

## Research Article

# Experimental Study of Hydraulic Fracture Propagation Behavior during Multistage Fracturing in a Directional Well

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Due to the limited space of offshore platform, it is unable to implement large-scale multistage hydraulic fracturing for the horizontal well in Lufeng offshore oilfield. Thus, multistage hydraulic fracturing technology in directional well was researched essentially to solve this problem. Modeling of fracture propagation during multistage fracturing in the directional and horizontal wells in artificial cores was carried out based on a true triaxial hydraulic fracturing simulation experiment system. The effects of horizontal stress difference, stage spacing, perforation depth, and well deviation angle on multifracture propagation were investigated in detail. Through the comparative analysis of the characteristics of postfrac rock and pressure curves, the following conclusions were obtained: (1) multistage fracturing in horizontal wells is conducive to create multiple transverse fractures. Under relatively high horizontal stress difference coefficient (1.0) and small stage spacing conditions, fractures tend to deflect and merge due to the strong stress interference among multiple stages. As a consequence, the initiation pressure for the subsequent stages increases by more than 8%, whereas in large stage spacing conditions, the interference is relatively lower, resulting in the relatively straight fractures. (2) Deepening perforation holes can reduce the initiation pressure and reduce the stress interference among stages. (3) When the projection trace of directional wellbore on horizontal plane is consistent with the direction of the minimum horizontal principal stress, fractures intersecting the wellbore obliquely are easily formed by multistage fracturing. With the decrease of well deviation angle, the angle between fracture surface and wellbore axis decreases, which is not conducive to the uniform distribution of multiple fractures. (4) When there is a certain angle between the projection trace of directional wellbore on horizontal plane and the direction of minimum horizontal principal stress, the growth of multiple fractures is extremely ununiform and the fracture paths are obviously tortuous.

## 1. Introduction

With the development of unconventional oil and gas reservoirs and the advancement of technology, directional wells, horizontal wells, and multistage fracturing technology are combined to increase the drainage area of the reservoir, hence to improve oil recovery and economic benefits. Currently, multistage fracturing is the main stimulation technology for unconventional resources; the principle of which is to enlarge the oil and gas discharge area by forming dense transverse fractures that are perpendicular to the wellbore [1–4]. However, due to the limited area of offshore plat-

forms, high equipment operating costs, and high operational safety risks, it is difficult to apply mature onshore staged fracturing technologies to offshore oilfields. Meanwhile, the development of offshore horizontal staged fracturing technologies is far behind that of onshore oilfields [5]. In order to adapt to the characteristics of offshore platforms and treat more production zones at the same time, the research on multistage fracturing technology in directional wells is of great importance.

Series of theoretical studies on hydraulic fracture initiation and propagation in directional wells have been conducted [6–10]. The models of stress distribution near the

wellbore of directional wells under different conditions have been established, and formulas of fracture initiation pressure and fracture initiation angle have been deduced. Zhou et al. [11] proposed the prediction model of fracture initiation by establishing the distribution model of stress field in the surrounding rock of directional wellbore and pointed out that the initiation mode of hydraulic fractures was affected by the azimuth of wellbore, in situ stress difference, and well deviation angle. Since the hypotheses of theoretical researches often somewhat differ from the actual conditions and studies of fracture propagation morphology are usually based on simplified two-dimensional or three-dimensional models, the results obtained have limitations to a certain degree. In addition to the theoretical model research, the physical simulation experiment is also an important means to study fracture initiation and propagation. Physical hydraulic fracturing simulation experiments of directional wells conducted by domestic and foreign scholars showed [12–17] that the controlling factors of hydraulic fracture initiation in directional wells mainly include well deviation angle, borehole azimuth, horizontal stress difference, and perforation parameters, and the fracture propagation is easy to deflect to produce complex forms. However, the earlier experiments mainly focused on the study of a single fracture in directional wells and did not take into account the interaction of simultaneous propagation of multiple fractures in directional wells. Many studies have shown that multifracture propagation tends to be unbalanced [4] due to the influence of (1) reservoir characteristics such as natural fractures, in situ stress distribution, and rock mechanical properties, (2) well completion factors such as stage spacing and cluster spacing, (3) perforation parameters, and (4) stress interference between fractures. The smaller the cluster spacing, the stronger the “stress shadow” effect between fractures, and the greater the influence on fracture propagation and fracture width [18–27]. In addition, some scholars established a finite element model for directional well fracturing based on the basic finite element theory and studied the propagation morphology of single fracture under uneven confining pressure [28, 29]. Although many theoretical and experimental studies have been carried out on hydraulic fracture initiation and propagation in directional wells and horizontal wells, most of the physical simulation experiments on fracture initiation and propagation in directional wells were carried out under the condition of single-fracture or multifracture fracturing in a single stage, and there were few studies on the fracture propagation of multistage fracturing in directional wells. Therefore, the propagation morphology of fractures formed in multistage fracturing under stress interference among stages in directional wells was not taken into account, and treating parameter optimization of multistage fracturing in directional wells still lacks direct experimental evidence.

To shed a light on the problem mentioned above, this paper presents the physical simulation research of staged fracturing and multifracture propagation in horizontal and directional wells using the true triaxial hydraulic fracturing physical simulation experiment system. Then, we compared and analyzed the influence factors that affect multifracture

initiation and propagation of two types of wells. The effects of horizontal stress difference, perforation depth, stage spacing, well deviation angle, and wellbore azimuth (the angle between projection of wellbore axis in the horizontal plane and the direction of maximum horizontal principal stress) on fracture propagation morphology and pressure curve characteristics of multistage fracturing were considered.

## 2. Experimental Method

*2.1. Sample Preparation.* The research area is located in the south of Lufeng Sag of Zhu I Depression, Pearl River Mouth Basin, South China Sea. The facies of research formation are shallow shore lake and braided river delta, with buried depth of 3563–4272 m. The reservoir varies greatly in vertical and horizontal directions, including silty mudstone, siltstone, and fine sandstone, with strong heterogeneity. The reservoir rocks have elastic modulus of 21.3–34.4 GPa, Poisson’s ratio of 0.18–0.31, tensile strength of 2.1–4.6 MPa, maximum horizontal principal stress of 78.4–86.6 MPa, and minimum horizontal principal stress of 64.1–70.3 MPa.

The experimental samples were cement cubes (G grade cement, quartz sand, and water in a 3 : 1 : 1 ratio) with a side length of 30 cm (Figure 1(a)). The physical properties were similar to those of the reservoir lithology. The wellbores were prefabricated in the cement. Each wellbore was divided into three sections (one perforation cluster in each section and four perforations in each cluster) to facilitate staged fracturing in horizontal and directional wells [4]. Since the size of the core samples and wellbores was limited and the effect of stress interference among stages on fracture propagation morphology can be reflected by the model with single cluster in each stage, the design of single cluster in each stage was adopted. Each wellbore was composed of three parts: outer casing, inner wellbore, and fluid injection pipelines. The inner wellbore was a steel pipe with an outer diameter of 1.5 cm, an inner diameter of 0.8 cm, and a length of 20.0 cm. The outer casing was a steel pipe with an outer diameter of 2.0 cm, an inner diameter of 1.6 cm, and a length of 20.0 cm, and a certain number of thread grooves were processed on its outer surface to strengthen the bond between the casing and cement. Four drain holes with a diameter of 3 mm were drilled on the outer casing in each section. A steel tube with the same diameter as the holes was welded perpendicularly at the position of each hole to simulate the perforation process. The annulus of each stage was sealed off with a gasket to simulate stage packer. Each stage in the inner wellbore was sealed by a steel plate and linked with an injection line which connected to an individual intermediate vessel. A six-way valve was connected between the injection lines and three intermediate vessels to control the injection. The staged fracturing can be achieved by operating the valves to have one injection line and one intermediate vessel connected at one time, while keeping the others closed.

Figures 1(b) and 1(c) show the layout of horizontal and directional wellbores inside the sample, respectively. The well deviation angle ( $\alpha$ ) is the angle between the axis of the wellbore and the direction of overburden stress ( $\sigma_v$ ), and

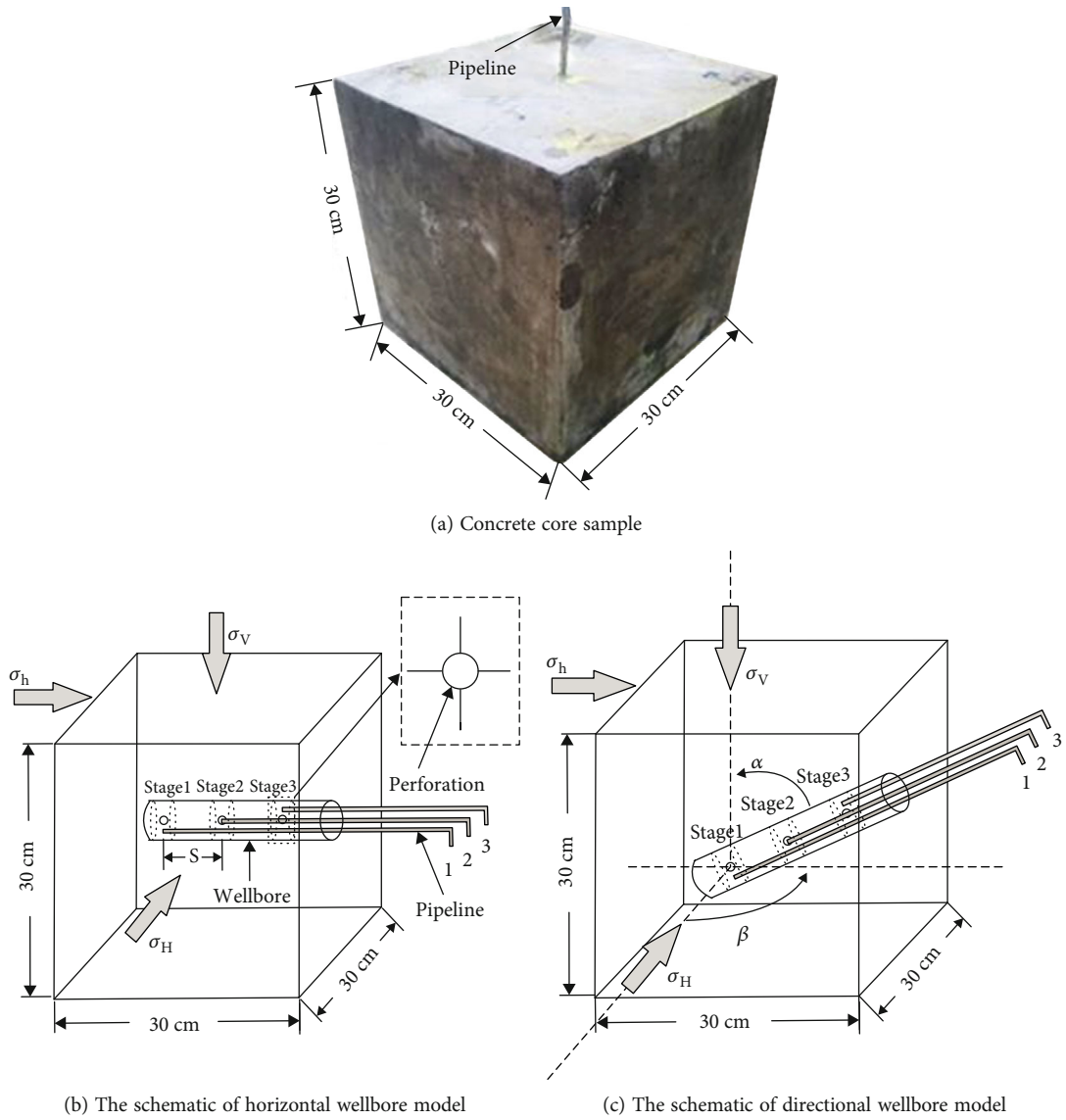


FIGURE 1: Concrete artificial core sample and well type.

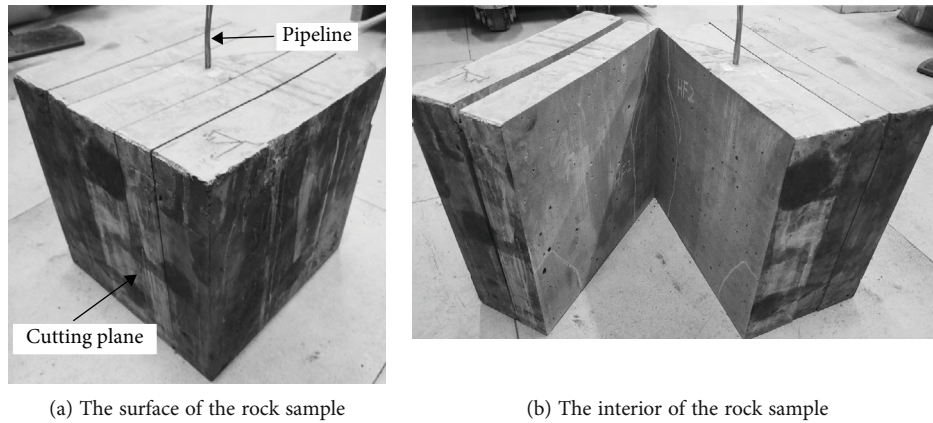


FIGURE 2: Rock specimen dissection after fracturing.

TABLE 1: Experimental parameter settings.

Sample number	In situ stress state				Stage spacing (cm)	Perforation depth (cm)	Well type	Deviation angle (°)	Azimuth angle (°)
	$\sigma_v$ (MPa)	$\sigma_H$ (MPa)	$\sigma_h$ (MPa)	$K_h$					
1	20.0	10.0	8.0	0.25	2.0	5.0	Horizontal	90	90
2	20.0	10.0	8.0	0.25	5.0	1.0	Horizontal	90	90
3	20.0	16.0	8.0	1.0	2.0	1.0	Horizontal	90	90
4	20.0	10.0	8.0	0.25	2.0	1.0	Directional	60	90
5	20.0	10.0	8.0	0.25	2.0	1.0	Directional	30	90
6	20.0	10.0	8.0	0.25	2.0	1.0	Vertical	0	90
7	20.0	10.0	8.0	0.25	2.0	1.0	Directional	30	60
8	20.0	10.0 <td 8.0	0.25	5.0	1.0	Directional	30	60	

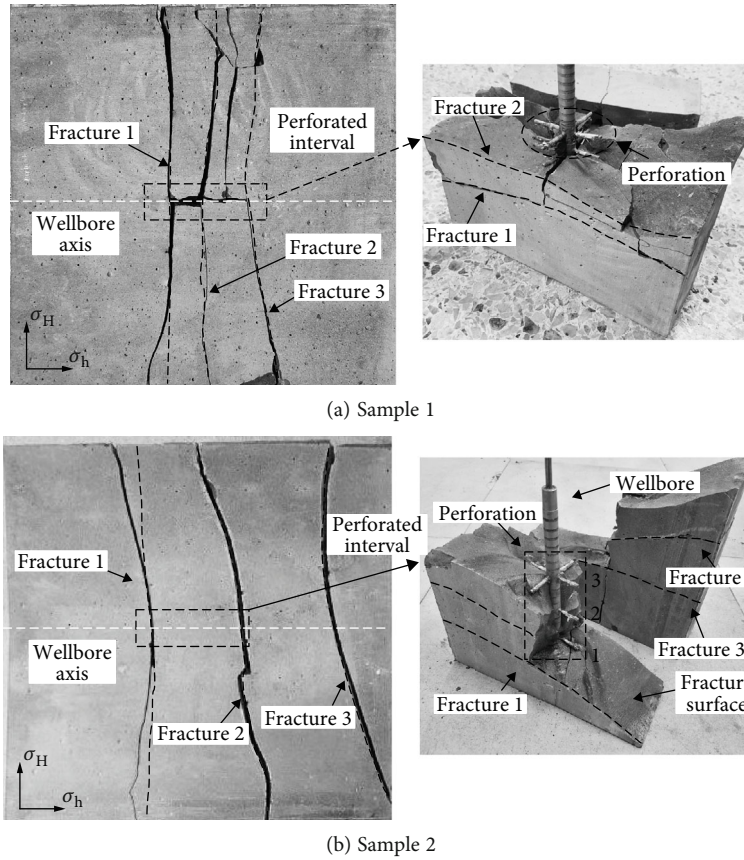


FIGURE 3: Fracture morphology for horizontal well under different stage spacing and perforating depth (samples 1 and 2).

the azimuth ( $\beta$ ) is the angle between the projection trace of the wellbore on horizontal plane and the direction of maximum horizontal principal stress ( $\sigma_H$ ). The deviation angle of horizontal wells was  $90^\circ$ , and the azimuth was set at  $90^\circ$ . The deviation angle of directional wells varied from  $0^\circ$  to  $90^\circ$ , and the azimuths were  $60^\circ$  and  $90^\circ$ .

**2.2. Experimental Procedures and Parameters.** A true triaxial hydraulic fracturing simulation system was used in fracturing experiments [4]. The experimental steps included the following. (1) Place the sample into the sample chamber in

the preset direction and use hydraulic pump set to apply triaxial stress to the rock sample to simulate the real reservoir stress condition according to the real in situ stress. (2) Connect three intermediate vessels which were filled with fracturing fluids mixed with blue, green, and red dye, respectively, and three injection lines to the six-way valve. (3) During staged fracturing, switch off all valves except the one connected with the injection line of first stage and the other one connected with the corresponding intermediate vessel. Then, inject a certain amount of fracturing fluid at a constant displacement rate. Meanwhile, monitor the wellhead

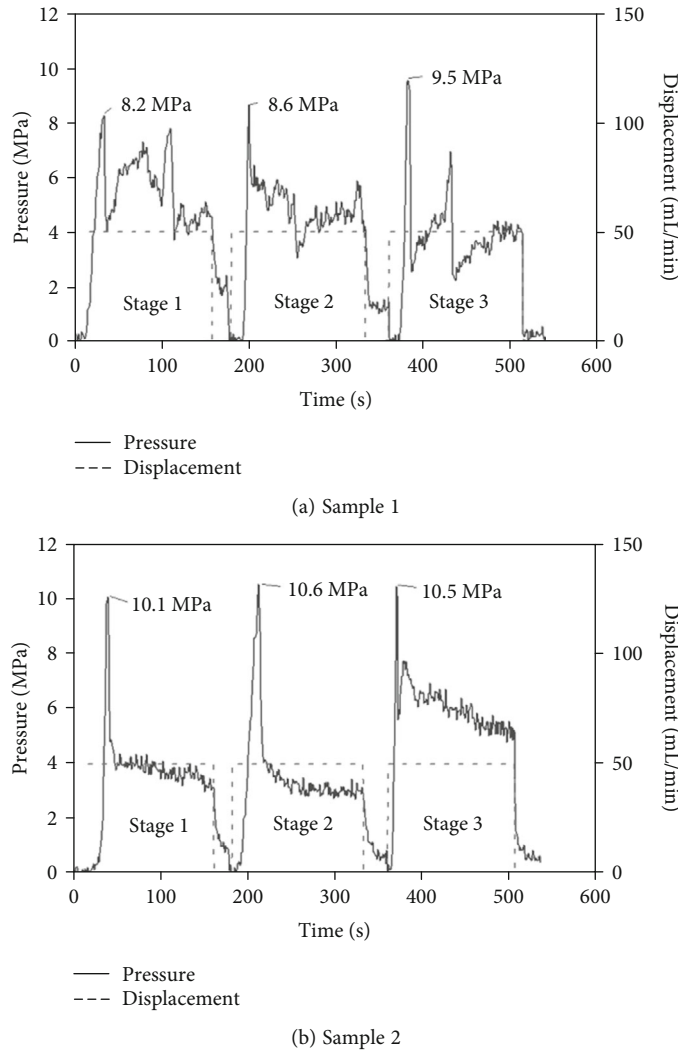


FIGURE 4: Treating pressure curve for horizontal well under different stage spacing and perforating parameters (samples 1 and 2).

pressure. Repeat the process above until all stages were completed. (4) After fracturing, observe and distinguish fractures of different sections in the rock sample by the different colors of the dye. Then, cut the fractured rock samples into pieces by the linear cutting machine (see Figure 2) to further identify the morphology of fractures inside the rock samples.

The stress state of the sample and the injection parameters were determined according to the parameters of experimental instruments and similarity criteria [4, 30]. In the experiment, the in situ stress difference coefficient (horizontal stress difference coefficient  $K_h = (\sigma_H - \sigma_h) / \sigma_h$ ) was taken into account to simulate the real formation stress environment. The fracturing fluid viscosity was 63 mPa·s, the pumping rate was 50 mL/min, and the cumulative pumping volume of a single group of experiments was 120-200 mL. Actual stage spacing in the field was mostly within the range of 30-100 m, which was converted to 1.75-5.6 cm (symbol  $s$  in Figure 1(b)). In order to facilitate experimental comparison, small stage spacing was set at 2 cm and large stage spacing was set at 5 cm, which were equivalent to 30 m and 80 m of actual stage spacing in the field. In order to reduce the

impact of additional wellbore stress field on fracture initiation, the perforation depth was 1-5 times of the wellbore diameter, namely, 1-5 cm [4]. A total of 8 rock samples were designed and their experimental parameters are shown in Table 1.

### 3. The Fracture Morphology and Pressure Curve Characteristics

#### 3.1. Fracture Characteristics of Staged Fracturing in Horizontal Wells

**3.1.1. The Influence of Stage Spacing and Perforating Depth.** The stage spacing of sample 1 and sample 2 was set at 2 cm and 5 cm, respectively, and the horizontal stress difference coefficient was 0.25. The experimental results showed that stage spacing was an important factor affecting fracture propagation. The propagation direction in the second and third stages (fractures 2 and 3) of sample 1 diverged from that of fractures in the first stage (fracture 1) (Figure 3(a)). This was because the induced stress field generated by the

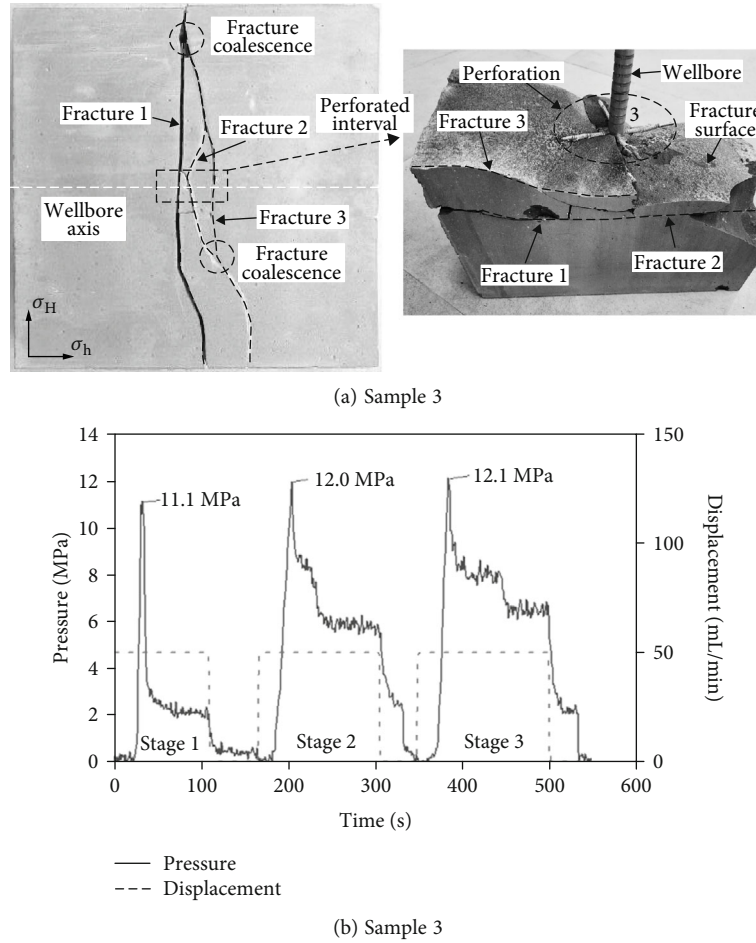


FIGURE 5: Fracture morphology and pressure curve of sample 3 (stress difference coefficient of 1.0).

first fracture changed the distribution of the original in situ stress and formed stress interference so that the subsequent fracture propagation paths were no longer parallel to the first fracture, but deflected at a certain angle. However, the fractures in the first and second stages of sample 2 with larger stage spacing were approximately perpendicular to the horizontal wellbore, while the fractures in the third stage were deflected at a certain angle from the fractures in the first two stages (Figure 3(b)). The stress interference decreased with the increase of stage spacing. For example, no obvious stress interference was found in the fracture of the second stage in sample 2. However, due to the superposition of the stress interference of the first two stages, the fracture propagation in the third stage showed a certain angle deflection. By comparing the fracture curves of sample 1 and sample 2, it can be found that the smaller stage spacing, the stronger the stress interference. The propagation pressure of each fracture in rock sample 1 fluctuated sharply and was about 1-2 MPa higher than that of sample 2 (Figures 4(a) and 4(b)). It also can be found in sample 1 that the fractures were more tortuous and the width of the fractures was smaller.

In addition, perforating depth was an important factor affecting the fracture initiation pressure. The perforation depths of sample 1 and sample 2 were 5 cm and 1 cm,

respectively. According to the pumping pressure curves of sample 1 and sample 2, the initiation pressures of each stage of sample 2 were 23.2%, 23.2%, and 10.5% higher than those of sample 1, respectively (Figure 4). As perforation depth increased, the area of the perforation hole on which fluid pressure acted increased, and the energy used for fracturing formation increased, resulting in the increase of the circumferential stress of the hole and the decrease of the breakdown pressure [31]. Smaller stage spacing is equivalent to high density perforation. The higher the perforation density, the stronger the stress concentration effect, and the greater the stress near the perforations. Therefore, the reduction of initiation pressure can be attributed to the result of stress concentration caused by multiple holes on an infinite object [32]. As a result, high density and deep penetration perforations can be used in the field to reduce the initiation pressure.

**3.1.2. The Influence of Horizontal Stress Difference.** The horizontal stress difference coefficient was set at 1.0. The stage spacing of sample 3 was 2.0 cm, and the perforation depth was 1.0 cm. The first fracture (fracture 1) formed in stage 1 was a transverse fracture perpendicular to the axis of the wellbore. The second fracture (fracture 2), formed in stage 2, deflected near the wellbore and merged with fracture 1 on the upper side distally, while its lower side propagated

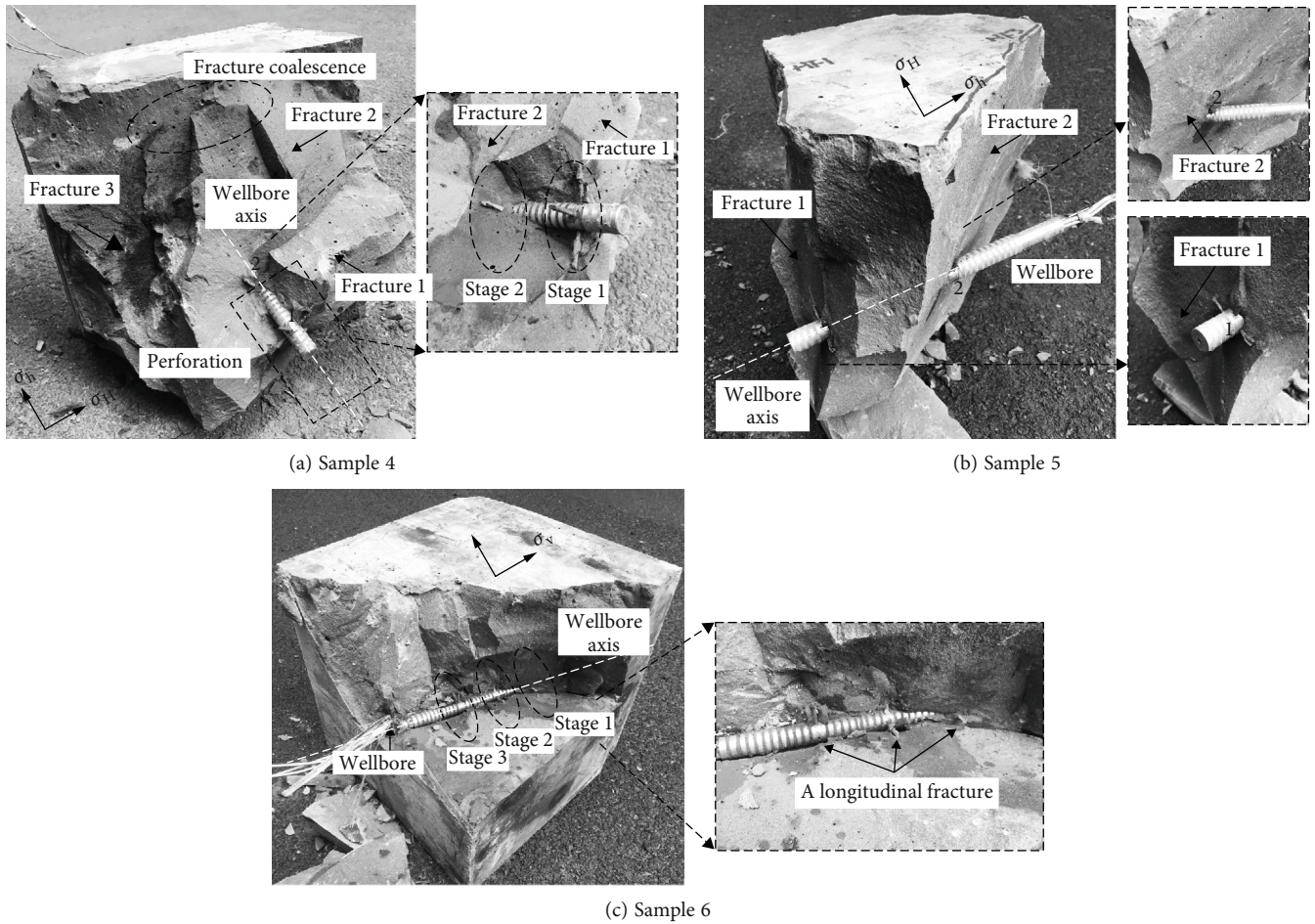


FIGURE 6: Fracture morphology of directional well with different deviation angles (azimuth angle 90°).

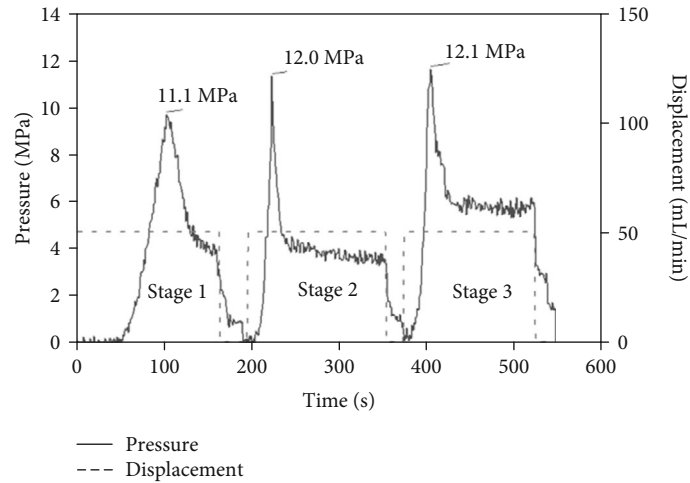
toward the direction of the original maximum horizontal principal stress distally. For the fracture in the third stage (fracture 3), it propagated a short distance near the wellbore, and then, both the upper and lower sides of it merged with fracture 2 (Figure 5(a)), which indicated that under the condition of high horizontal stress difference and small stage spacing, multiple fractures may merge in staged fracturing in horizontal wells. The fracture tip of the first stage may close under the action of fluid friction and filtration effect, which changed the distribution of induced stress field and made the maximum horizontal principal stress near the fracture surface deflected to fracture 1 by a certain angle. Because of the small stage spacing, fracture 2 merged with fracture 1 after propagating a certain distance, and fracture 3 merged with fracture 2 immediately after initiation.

Under the influence of the superposition of induced stress field, the initiation pressure of subsequent fractures showed a gradually increasing trend. According to the pressure curve of sample 3 (Figure 5(b)), when the dimensionless net pressure in the first fracture was 0, the initiation pressures of the last two fractures in sample 3 were 8.1% and 9.0% higher than those of the first fracture, respectively. Moreover, the propagation pressures of the last two stages were more fluctuating than those of the first stage. Due to the influence of stress interference on the last two fractures,

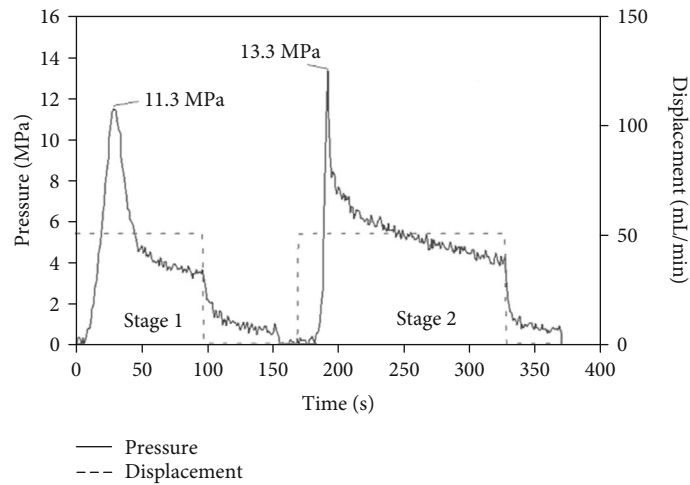
the fractures became narrower and more complex in shape, thus resulting in greater flow resistance to the fluid. Therefore, the pumping pressure curve could reflect the state of stress interference, fracture initiation, and propagation and has important guiding significance for the optimization of treating parameters.

### 3.2. Fracture Characteristics of Staged Fracturing in Directional Wells

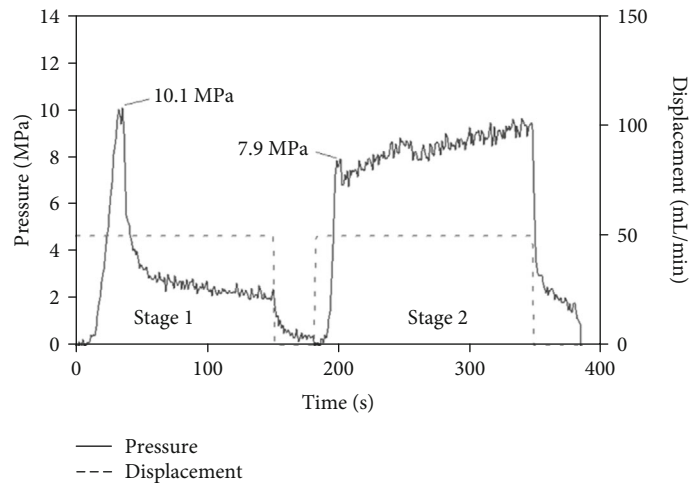
3.2.1. *The Influence of Well Deviation Angle When Azimuth Is 90°.* The horizontal stress difference coefficient was set at 0.25. The stage spacing was 2.0 cm, and the perforation depth was 1.0 cm. When the directional wellbore azimuth was 90° (the projection trace of directional wellbore on horizontal plane was consistent with the direction of the minimum horizontal principal stress), the effect of different well deviation angle on the fracture morphology and pressure curve characteristics of multistage fracturing was analyzed. As shown in Figure 6, as the deviation angle decreased, the multiple fractures obliquely intersected with the wellbore during staged fracturing became a single longitudinal fracture propagating along the wellbore. There were three transverse fractures obliquely across the wellbore in sample 4 and the wellbore deviation was 60°. The upper side of the fracture



(a) Sample 4



(b) Sample 5



(c) Sample 6

FIGURE 7: Pressure curve of directional well under different deviation angles (azimuth angle  $90^\circ$ ).

in the second stage was deflected toward the wellhead due to the influence of the fracture of the first stage, while the upper side of the fracture of the third stage was merged with the that of the second stage when it was far away from the well-

bore (Figure 6(a)). Accordingly, the pressure curve showed that the initiation pressure and propagation pressure in the third stage gradually increased (Figure 7(a)). The well deviation angle of sample 5 was  $30^\circ$ , and the first and second



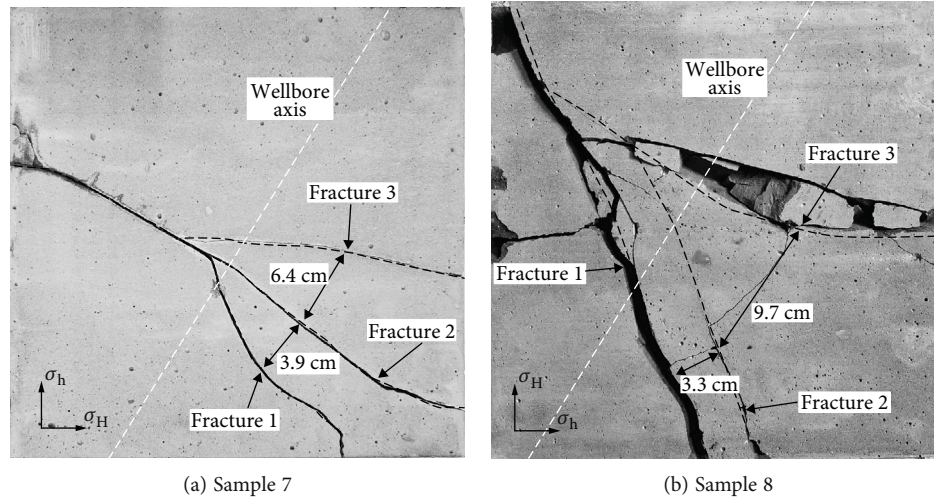


FIGURE 8: Fracture morphology in directional wells (azimuth angle  $60^\circ$ ) under different stage spacing.

stages each had a transverse fracture obliquely intersecting with the wellbore. However, it can be seen that the angle between the fracture in the second stage and the wellbore was relatively small (less than  $20^\circ$ ), which led to the perforation hole in the third stage being connected to fracture 2 and unable to initiate new fractures (Figure 6(b)). In addition, the initiation pressure of the second stage was 2 MPa higher than that of the first stage, while there was no initiation pressure at the third stage (Figure 7(b)). The well deviation angle of sample 6 was  $0^\circ$  (vertical well), and a single longitudinal fracture propagating along the wellbore was formed in the first fracturing stage. As a result, fractures cannot be formed in the next two stages (Figure 6(c)). The pressure curve showed that there was no significant initiation pressure in stage 2 (only 7.9 MPa), while there was no initiation pressure in stage 3 (Figure 7(c)). Fractures formed in directional wells with an azimuth angle of  $90^\circ$  propagated along the direction of the maximum horizontal principal stress on the whole, but the stress interference was obviously enhanced, and the subsequent fractures diverted significantly.

**3.2.2. The Influence of Stage Spacing When Azimuth Is  $60^\circ$ .** For sample 7 and sample 8, the stage spacing was set at 2 cm and 5 cm, respectively. Other variables of those two samples were the same: the horizontal stress difference coefficient was 0.25, perforation depth was 1 cm, well deviation was  $30^\circ$ , and azimuth was  $60^\circ$ . As shown in Figure 8(a), there were three fractures obliquely across the wellbore in sample 7, and the fractures were relatively tortuous. The fractures in the second and third stages (fractures 2 and 3) merged with the fractures in the first stage on the upper left side of the wellbore, while the fractures of three stages on the lower right side of the wellbore were mutually repellent. The spacing between fractures (3.9 cm between fractures 1 and 2, 6.4 cm between fractures 2 and 3) was significantly larger than the stage spacing (2 cm). In sample 8, the stage spacing was increased to 5 cm. Three fractures obliquely across the wellbore were also formed. Similar to sample 7, the three fractures formed in sample 8 had obvious deflection. The

fractures in the second and third stages (fractures 2 and 3) merged with fracture 1 on the upper left side of the wellbore, while the fractures of the three stages on the lower right side of the wellbore were mutually repellent (Figure 8(b)). Overall, compared with the directional well whose azimuth angle was  $90^\circ$ , fractures formed in directional wells whose azimuth angle was  $60^\circ$  more likely exhibited uneven distribution (merger or repulsion) under the condition of small stage spacing, resulting in more tortuous and complex fractures. In particular, for subsequent fractures, they were more likely to initiate along the direction perpendicular to the wellbore and then deflected substantially to propagate in the direction of the maximum horizontal principal stress.

## 4. Conclusions

Based on the true triaxial hydraulic fracturing simulation experiment system, multifracture propagation and pressure curve of staged fracturing in horizontal well and directional well were investigated. The understandings and suggestions are as follows:

- (1) In horizontal wells, under the conditions of high horizontal stress difference coefficient (1.0) and small stage spacing, multiple fractures tend to merge, and stress interference among multistage is obvious. As a response, the increase of initiation pressure for the subsequent stages is more than 8%. The degree of stress interference is low for large stage spacing, resulting in relatively straight fractures. Deepening penetration hole can reduce the initiation pressure by more than 10% and reduce the stress interference among stages
- (2) When the projection trace of directional wellbore on horizontal plane is consistent with the direction of the minimum horizontal principal stress, multiple fractures intersecting the wellbore obliquely are easily formed by staged fracturing. With the decrease

of well deviation, the angle between fracture surface and wellbore axis decreases, which is not conducive to the uniform distribution of multiple fractures. Only one vertical fracture extending along the wellbore is formed for the extreme case that the well deviation angle is 0 degree (namely, vertical well)

- (3) When there is a certain angle between the projection trace of directional wellbore on horizontal plane and the direction of minimum horizontal principal stress, the propagation of multiple fractures is extremely ununiform and the fracture paths are obviously tortuous. When the stage spacing is small, multiple fractures tend to merge near the upper part of wellbore or repel far away from the lower part of wellbore and deflect to the direction of maximum horizontal principal stress. The initiation pressure increases significantly stage by stage and the propagation pressure is relatively high

## Nomenclature

- $s$ : Stage spacing (cm)  
 $d$ : Perforation depth (cm)  
 $\sigma_h$ : Minimum horizontal principal stress (MPa)  
 $\sigma_H$ : Maximum horizontal principal stress (MPa)  
 $\sigma_v$ : Vertical stress (MPa)  
 $K_h$ : Horizontal stress difference coefficient, dimensionless.

## Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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