Analysis of Hydraulic Fracture Morphology and Propagation under Different Perforation Azimuth Angles

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Abstract. Perforation azimuth has an important influence on the nucleation, propagation path and morphology of hydraulic fractures. In this paper, the true triaxial hydraulic fracturing simulation experimental system is used to analyze the hydraulic fracture morphology and propagation path under different perforation azimuth angles. With the increase of the azimuth angle of perforation, the stable fracture propagation pressure of the fracturing sample also increases. When the azimuth angle of perforation is 0°, the propagation pressure is about 18 MPa, and when the azimuth angle of perforation is 90°, the propagation pressure is about 26.5 MPa, increasing by nearly 47.22%.

Keywords: Perforation Azimuth, Fracture Morphology, Propagation Path, Hydraulic Fracturing Simulation.

1. Introduction
Fuyu reservoir is a tight reservoir. In the development process, it is easy to have poor receiving efficiency of oil well, high pressure of water well and poor water absorption, so it is difficult to establish effective drive [1-4]. Therefore, the primary problem for the efficient development of Fuyu reservoir is to establish a set of matching well completion technology according to the geological properties of the block, improve the seepage capacity of the reservoir, and guide the subsequent development of Fuyu block [5-8]. Due to the small scale of field test in the development of Fuyu reservoir, the immaturity of well pattern deployment in the well area, and the limitation of geological understanding and technological conditions at that time, there is a lack of guidance for the completion development of Fuyu reservoir under the current well pattern condition [9-12]. This study is mainly aimed at exploring the matching well completion technology of Fuyu reservoir under the condition of current well pattern and completion technology.

After fracturing, artificial fractures generally extend along the maximum aclinic principal stress in Fuyu reservoir. The selection of perforating parameters has a certain impact on the fracture pressure and the initial fracture morphology [13, 14]. Reasonably formulating perforating parameters is helpful to reduce the fracture pressure and improve the fracture morphology. At present, no relevant research has been carried out in Xingbei Development Zone. The reasonable perforation parameters of Fuyu reservoir need to be programmed and verified.
2. Experimental Equipment and Scheme

2.1 Experimental Equipment
The true triaxial hydraulic fracturing simulation experimental system was used in this experiment (Fig. 1). The equipment loads the cube sample in the true triaxial loading way to simulate the aclinic maximum principal stress, aclinic minimum principal stress and vertical stress in the stratum, which can reflect the actual stress situation in the stratum more truly.

![Figure 1. Hydraulic fracturing simulation experimental system](image)

2.2 Experimental Scheme
Under the condition of directional perforation fracturing, this test plan intends to use the true triaxial hydraulic cracking simulation experimental system to analyze the initiation and extension of hydraulic cracks in artificial cores under different perforation azimuth angles and aclinic stress differences. Red impermeable dye, which will not change the performance of the fracturing fluid, was added to the fracturing fluid before the experiment to make the propagation path of the fracture more obvious.

| Sample number | In-situ stress (σv/σH/σh)/MPa | aclinic stress difference /MPa | perforation depth /mm | fracturing fluid viscosity /mPa·s | fracturing fluid displacement /mL·min⁻¹ | perforation azimuth (/°) |
|---------------|--------------------------------|-------------------------------|-----------------------|-----------------------------------|----------------------------------------|-------------------------|
| S-1           | 34/32.9/26.5                  | 5.4                           | 2                     | 4                                 | 5                                      | 0                       |
| S-2           | 34/32.9/26.5                  | 5.4                           | 2                     | 4                                 | 5                                      | 30                      |
| S-3           | 34/32.9/26.5                  | 5.4                           | 2                     | 4                                 | 5                                      | 60                      |
| S-4           | 34/32.9/26.5                  | 5.4                           | 2                     | 4                                 | 5                                      | 90                      |

In order to explore the angle relationship between perforation orientation and aclinic maximum principal stress direction and the influence of aclinic stress difference on hydraulic fracture extension shape, simulated wellbore with different perforation parameters was preset in the sample (Table 1). Considering the size of the sample and the expansion space of the fracture, the machining specifications of the simulated wellbore were: outer diameter 12mm, inner diameter 10mm. The bottom of the wellbore is closed, and the internal thread at the upper end is sealed and connected to the fracturing fluid pumping pipeline. Z1Z-FFO2-250 diamond drilling machine was used to drill holes with different combinations of perforation parameters on the fracturing pipe to preset the simulated wellbore. In order to prevent the cement slurry from flowing into the wellbore, the perforation holes should be sealed with absorbent paper before presetting. In the experiment, the azimuth angles of perforations were set at 0°, 30°, 60°, and 90° respectively. Aclinic stress is set according to the actual block, and the aclinic differential stress is 0 MPa, half of the actual value or consistent with the actual value. The cracking fluid viscosity is 4
MPa·s, and the fracturing displacement is 5mL·min⁻¹ (as shown in Table 1-1). Hydraulic cracking simulation is carried out on the directional perforated artificial cores respectively to study the initiation and extension of fractures under different perforation azimuth angles and aclinic stress differences.

3. Result
After the completion of hydraulic fracturing of artificial samples, the morphological characteristics of hydraulic fractures can be observed by cutting the samples. The fracture propagation path after hydraulic fracturing experiment can be judged according to the depth of stain and the pump pressure-time curve. According to the morphology characteristics and corresponding propagation mechanism of hydraulic fractures under different perforation parameters, the fracture propagation law can be obtained.

(1) Sample S₁
After hydraulic fracturing test, the S₁ sample was cut along the surface fractures, and two symmetrical hydraulic cracks were formed, which started on the two wings of directional perforation and extended along the orientation of perforation to the contact of the artificial sample. Classical rock mechanics studies show that hydraulic fractures always extend along the direction of the maximum principal stress, or perpendicular to the direction of the minimum principal stress. In sample S₁ (Fig. 2), the initiation direction of hydraulic fractures is consistent with the orientation of the maximum aclinic principal stress, and the two fractures extend symmetrically on both sides of the simulated wellbore, presenting a flat, elliptical and symmetrical two-wing fracture.

(2) Sample S₂
In the fracturing process of sample S₂ (Fig. 3), after the initiation of the two wings of the perforation hole, the hydraulic fractures first extend along the direction of the perforation, then turn, and finally extend along the orientation of the maximum aclinic principal stress to the sample border, showing the "S" shape distribution of the two-wing fracture surface. Compared with S₁ sample, S₂ specimen has an azimuth Angle of 30°, but the fracture eventually expands along the direction of the maximum aclinic principal stress, so there is an obvious turning after the crack initiation, and the fracture plane area is larger.

(3) Sample S₃
The fracture propagation pattern of the S₃ sample is similar to that of the S₂ sample (Fig. 4). The hydraulic fractures all start from both sides of the perforation and extend initially along the orientation of the perforation, and then deflect along the orientation of the maximum aclinic principal stress.
However, according to the hydraulic fracturing morphology and fracture morphology diagram of the sample, it can be seen that with the increase of the fracture deflection angle, the fracture length decreases significantly, and the fracture width increases. Finally, the two-wing fracture also presents an "S" shape.

\[ \text{Figure 4. Fracture morphology of Sample S-3 after fracturing} \]

(4) Sample S-4

In S-4, hydraulic fractures begin on both sides of the perforation, propagate in the direction of the perforation, and then deflect slightly (Fig. 5). In S-4, the orientation of the crack perforation is perpendicular to the orientation of the maximum aclinic principal stress. When the fracture expands for a certain distance, since not all parts of the sample have the same material properties and there may be small bubbles, the stress of the sample is unbalanced, and the crack propagation begins to deflect. Compared with the samples S-2 and S-3, the fracture propagation area is greatly reduced, showing a small angle of "S" distribution, and the fracture does not extend to the aclinic boundary of the sample, but extends to the upper and lower boundary.

\[ \text{Figure 5. Fracture morphology of Sample S-4 after fracturing} \]

4. Discussion and Conclusion

According to the curve of the change of fracture initiation pressure and expansion pressure with the perforation azimuth, with the aggrandize of the perforation azimuth, the fracture initiation pressure of the fracturing sample also increases. When the perforation azimuth is 0°, the fracture initiation pressure of the sample is 28.53MPa, while when the perforation azimuth is 90°, the fracture initiation pressure reaches 38.16MPa, an increase of 33.75%. Analysis considered due to the expansion of fractures in the process, in parallel to the orientation of the maximum aclinic in-situ stress broken hole in the wall of least resistance, the required minimum burst pressure, and increase along with the perforation azimuth, fracture extension of braking action by maximum aclinic principal stress, pressure of formation energy, the more the crack the greater the pressure.

With the increase of the azimuth angle of perforation, the stable fracture propagation pressure of the fracturing sample also increases. When the azimuth Angle of perforation is 0°, the propagation pressure is about 18MPa, and when the azimuth Angle of perforation is 90°, the propagation pressure is about 26.5MPa, increasing by nearly 47.22%. The analysis shows that the fracture propagation deflects due to the increase of perforation orientation. Due to the effect of aclinic principal stress, the energy consumed by the fracture propagation in this process increases, and the extension pressure required for the fracture propagation also increases.
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