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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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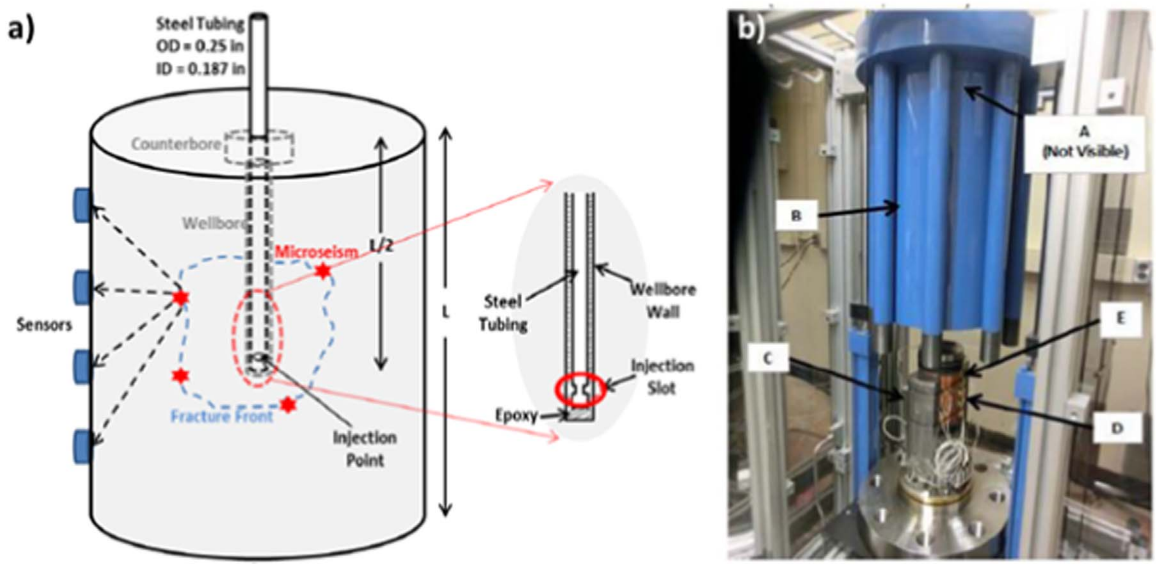

Fig. 1. (a) Schematic of sample completed with steel tubing cemented at the center of the sample; (b) Triaxial loading system (A) axial loading (σ_v) (B) confining vessel (σ_h) (C) flat jacks to apply transverse stress (σ_H) (D) acoustic transducers attached to sample (E) copper jacket covering the sample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

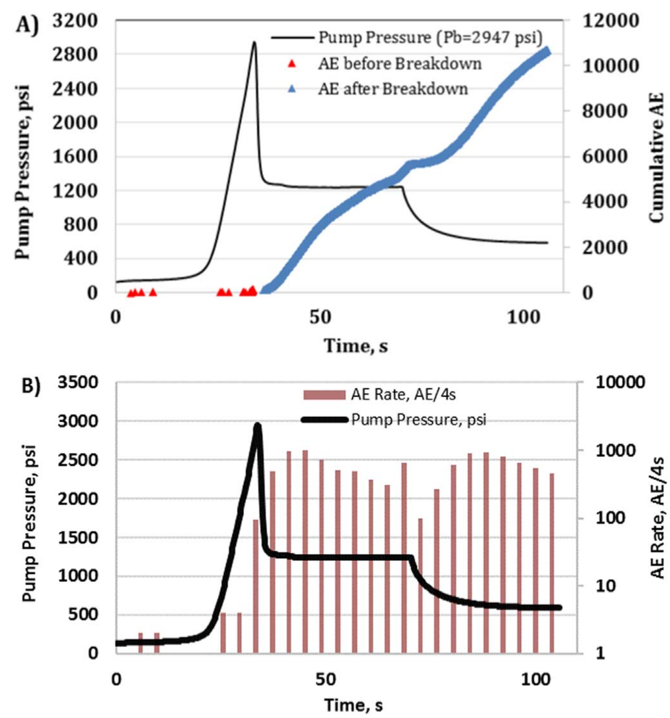

Fig. 2. (A) Pump pressure (black) and pre- and post- breakdown AE (red and blue triangles) as a function of time for dry Tennessee sandstone, hydraulically fractured by conventional injection (Sample-T1); (B) pump pressure (black) and AE rate (pink) as a function of time. The average breakdown pressure 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