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Shuhui Zhang, Xiao Li, and Quanchen Gao

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Experimental study on shale fracturing effect and fracture mechanism under different fracturing fluid viscosity: A case study of Guanyinqiao Member shale in Xishui, Guizhou, China

Shuhui Zhang,1,a) Xiao Li,2 and Quanchen Gao1

AFFILIATIONS
1School of Mechanics and Civil Engineering, China University of Mining and Technology (Beijing), Beijing 10083, China
2Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

a)Author to whom correspondence should be addressed: zhbeyond@126.com

ABSTRACT
In this study, a series of laboratory fracturing experiments were conducted on samples mined from reservoirs of the Guanyinqiao Member shale in Xishui County, Guizhou Province, using a traditional triaxial fracturing simulation system. Based on the experimental results, the breakdown pressure and effective stimulated reservoir volume were obtained for four fracturing fluids (supercritical carbon dioxide, water, NO-sand, and sand). The fracture mechanism was then analyzed using acoustic emission monitoring data. Based on the curves of pressure vs injection time for different fracturing fluids, the breakdown pressure increased with increasing fracturing fluid viscosity. When sands with different viscosities were used as the fracturing fluid, the breakdown pressure first increased and then decreased with an increase in the sand viscosity. The distribution of the tracer or proppant was not only correlated with the fracturing effect, but also promotes the filling crack of the tracer and proppant at a certain viscosity as the best fracturing effect. During sand fracturing, the proppant mainly formed shear cracks. The results provide a valuable technical reference for shale gas mining.

I. INTRODUCTION
Shale reservoirs are characterized by low porosity, low permeability, high brittleness, strong heterogeneity, bedding, and natural fracture development. Shale reservoirs generally do not exhibit natural productivity, and commercial development potential is only achieved through large-scale fracturing transformation, which forms a certain stimulated reservoir volume (SRV). Therefore, hydraulic fracturing stimulation is essential for producing oil and gas in an economical way. Recently, supercritical carbon dioxide (SC-CO2) was proposed as a fracturing fluid because of its particular physical and chemical properties. Many scholars have studied the initiation and propagation mechanisms of fractures through physical experiments, numerical simulations, and analytic approaches. Zhang et al. investigated fracture initiation and propagation in shale subjected to SC-CO2 fracturing and concluded that the use of SC-CO2 compared to water reduced the pressure needed to initiate fractures and resulted in the formation of numerous crooked fractures and abundant secondary fractures. Ma et al. revealed the acoustic emission (AE) response characteristics of the hydraulic fracture propagation. The authors compared the fracture propagation geometry obtained by specimen splitting and computed tomography (CT) scanning with the AE monitoring results and discussed the difference in the hypocenter mechanism between hydraulically connected...
and unconnected regions. Based on AE monitoring and hydraulic fracturing experiments with SC-CO\textsubscript{2} and liquid CO\textsubscript{2}, Ishida \textit{et al.}\textsuperscript{5} showed that the wavelike fractures induced in granite samples by SC-CO\textsubscript{2} were thinner and had more branches than those induced by liquid CO\textsubscript{2}. Lou and Zhang\textsuperscript{8} studied the initiation and propagation of hydraulic cracks under cyclic stress conditions using indoor hydraulic fracturing tests with different fracturing fluid viscosities.

In the present study, laboratory fracturing tests were conducted to evaluate the initiation and propagation mechanisms of fractures. Few studies have focused on the fracturing effect and fracture mechanism under different fracturing fluid viscosities. The aim of this study was to investigate the differences and similarities in fracture propagation among SC-CO\textsubscript{2} fracturing, hydraulic fracturing, and sand fracturing. The fractures in the specimens were monitored by AE during the experiments to explore the effects of the fracturing fluid viscosity on the effective SRV (SRVe) and fracture mechanism.

II. EXPERIMENTAL PREPARATION

A. Shale samples

Shale samples were collected from the outcrop near the scientific research well named K3. The K3 well (28° 32′ latitude and 106° 22′ longitude) is located in Xishui County, Guizhou Province, and is part of a special shale gas project of the Institute of Geology and Geophysics, Chinese Academy of Sciences. The mineral components of the shale samples mainly included quartz, white mica, cristobalite, and clay minerals consisting of illite, montmorillonite, and albite with a small quantity of pyrite and organic matter. Quartz accounted for ∼51.29%–58.34% of the mineral content, while the contents of the calcite and albite were negligible. The shale samples contained a small amount of indistinguishable amorphous material. According to the evaluation method of Rickman \textit{et al.},\textsuperscript{9} the shale has a high brittleness index. The following basic mechanical parameters were obtained via uniaxial compression tests: compressive strength = 89.7 MPa; elastic modulus = 36.4 GPa; and Poisson’s ratio = 0.23.

After the rock cores were obtained from the site, they were intercepted and ground into regular cylindrical samples with diameters of 100 mm and heights of 200 mm. Holes with diameters of 10 mm and depths of 100 mm were drilled in the centers of the cylindrical samples to simulate fracturing wellbores. A 100-mm bare section on each sample was reserved to simulate the open-hole completion. Schematic diagrams showing the sample dimensions and the direction of the applied stress in experiments are shown in Fig. 1.

| Sample name | Stress (MPa) | Fracturing fluid | Injection rate (ml/min) | Viscosity (mPa s) |
|-------------|--------------|------------------|-------------------------|------------------|
| G1          | 15           | SC-CO\textsubscript{2} | 40                     | 0.05             |
| G2          | 15           | Water            | 40                     | 0.8              |
| G3          | 15           | NO-sand          | 40                     | 50               |
| G4          | 15           | Sand             | 40                     | 100              |
| G5          | 15           | Sand             | 40                     | 200              |

FIG. 1. Schematic diagrams showing the dimensions of each sample (a) and the direction of the applied stress (b). \(\sigma_v\) indicates the axial pressure and \(\sigma_H\) indicates the confining pressure.
B. Experimental design

This study mainly focused on the effects of the fracturing fluid viscosity. Thus, the fracturing test was designed to be performed with fracturing fluids possessing different viscosities. The six test specimens were divided into four groups based on the type of fracturing fluid (Table I). The viscosity of the fracturing fluid depends on the ratio of guar to water. The proppant content, which is the ratio of the mass of quartz sand (200 mesh in diameter) to the mass of water, was 5% in this study. The fracturing fluids were selected to evaluate the fracturing effect and fracture mechanism under hydraulic fracturing (water), SC-CO₂ fracturing (SC-CO₂), and sand fracturing (NO-sand and sand with three different viscosities). The experimental equipment, which included an AE system, is schematically shown in Fig. 2.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Breakdown pressure

The accurate prediction of the breakdown pressure is important for the design of fracturing schemes and for the selection of fracturing equipment and materials. The fracturing experiments in this study were conducted on Guanyinqiao Member shale samples using fracturing fluids with different viscosities (Table I): SC-CO₂, water, NO-sand, and sands with three different viscosities. Figure 3 shows the curves of pressure vs injection time under different fracturing fluids. As shown in Fig. 3(a), for different types of fracturing fluids, the breakdown pressure increased as the viscosity of the fracturing fluid increased. For the same type of fracturing fluid with different viscosities (i.e., sand with viscosities of 50 mPa s, 100 mPa s,
and 200 mPa s), the breakdown pressure first decreased and then increased with increasing viscosity [Fig. 3(b)], with the minimum breakdown pressure occurring at the viscosity of 100 mPa s. To understand the observed differences in the breakdown pressure, it is necessary to study the fracture mechanism, which can differ based on the fracturing fluid used.

**B. Effective stimulated reservoir volume**

In shale fracturing experiments, the communication of the main fracture is an important factor for evaluating hydraulic fracturing. Based on the microseismic mapping results, Ma et al. estimated the hydraulic fracturing SRV in a random naturally fractured and laminated block. In this study, two parameters, SRV and SRVe, were employed to quantitatively evaluate the fracturing effectiveness. SRV is defined as the envelope volume of all AE events, as illustrated in Fig. 4. Meanwhile, SRVe is defined as the volume of the red tracer when the fracturing fluid is SC-CO\textsubscript{2}, water, or NO-sand or the volume of the white proppant when the fracturing fluid is sand (Fig. 4).

As shown in Fig. 5, the fracture width was measured at all specified locations, and the average width was calculated. Based on the AE results, SRV was calculated using the contour envelope method, in which SRV is defined as the envelope volume of all AE events (Fig. 6). The area was determined using a three-dimensional scanner based on the distribution of the red tracer or proppant after fracturing. As illustrated in Fig. 4, the calculation of SRVe was divided into three parts: first, the area of the red tracer or proppant distribution was sprayed with the developing agent; second, these areas were scanned with the three-dimensional scanner; and finally, Geomagic Studio software was used to calculate the area.

To better quantitatively analyze the effect of fracturing on the distribution of the red tracer or proppant, the coefficient $\lambda$ was introduced as follows:

$$\lambda = \frac{\text{SRVe}}{\text{SRV}}.$$ (1)
A larger $\lambda$ value indicates a better fracturing effect, while a larger SRVe value corresponds to more effective fracturing stimulation.

Many scholars\textsuperscript{12} have shown that low-viscosity fracturing fluids produce better fracturing effects than high-viscosity fracturing fluids across fracturing fluid types, in agreement with the results obtained for samples G1, G2, and G3 (Table II). However, for sand with different viscosities, the low-viscosity sand did not produce better hydraulic cracking than the high-viscosity sand. To explain this phenomenon, Sec. III C presents an analysis of the fracture mechanism.

| Sample no. | SRV (mm$^3$) | SRVe (mm$^3$) | $\lambda$ |
|------------|--------------|--------------|-----------|
| G1         | 981.6        | 858.3        | 0.87      |
| G2         | 862.5        | 683.8        | 0.79      |
| G3         | 833.4        | 590.7        | 0.71      |
| G4         | 1008.4       | 759.4        | 0.75      |
| G5         | 1517.2       | 1274.5       | 0.84      |
| G6         | 1384.6       | 1020.2       | 0.74      |

FIG. 7. Classification of cracks based on AE localization in samples (a) G1, (b) G2, (c) G3, (d) G4, (e) G5, and (f) G6. The red dots, green dots, and black dots indicate tensile, shear, and mixed-mode cracks, respectively.
C. Analysis of failure mechanism

The self-returning model and Akaike’s information criterion were used to identify the signal arrival time, while the simplex method was used to calculate the AE event. Based on the AE localization results, the AE focal mechanism was analyzed using moment tensor theory with a Green’s function. For the signal monitored by AE, the initial amplitude of the signal $A(x)$ can be expressed as

$$ A(x) = \frac{C_r \text{Ref}(t,r)}{R} \left( \begin{array}{c} r_1 \\ r_2 \\ r_3 \end{array} \right) \times \left( \begin{array}{ccc} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & m_{33} \end{array} \right) \left( \begin{array}{c} r_1 \\ r_2 \\ r_3 \end{array} \right), \tag{2} $$

where $C_r$ is the calibration coefficient of the AE sensor, $R$ is the distance between the AE source at point $y$ and the sensor located at point $x$, $\text{Ref}(t,r)$ is the reflection coefficient between the vector $r$ and the direction $t$ of the sensor sensitivity, and $C_r$ is a calibration coefficient. The value of $C_r$ in this study was relative since the main concerns in this study were crack classification and orientation.

Since the moment tensor is symmetric, six independent unknown $M$ must be solved. Thus, multichannel observations of the first motions at more than six channels were required to determine the moment tensor components. The crack type can be determined from the eigenvalue analysis of the moment tensor,

$$ \begin{align*}
\lambda_1/\lambda_1 &= X + Y + Z, \\
\lambda_2/\lambda_1 &= 0 - 0.5Y + Z, \\
\lambda_3/\lambda_1 &= X - 0.5Y + Z,
\end{align*} \tag{4} $$

where $\lambda_1$, $\lambda_2$, and $\lambda_3$ are the maximum, intermediate, and minimum eigenvalues, respectively, $X$ is the shear ratio, $Y$ is the deviatoric tensile ratio, and $Z$ is the isotropic tensile ratio.

Considering the accuracy of the SiGMA procedure, Ohtsu classified AE sources as follows: $X > 60\%$, shear crack; $X < 40\%$ and $Y + Z > 60\%$, tensile crack; and $40\% < X < 60\%$, mixed-mode crack.

The proportions of different crack types in the samples determined based on the AE location results (Fig. 7) are listed in Table III. As shown in Table III, the proportion of tensile cracks was relatively large when the fracturing fluid was SC-CO$_2$, water, or NO-sand. Comparing samples G2 with G3, indicating a larger viscosity resulted in a greater proportion of tensile cracks, larger breakdown pressure, and smaller $\lambda$. As shown by the results obtained for samples G3 and G4, the presence of the proppant in the fracturing fluid increased the proportion of shear cracks. When the fracturing fluid was sand (samples G4, G5, and G6), the proportion of shear cracks first increased and then decreased as the viscosity increased; among these samples, the proportion of shear cracks and $\lambda$ were maximized when the sand viscosity was 100 mPa s, while the breakdown pressure was minimized.

IV. CONCLUSIONS

Laboratory fracturing experiments were conducted with fracturing fluids possessing different viscosities under real-time AE monitoring, and the effects of the fracturing fluid viscosity on the breakdown pressure and SRV$_e$ were evaluated. Moreover, the fracture mechanism was studied in detail based on the AE monitoring data. The main conclusions can be summarized as follows:

1. Increasing the viscosity of the fracturing fluid was unfavorable for decreasing the breakdown pressure necessary to form the fracture network. Among the fracturing fluids considered (SC-CO$_2$, water, NO-sand, and sand), SC-CO$_2$ resulted in the lowest breakdown pressure. When sands with different viscosities were used as the fracturing fluid, the lowest breakdown pressure was obtained when the viscosity was 100 mPa s.
2. The fracturing effect and fracture distribution were analyzed based on the calculated values of SRV$_e$ and $\lambda$. Under the same fracturing conditions, the largest $\lambda$ value was obtained for sample G1, indicating the best fracturing effect, followed by sample G5.
3. To better understand the observed trends in the breakdown pressure and $\lambda$, the fracturing mechanism was evaluated for different fracturing fluid viscosities based on the AE monitoring data. The spatial distributions and focal mechanisms of AE events were consistent with the ultimate failure modes of the rock samples. Thus, AE monitoring is an effective method for analyzing the fracture mechanism and can be applied in more detailed research on the shale fracturing process.

NOMENCLATURE

| AE | acoustic emission |
| SC-CO$_2$ | supercritical carbon dioxide |
| SRV | stimulated reservoir volume |
| SRV$_e$ | effective stimulated reservoir volume |

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