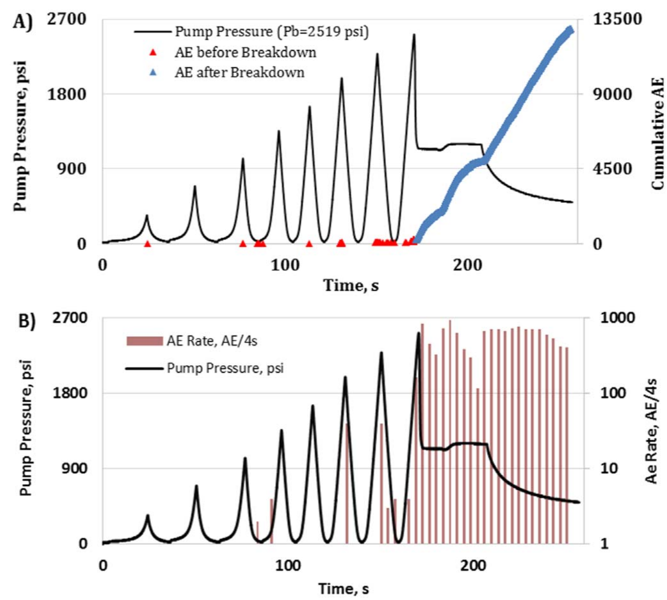

Fig. 4. (A) Pump pressure (black) and pre- and post- breakdown AE (red and blue triangles) as a function of time for dry Tennessee sandstone, hydraulically fractured by cyclic injection (Sample-T2); (B) pump pressure (black) and AE rate (pink) as a function of time gives idea of cycles contributing to increase in AE before breakdown. The cyclic injection decrease the breakdown pressure of dry Tennessee sandstone by 16%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

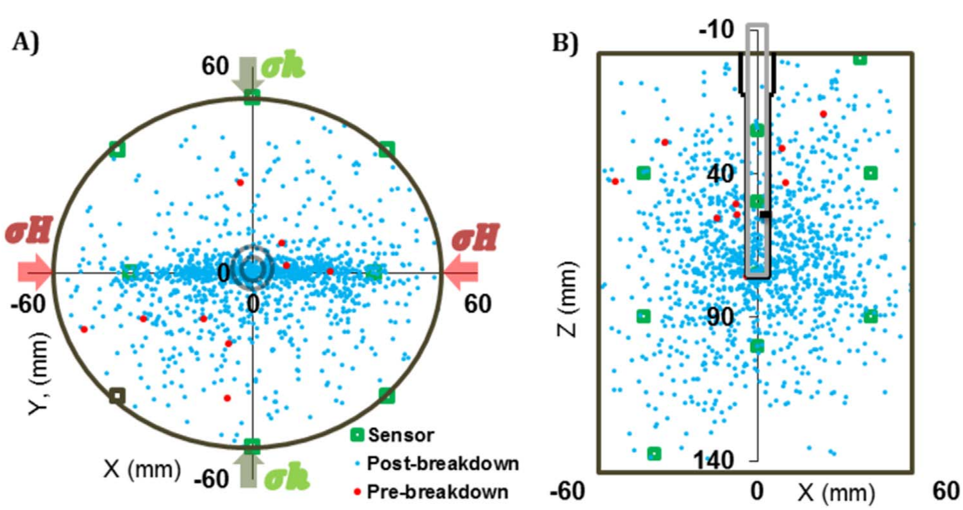

Fig. 3. Schematic view of the Sample-T1 showing AE hypocenters; dry Tennessee sandstone hydraulically fractured by conventional injection. The pre-breakdown events are shown in red and post-breakdown events are shown in blue; (A) plan view of the sample; (B) side views of the sample and events. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

after injection is stopped. The pressure stabilizes at 500 psi which is equal to confining pressure or minimum applied stress.

Damani[9] has shown that the direction of fracture is not always parallel to the maximum horizontal stress, but depends on the magnitude of differential stress. His hydraulic fracturing experiments proved that only under high differential horizontal stress will the fracture be parallel to the maximum horizontal stress otherwise it will be governed by the rock fabric. Since, the differential stress in all the experiments is high (2500 psi), the fracture is parallel to maximum horizontal stress and perpendicular to the minimum horizontal stress which is further confirmed by mapping acoustic events hypocenter locations as shown in Fig. 4. Similar results were obtained when a conventional hydraulic fracturing experiment was performed on another dry Tennessee sandstone sample (see Table 1; Sample T1-1). The breakdown pressure recorded in the experiment was 3067 psi. The average breakdown pressure of Sample T1 and Sample T1-1 was 3007 psi with a standard deviation of 60 psi, which was used as a reference breakdown pressure. The reference breakdown pressure is needed to quantitatively map the change in breakdown pressure by cyclic injection.

3.2. Cyclic hydraulic fracturing of dry Tennessee sandstone

In this experiment the fluid was injected in cycles before breakdown pressure was reached. The peak pressure of each cycle was incremented by 10% of the reference breakdown pressure obtained from conventional hydraulic fracturing experiments on dry samples (see Fig. 4). The minimum pressure was decreased to 15 psi in each cycle. Fig. 5 shows that the total number of cycles applied before the rock failure is eight. The breakdown pressure of the rock is observed in the 8th cycle. The breakdown pressure recorded in this experiment was 2519 psi which is 16% lower than the reference breakdown pressure (3007 psi). The decrease in the breakdown pressure is considered significant and is attributed to fatigue caused due to cyclic injection.

Fig. 5a shows that AE activity occurs in nearly in all pre-breakdown pressure cycles. Fig. 5b show that the increase in the AE activity actually starts from cycle 6 in which the peak pressure was 60% of the reference breakdown pressure. It is believed that the initiation of the microfractures starts at around this pressure. From cycle 6 onwards, the AE activity rate increases in each consecutive cycle. The maximum AE rate is observed in the 8th cycle where the breakdown occurs. Thus, it is believed that the amalgamation of the microfractures created in the previous cycles occurs in cycle 8. The total number of good events recorded in the experiment were 9904 which is approximately 1.5 times than that recorded during the conventional hydraulic fracturing. A total of 226 AE was recorded before the breakdown, which is twice than that recorded during conventional hydraulic fracturing. The increase in the AE activity indicates increased damage. The increased damage might be due to fatigue induced failure. Mighani (2014) observed more number of intergranular cracks in cyclic loading Brazilian tests compared to the monotonous loading test. A similar effect during pre-breakdown cyclic injection hydraulic fracturing would produce a greater number of acoustic events and an increased damage around hydraulic fracture. Due to high differential stress (2500 psi), the hydraulic fracture is parallel to maximum horizontal stress (see Fig. 6a).

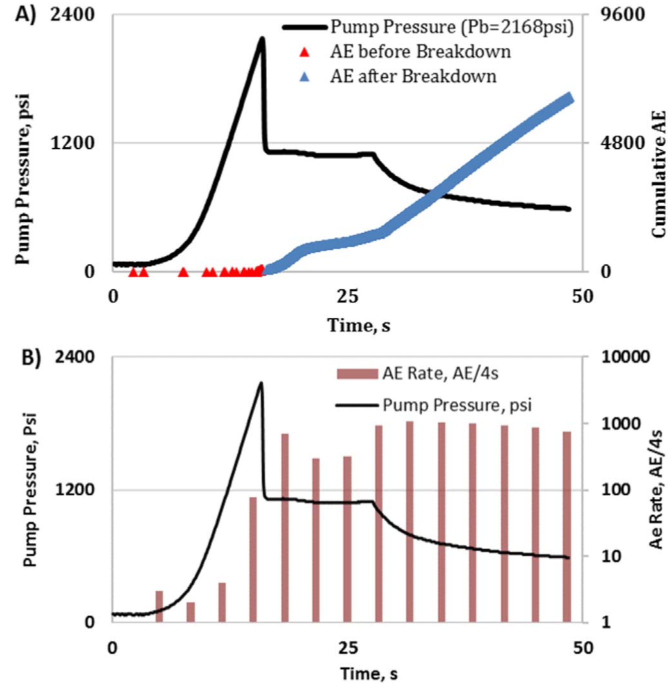

Fig. 6. (A) Pump pressure (black) and pre- and post- breakdown AE (red and blue triangles) as a function of time for dry Tennessee sandstone, hydraulically fractured by conventional injection (Sample-T9); (B) pump pressure (black) and AE rate (pink) as a function of time. The average breakdown pressure of saturated Tennessee sandstone was 2114 psi. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

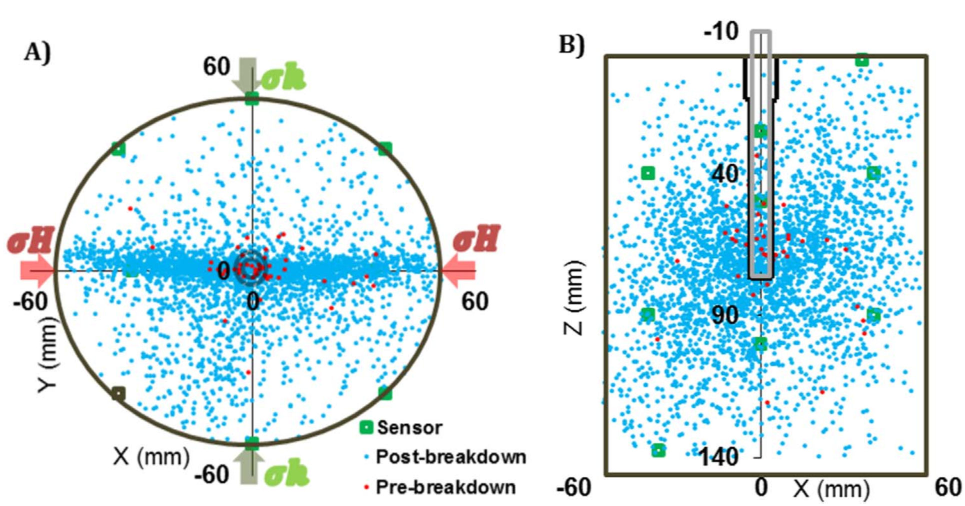

Fig. 5. Schematic view of the Sample-T2 showing AE hypocenters; dry Tennessee sandstone hydraulically fractured by cyclic injection. The pre-breakdown events are shown in red and post-breakdown events are shown in blue; (A) plan view of the sample; (B) side views of the sample and events. The total number of good events located in cyclic injection experiment is 1.5 times the conventional injection experiment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

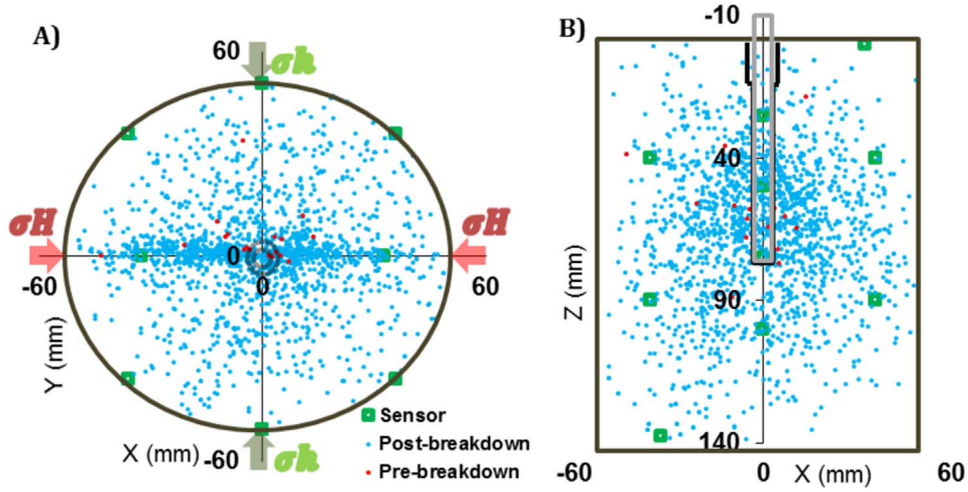

Fig. 7. Schematic view of the Sample-T9 showing AE hypocenters; saturated Tennessee sandstone hydraulically fractured by conventional injection. The pre-breakdown events are shown in red and post-breakdown events are shown in blue; (A) plan view of the sample; (B) side views of the sample and events. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3.3. Conventional hydraulic fracturing in saturated Tennessee sandstone

Two conventional hydraulic fracturing experiments were conducted on saturated Tennessee sandstone under the same experimental conditions as the dry samples discussed above. The saturation was carried out by subjecting the sample, immersed in brine solution, to vacuum for twenty-four hours and then pressurizing at 3000 psi for forty-eight hours in the same brine solution. An average value of 96% saturation was measured. The saturation was calculated by measuring the weight of the sample before and after saturation.

The average breakdown pressure recorded from the two experiments was 2114 (± 54 psi). This value was used as the reference breakdown pressure of saturated Tennessee sandstone to map the change in breakdown pressure obtained during cyclic injection. Fig. 7 show injection rate, pump pressure, cumulative AE and AE rate as a function of time for one of the sample (Sample T9, see Table 1). In sample T9, a total of 1736 events were located inside the sample. A total of eighty-five pre-breakdown events were recorded which is approximately same as recorded in dry Tennessee sandstone. Similar result was obtained in the second experiment on saturated Tennessee sandstone. The hypocenter locations of the AE events show that the hydraulic fracture is parallel to the maximum horizontal stress (see Fig. 8).

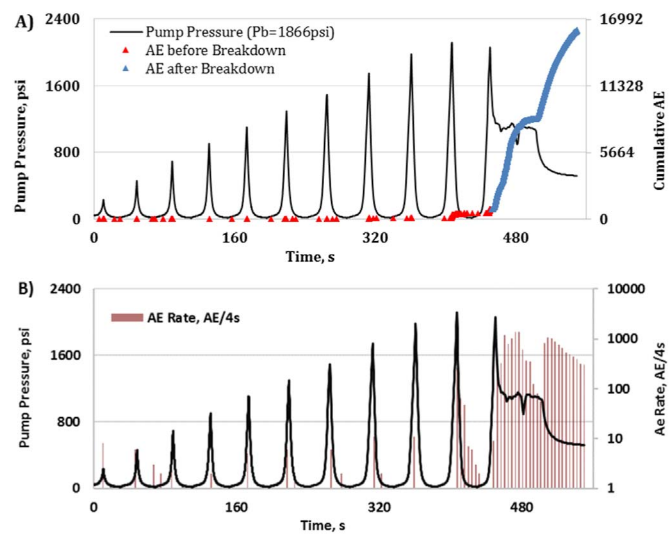

Fig. 8. (A) Pump pressure (black)and pre- and post- breakdown AE (red and blue triangles) as a function of time for saturated Tennessee sandstone, hydraulically fractured by cyclic injection (Sample-T12); (B) pump pressure (black) and AE rate (pink) as a function of time. The cyclic injection did not cause any decrease in breakdown pressure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3.4. Cyclic hydraulic fracturing in saturated Tennessee sandstone

In this experiment the fluid was injected in cycles with peak pressure of each cycle incremented by 10% of the reference breakdown pressure (2114 psi) and the minimum pressure of each cycle was decreased to 15 psi (Fig. 9). The breakdown pressure recorded in this sample was 2062 psi which is not significantly different than the reference breakdown pressure of saturated Tennessee sandstone.

Since the results were counterintuitive the saturated cyclic injection experiment was repeated on two more samples to confirm the observations. The breakdown pressures observed in the three experiments are reported in Table 2 which shows that the breakdown pressure of saturated Tennessee sandstone does not change significantly by cyclic injection hydraulic fracturing. This implies that the cyclic injection did not cause fatigue in the saturated sample.

Unlike dry Tennessee sandstone, spikes of acoustic activities are observed in all the pre-breakdown cycles. A total number of 803 pre-breakdown AE events were recorded which is ten times greater than number recorded during conventional hydraulic fracturing on saturated sample. A total of 9600 good AE events were recorded during the experiment which is twice that recorded during conventional hydraulic fracturing on saturated samples. Fig. 10 shows the schematic of the sample T12 along with AE hypocenters. Even though there is increase in pre-breakdown acoustic events compared to dry Tennessee sandstone, the breakdown pressure does not decrease for saturated samples; the results are counterintuitive. Thus, a further investigation is recommended to understand the cause of increase in pre-breakdown acoustic emissions in saturated Tennessee sandstone during cyclic injection hydraulic fracturing.

3.5. Effect of cyclic injection on fracture permeability

Permeability was measured on a 1 in. in diameter core plug extracted from the HF samples; these core plugs were cut parallel to borehole axis and at an azimuth and radius to capture the hydraulic fracture. Fig. 11 shows the position of the core plugs with reference to borehole axis.

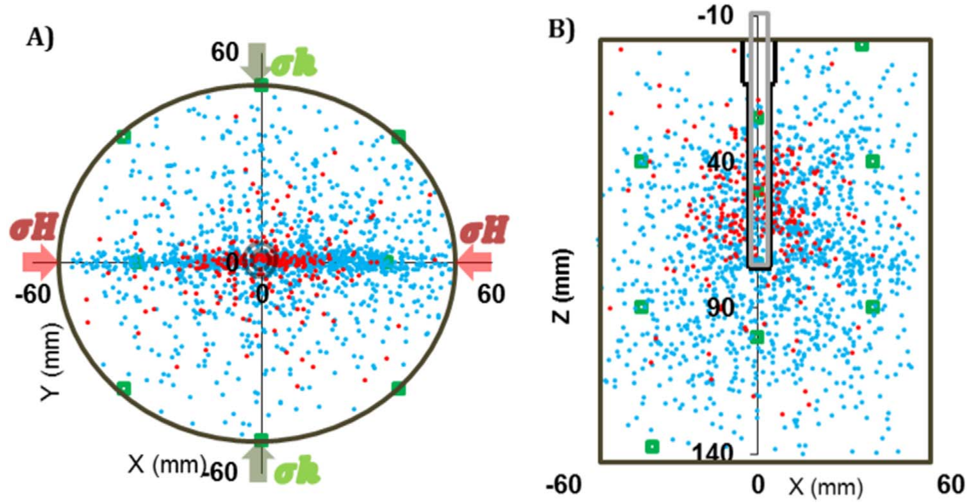

Fig. 9. Schematic view of the Sample-T12 showing AE hypocenters; saturated Tennessee sandstone fractured by cyclic injection. The pre-breakdown events are shown in red and post-breakdown events are shown in blue; (A) plan view of the sample; (B) side views of the sample and events. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 2
Breakdown pressures of saturated Tennessee sandstone hydraulically fractured by cyclic injection.

Sample number	Experiment type	Breakdown pressure Pb (Psi)
T12	Cyclic HF	2062
T13	Cyclic HF	2168
T14	Cyclic HF	2100

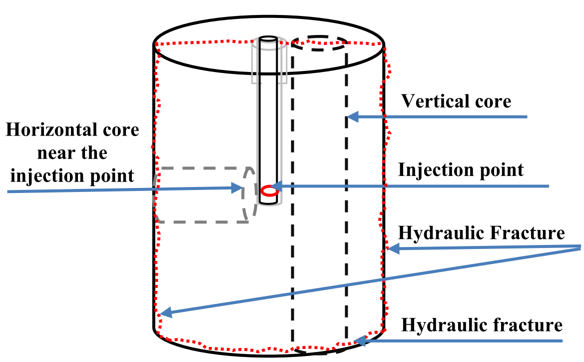

Fig. 10. Schematic of horizontal and vertical core plugs extracted from the cylindrical HF sample. The horizontal core was used for measuring the extent of fracture network using SEM. The vertical core was used for permeability measurement using AP608™.

The vertical core extracted length was the entire length of the test specimen. Remarkably, the core contained the hydraulic fracture and was intact, i.e. it did not fall apart. This implies that the fracture did not extend through out the core plug. Pulse decay permeability was measured on a section of the core containing the fracture as a function of confining pressure. Jones[10] describes the pulse decay technique in detail. Fig. 12 shows the Klinkenberg corrected permeabilities for virgin and fractured samples as a function of confining pressure.

The measured permeability in all the fractured samples is two to three orders of magnitude greater than the native sample permeability. The increase in the permeability is due to: (1) mismatching of the rough fracture faces when the fracture closes and (2) the asperities generated during creation of the fracture work as a proppant which does not let the fracture close completely. Fig. 12 shows that the permeability of the fracture created by cyclic injection is greater than conventional (normal HF) by a factor of 3–10, but the pressure dependence of the fracture permeability is same. The reason for the increase might be greater damage around hydraulic fracture. The

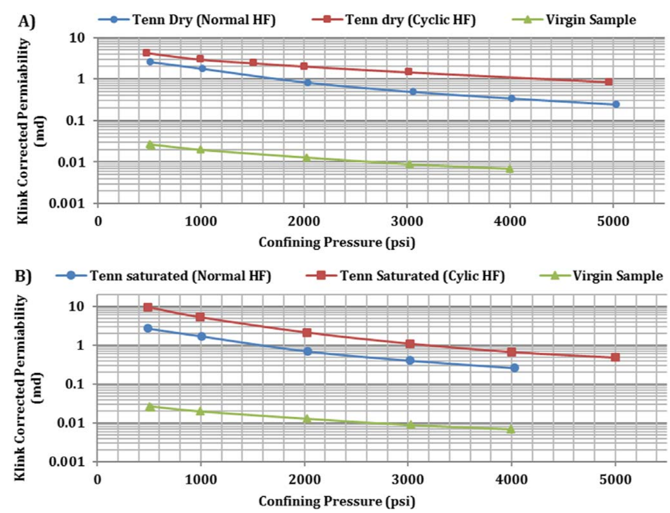

Fig. 11. Klinkenberg corrected permeability of core plugs containing the hydraulically induced fractures as a function of confining pressure for (A) dry Tennessee sandstone and (B) saturated Tennessee sandstone. The permeability of the fracture caused by cyclic injection is greater than conventional by a factor of 3–10.

similarity in the pressure dependence implies that the fracture roughnesses are not too different for cyclic and conventionally induced hydraulic fractures.

3.6. Measurement of the width of the process zone using SEM images

The increase in AE events and fracture permeability with cyclic injection imply an increase in process zone. A measurement of the width of the process zone created around hydraulic fracture was carried out on backscattered SEM images to quantify the process zone. The analysis was done on two dry Tennessee sandstone samples: (i) fractured by conventional injection, and (ii) fractured by cyclic injection. A 1 in. core plugged near the injection zone, perpendicular to the borehole axis, was used in the analysis (Fig. 11). The length of the core is half the diameter of the sample. The plug was cut into half producing an upper and lower hemi-cylindrical section, perpendicular to the fracture; these sections were further split into three “parts” to facilitate surface preparation (Fig. 13). The measurement of the fracture network was performed on the middle “part” of the lower hemi-cylindrical section (Fig. 13b) which is ~10 mm away from the injection point. The sample was polished and ion milled. The ion milling process was

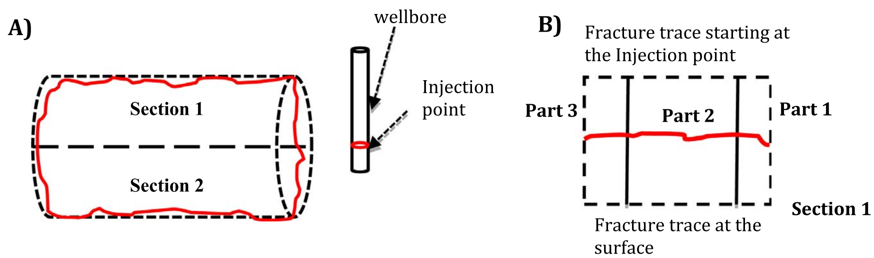

Fig. 12. Sample preparation methodology for measuring width of the process zone, (A) the cylindrical core is cut into half, perpendicular to the fracture (black plane) producing an upper and lower section; one of the sections is used for study; (B) the schematic shows the plan view of the section 1. The fracture is visible on the surface. Section 1 is cut into 3 parts to facilitate surface preparation; part 2 is used for measuring the extent of the process zone.

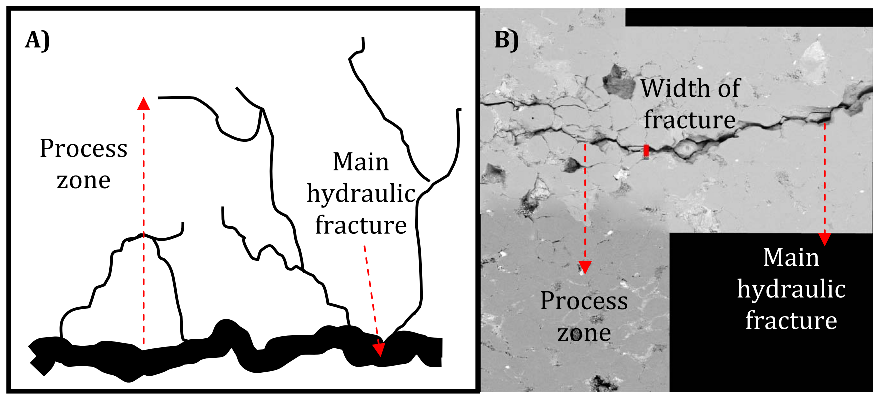

Fig. 13. (A) Schematic showing hydraulic fracture and process zone; (B) a part of the mosaic of Sample-T2 showing width of the hydraulic fracture and process zone. The residual, unstressed width of the fracture was measured 25 µm.

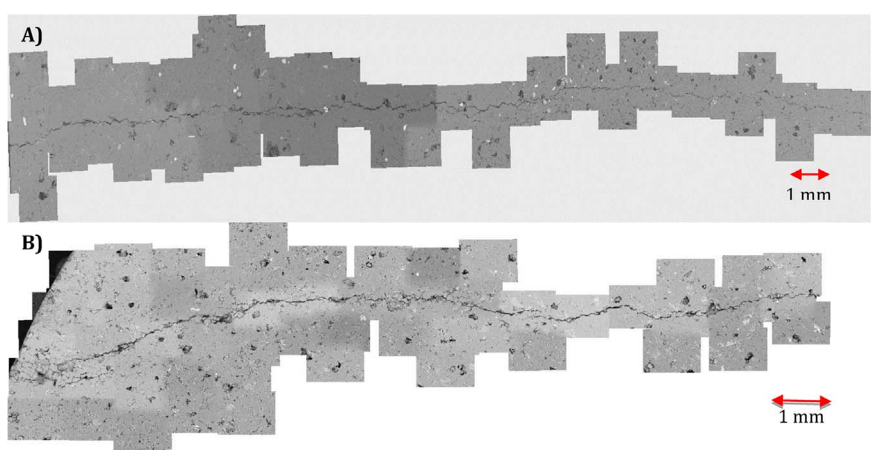

Fig. 14. Mosaic of BSE-SEM images of dry Tennessee sandstone fractured by (A) conventional injection and (B) cyclic injection hydraulic fracturing. The fracture is more complex when created by cyclic hydraulic fracturing compared to conventional.

carried out using Fischione Model 1060 SEM mill for nine hours at an accelerated voltage of 5–6 kV.

BSE-SEM images were captured along and perpendicular to the length. A mosaic of images was created for further analysis. Fig. 14 show the mosaic of the SEM images captured for dry Tennessee sandstone, fractured by conventional and cyclic injection, respectively. Width of the process zone was measured at 0.5 mm intervals.

A graphical analysis of the width of the process zone as a function of distance from wellbore reveals a cyclic pattern in both the tests (Fig. 15). Rummel and Hansen11 predicted a similar texture based on a fracture mechanics model. The average width of the fracture is 25 µm in both the samples. The process zone is twelve times the main fracture width in sample fractured by conventional injection (Fig. 15a). The cyclic injection process zone is twenty-four times the main fracture width (Fig. 15b). The comparison reveals that the process zone generated by cyclic injection can be twice that induced by conventional fracturing. Similar results are expected for regions far away from the borehole. To confirm the results at region far away from the borehole, a similar kind of study is recommended on larger sample. It is believed that the process zone expands during long injection period that follow breakdown leading to the creation of greater drainage volume around the fracture.

4. Conclusions

Triaxial laboratory test on hydraulic fracturing were carried out on Tennessee sandstone to assess the effects of cyclic injection on reducing the breakdown pressure and increasing the damage around hydraulic fracture. In dry Tennessee sandstone, cyclic injection decreases breakdown pressure by 16% but it does not have any effect on breakdown pressure in saturated Tennessee sandstone. A further investigation is needed to understand the effect of fatigue on saturated Tennessee

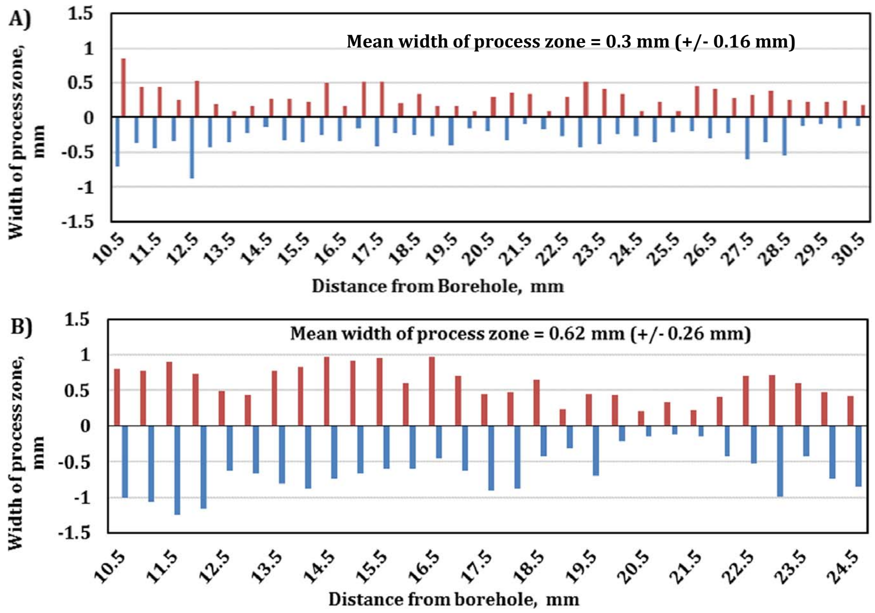

Fig. 15. Width of the process zone as a function of distance from borehole generated by (A) conventional injection and (B) cyclic injection hydraulic fracturing as a function of distance from borehole. The blue bars and orange bars represent the process zone left and right of the horizontal fracture as viewed relative to the direction of propagation. The mean width of the process zone is 0.3 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

sandstone as there is an increase in pre-breakdown acoustic activities but no decrease in breakdown pressure. An increase in total number of AE events and pre-breakdown AE events is observed by cyclic injection in both dry and saturated Tennessee sandstone. Hydraulic fracturing by cyclic injection increases the fracture permeability compared to conventional hydraulic fracturing by a factor of three to ten in Tennessee sandstone. Cyclic and conventional induced fracture permeability show similar dependency on confining pressure. The unpropped fracture permeability is more than 100 times higher than the intrinsic permeability. The increased permeability persists even at high confining pressure. The increase in AE events and fracture permeability by cyclic injection suggest an increase in process zone which is confirmed by measuring the width of the process zone as a function of distance from the injection site using BSE-SEM images. The analysis show that damage around hydraulic fracture generated by cyclic injection is twice than that generated by conventional injection in dry Tennessee sandstone. Future experiments are designed to examine the generalization to other lithologies but the initial results are sufficiently encouraging to recommend field trials.

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