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Laboratory scale research on the impact of stress shadow and natural fractures on fracture geometry during horizontal multi-staged fracturing in shale

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1. Introduction

With the development of shale gas in the last decades, multi-stages hydraulic fracturing have become more and more valuable technique for stimulation of shale reservoirs. The presence of natural fractures alters the way the induced fracture propagates through the rock. The early studies have shown that the propagating fracture crosses the natural fracture, turns into the natural fracture, or in some cases, turns into the natural fracture for a short distance, then breaks out again to propagate in a mechanically more favorable direction, depending primarily on the orientation of the natural fracture relative to stress field.[1–4] Then several fracture interaction criterions were discussed.[5,6] Scaled laboratory experiments and numerical tests proved that high flow rate or viscosity yields fluid-driven fractures, while low flow rate just opens an existing fracture network.[7,8] Laboratory scale tests also found that interaction of a hydraulic fracture with a natural fracture depended heavily on the stress state, inclination of the natural fracture with respect to the hydraulic fracture, and the strength of the natural fracture.[9,10] For the case of natural fractures in shale are mineralized, research showed that obliquely embedded fractures are more likely to divert a fluid-driven hydraulic fracture than those occurring orthogonally to the induced fracture path.[11]

Stress shadow alters the magnitude and orientation of principal stresses, which has obvious impact on fracture orientation and fracture length, especially under the condition of multi-clusters perforation. Fisher et al.[12] demonstrated that creation of a hydraulic fracture generates a zone of altered local stresses that may impact the orientation of subsequent fractures in a phenomenon known as the stress shadowing effect. Wong et al.[13] studied the interaction between adjacent hydraulic fractures using analytical and numerical methods in two dimensions, and they observed diverging hydraulic fractures outward or even, collapsing of inside fractures on the outside ones as a result of the stress shadow effect. Singh and Miskimins[14] indicated that an increase in spacing between the fractures induced less interference, and hence requires less breakdown pressure to initiate a fracture. By locating the next treatment in this region, fracture growth is likely to deviate or even occur parallel to the borehole axis and consequently, necessitates optimizing fracture spacing to obtain the maximum number of fractures oriented perpendicular to the wellbore.[15,16] The shadow size around a hydraulic fracture was also calculated. And it was observed that Young's modulus of the rock does not change the shadow size. Stress anisotropy, poisson's ratio, aspect ratio, and hydraulic pressure directly increase the shadow size.[17]

However, regarding the addressed numerical simulation of stress shadow considering stress anisotropy, Poisson's ratio, aspect ratio hydraulic pressure, et al., it is important to notice that the best production should be obtained by an efficient fracture network with the least cost, which means the understanding the interaction between natural factures and staged fractures are also takes a significant position in shale fracturing. Therefore, an optimized design and experimental tests were performed in lab scale, and possible impact of natural fractures and stress shadow on staged fracture geometry was discussed as well.

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Table 1
Basic rock mechanics parameters of blocks.

Symbol	Parameter	Value	Units
E	Young's modulus	23.9–28.8	GPa
υ	Poisson's ratio	0.32–0.36	
σ_c	Unconfined Compressive Strength	100.8–120.1	MPa
T_o	Tensile strength	9.70–11.67	MPa

2. Experimental setup and procedure

2.1. Experimental set up and shale blocks preparation

A triaxial test equipment was introduced to carry out all the hydraulic fracturing simulation in the lab scale. The blocks were positioned in between the loading frames which were capable of stress simulation up to 30 MPa, in which the block size had been designed to 300 mm × 300 mm × 600 mm. In further, some improvement had conducted for the purpose of monitoring dynamic fracture propagation and post-fracturing evaluation. For instance, a set of acoustic system with 16 AE channels in total was adopted in the tests, and 12 sets of passive acoustic transducers with diameter of Φ22 mm × 36.8 mm were positioned on the three sides of blocks, which could real time acquire microsesmics (MS) events during the fracture initiation and propagation in the tests.

The fresh outcrop of shale collected in the field was from rich organic contained Longmaxi shale, Sichuan Basin, China. After that, the samples were prepared for the staged fracturing tests in the lab, and some cores were sampled for rock mechanic tests, Table 1 lists the basic rock mechanics parameters of rock samples.

Two Φ25 mm holes were drilled in the center of surface 300 mm × 300 mm of each sample, in which there were two notches rings, two casing tubing in the hole. In further, two notch rings were slotted in each sample with Φ30 mm and width of 1 mm for getting easy fracture initiation. After that, two casing tubing with an internal Φ20 mm were epoxied into two wellbore of each sample. The notch distance was pre-set as 80 mm, 120 mm, 160 mm, 200 mm respectively, for simulating engineering parameter of perforation spacing or cluster spacing.

2.2. In-situ stresses simulation

One key point of the experiments of hydraulic fracturing is stresses setup. Some researcher indicated that a straight main fracture is easily formed in the condition of a high coefficient of horizontal stress difference K_h, which is defined as[6]

$$K_h = \frac{\sigma_H - \sigma_h}{\sigma_h} \tag{1}$$

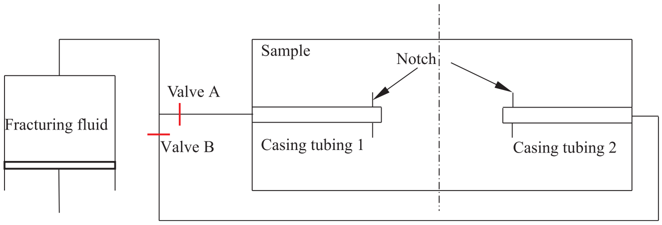

Fig. 1. Schematic positions of notches, and casing tubing for each rock sample.

The stress differential coefficient of Fuling Longmaxi shale in certain formation is about 0.15. Therefore, in our tests, the maximum stress is vertical, the constant value of σ_v is 8 MPa, meanwhile the horizontal stresses is 6 MPa and 5.22 MPa, respectively, which means that the coefficient of horizontal stress difference K_h coincides with the above Longmaxi shale formation, Sichuan Basin. With this level of stress, we can also ensure open discontinuity in the model block during the injection tests.

2.3. Procedure

High viscous gel was still used for the fracturing tests in shale, even though slickwater with much lower viscosity is widely used in field of shale for staged fracturing. First of all, due to scaling law, the fluid viscosity used in the lab should be much higher than that of used in the field for acquiring stable fracture propagation during the tests. Secondly, we expect to reduce "interaction effect of edge" maximally, so that the high viscous gel was used instead of low viscous slickwater. At last, the injection rate of the facility could not perform as high as that of used in the field, as a result, it is very difficult for fracture initiation in shale if the low viscous slickwater is used in the tests.

In this case, a fracturing fluid with the viscosity of 90 mPa·s used and several injection rates are also adopted in the tests. In terms of tracer, a green tracer was added in the fracturing fluid for a better analysis of fracture geometry during block excavation. Table 2 indicates the experimental conditions in the tests, including notch number, injection rate, the viscosity of fluid, stresses.

For ensuring multi fracture initiation from two notches during the tests, an optimized injection procedure was designed and executed using valves of A and B (Fig. 1) as following steps.

Step 1, open valve A and B simultaneously, start fluid injection. In this case, the fracturing fluid is injected into two notches. When the

Table 2
Experimental conditions in the tests.

Number	Notch number	injection rate mL/s	Viscosity in 25 °C mPa s	Notch distance mm	σ_V MPa	σ_H MPa	σ_h MPa	K_h $(\sigma_H\text{-}\sigma_h)/\sigma_h$
Y-2–1	two	0.5	90	120	8	6	5.22	0.15
Y-2–2	two	0.5	90	120	8	6	5.22	0.15
Y-2-3	two	0.5	90	120	8	6	5.22	0.15
Y-3-1	two	0.1	90	200	8	6	5.22	0.15
Y-3-2	two	0.2	90	200	8	6	5.22	0.15
Y-4-1	two	2.0	90	160	8	6	5.22	0.15
Y-1-1	two	2.0	90	80	8	6	5.22	0.15
Y-4-2	two	0.1	90	160	8	6	5.22	0.15
Y − 1-2	two	0.1	90	80	8	6	5.22	0.15
Y − 2-4	two	0.1	90	120	8	6	5.22	0.15