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Original Paper

Experimental study of hydraulic fracture propagation with multi-cluster in-plane perforations in a horizontal well

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ABSTRACT

Tri-axial fracturing studies were carried out to understand the impact of lateral mechanical parameters on fracture propagation from multiple in-plane perforations in horizontal wells. Additionally, the discussion covered the effects of geology, treatment, and perforation characteristics on the non-planar propagation behavior. According to experimental findings, two parallel transverse fractures can be successfully initiated from in-plane perforation clusters in the horizontal well because of the in-plane perforation, the guide nonuniform fishbone structure fracture propagation still can be exhibited. The emergence of transverse fractures and axial fractures combined as complex fractures under low horizontal principal stress difference and large pump rate conditions. The injection pressure was also investigated, and the largest breakdown pressure can be also found for samples under these conditions. The increase in perforation number or decrease in the cluster spacing could provide more chances to increase the complexity of the target stimulated zone, thus affecting the pressure fluctuation. In a contrast, the increase in fracturing fluid viscosity can reduce the multiple fracture complexity. The fracture propagation is significantly affected by the change in the rock mechanical properties. The fracture geometry in the high brittle zone seems to be complicated and tends to induce fracture reorientation from the weak-brittle zone. The stress shadow effect can be used to explain the fracture attraction, branch, connection, and repulsion in the multiple perforation clusters for the horizontal well. The increase in the rock heterogeneity can enhance the stress shadow effect, resulting in more complex fracture geometry. In addition, the variable density perforation and temporary plugging fracturing were also conducted, demonstrating higher likelihood for non-uniform multiple fracture propagation. Thus, to increase the perforation efficiency along the horizontal well, it is necessary to consider the lateral fracability of the horizontal well on target formation.

1. Introduction

Unconventional reservoirs, especially shale gas or tight oil reservoirs, have emerged as promising contributors to the global energy demand (Cruz et al., 2018; Shakiba and Sepehrnoori, 2018; Alrashed et al., 2019). The demand for fracture complexity in unconventional oil and gas flow necessitates a sufficient number of perforations in each stage, thereby generating complex fracture networks. Field operators generally perform multiple perforations on each fracturing stage, thus the multiple fracture propagation competition is inevitable. In many cases, multiple fractures fail to be created from each perforation because of the strong stress

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shadow interaction, resulting in asymmetric and incomplete fractures. In addition, the lateral reservoir heterogeneity is also an intrinsic rock property that affects fracture behavior in adjacent stages on the horizontal well, which possibly deteriorate un-uniform fracture propagation (Hisanao et al., 2017). Due to combining factors including complex local stress alteration and differences in mechanical properties stemming from multiple perforations along the wellbore, wellbore tortuosity occurs while inducing abnormally high pressure in the hydraulic fracturing with closing perforations (Abass et al., 1994; Fallahzadeh et al., 2015; Akash et al., 2019; Zeng et al., 2019). Thus, to make sure successful uniform multiple fracture initiation and propagation for multi-stage hydraulic fracturing treatment, the effective fracturing design considering the lateral rock mechanical heterogeneity and stress interaction is of great significance.

Most hydraulic fracturing treatments are performed through perforations to increase the connectivity and ease the flow of hydrocarbons from the reservoir to the wellbore (Shan et al., 2022). The main purpose of perforations is to provide a straight, highly conductive channel that is not too tortuous. However, because of the intense fluid competition and stress interference in one stage, not every fracture can properly initiate from every perforation tunnel. In addition, hydraulic fractures tend to begin and spread along the path of the least resistance, which may not coincide with the intended fracture orientation. Consequently, abnormal fracture pressures and unusual fracture geometries can occur (Hossain et al., 2000; Fallahzadeh et al., 2017). Numerous studies have been conducted to address the issue of fracture initiation and propagation from perforated wellbores in difficult geological circumstances. Sepehri et al. (2015) developed a model to examine the influence of different parameters on fracture propagation from a set of perforations. They proved that when two perforations are placed close to one another, the stress interference between them causes either perforation breakdown or fracture propagation away from the pair. Liu et al. (2018) studied the effects of the initial pore pressure, horizontal differential stress, fracturing fluid, and previous perforation angle on the complexity and spread of fractures for oriented perforations. However, if there is a misalignment between the orientation of the perforation and the in-situ stress state, typically oriented perforations generally create one perforation path for each perforation and thus may fail to produce the optimal fracture geometry (Huang et al., 2020). However, majorities of research focus on the understanding the propagation of multiple fractures from multiple perforations in heterogeneous rocks (Abass et al., 1994; Wu and Olson, 2015; Sesetty and Ghassemi, 2019; Bai et al., 2020; Shan et al., 2021). Comparing to the stress interaction, lateral heterogeneity is also a great potential factor for fracture propagation, but the reservoir lateral variations were rarely considered in the experimental and numerical study (Gokaraju and Eckert, 2014; Manchanda et al., 2016; Alzahabi et al., 2017; Sesetty et al., 2018; Zeng et al., 2018).

Recently, a technique for oriented in-plane holes was suggested for the horizontal well, which can increase the likelihood that a hydraulic fracture will spread along the preferred fracture plane (PFP). Multiple perforations with differently shaped charges placed in the same plane can function together to produce a fan-shaped fracture structure with multiple perforation tunnels. Thus, the larger and deeper tunnel planes created can increase the likelihood that the following hydraulic fracture propagates along the intended plane. The fracture behavior-oriented in-plane perforation approach has been investigated by several authors. Falser et al. (2016) performed large-scale triaxial fracturing experiments on tight sandstone, and the fracture geometry and breakdown pressure indicated that the in-plane perforation technique is beneficial to avoiding tortuous near-wellbore fractures and reducing the breakdown pressure. Yuan et al. (2016) designed a cement block and conducted triaxial fracturing experiments with multiple perforations in a single plane. They verified that a high principle horizontal stress difference creates a single straight transverse fracture, whereas a low principle horizontal stress difference creates multiple straight fractures without interactions. Sun et al. (2019) developed a 3D coupled hydro-mechanical finite-element model to indicate the stress interference between perforations, and they believed that the interaction is beneficial to transverse fracture creation. Wang et al. (2019) investigated the near-wellbore fracture geometry and demonstrated that three types of microfractures occur around the perforation tunnel during perforation. The proposed interlaced perforation on fixed planes can yield a more desirable fracture geometry. Shi et al. (2021) studied the fracture geometry of a horizontal well with in-plane perforations and believed that the existence of perforation tunnels can guide hydraulic fracture propagation within one plane. However, most studies have discussed fracture geometry using in-plane perforations on the fracture propagation of vertical wells, while mostly for heterogenous rock (Zhang et al., 2019). Moreover, several treatment methods of migration of multi-cluster perforations undistributed flow, such as temporary plugging and variable density perforation fracturing treatment methods. The temporary plugging fracturing applies the diverting agents to plug the previously fractured fractures and isolate to the lateral, these techniques are commonly used in highly inhomogeneous rocks. Variable density perforation refers to the perforation density control and thus inflow profile into per fracturing zone can be balanced, but this method needs more geological and geomechanical information about the target zone. All fracturing methods above were devoted to create more even propagation fractures from each perforation clusters and enhance reservoirs production more efficient. However, both are not combined together with the in-plane perforation mode for the horizontal well.

Therefore, in this study, the geological and fracturing conditions for the creation of hydraulic fractures are investigated on the multiple fracture initiation and propagation from an in-plane perforated horizontal wellbore during tri-axial fracturing, as well as the fracture mechanism of multiple fracture geometry was discussed. Moreover, the temporary plugging fracturing and variable density perforation treatment methods are used to validate the migration capability of the non-uniform fracture propagation. This work considers the lateral rock heterogeneity in the horizontal well fracturing, which can provide fundamental support for fracturing treatment on more actual geological condition.

2. Experimental

2.1. Sample preparation

To investigate the initiation and propagation of fractures with multiple cluster in the plane along the heterogeneous rock, artificial cube concrete samples are cut and processed with the size of 300 mm × 300 mm × 300 mm. The mixture of cement and quartz sand in a constant mass ratio of 1:1, is poured around the horizontal wellbore to form the perforated sample. The center of the concrete sample is drilled through with stainless steel to represent the horizontal wellbore and the outer and inner diameters of the wellbore are 15 and 10 mm, respectively. A circular tray and several circular columns were installed on the wellhead and chamber, which can provide a good cementing effect for the prevention of fracturing fluid during hydraulic fracturing. As for conventional in-plane perforations mode, four perforation tunnels are set for each perforation cluster. The variable density in-plane perforations mainly involve considering three perforations for one perforation cluster and four perforations for another perforation cluster, thus the total perforation number is 7. In addition, two different layers with different mechanical properties were set, so these samples can simulate lateral mechanical heterogeneous properties along the horizontal wellbore. However, each layer is homogeneous and isotropous. Each perforation is numbered clockwise from the top to bottom of the wellbore as shown in Fig. 1. Fig. 1(b) shows the perforation design with different phases. For example, group 1 represents the in-plane perforations of the first perforation interval for the high brittle zone, and group 2 the in-plane perforations of the first perforation interval for the low brittle zone. Three in-plane perforations are set in one plane as a group on the horizontal wellbore while the perforation tunnel for one perforation is perpendicular to the maximum horizontal principal stress direction, thus the perforation angle in the plane is 120°. All perforations have uniform size specifications and the diameter of the perforation hole is 3.5 mm. The shot interval spacing for three groups of perforation clusters is 0.1 m. The wellbore and rock are joined together using high-strength glue to prevent fracturing fluid leakage during tri-axial fracturing experiments. Following maintenance, all specimens are kept in a dry, airy condition for 14 days. To ascertain Young's modulus and Poisson's ratio in various core directions, two sets of triaxial compression tests are utilized, and two groups of Brazilian compression tests are tested to ascertain their tensile strength. The basic mechanical characteristics of the two layers are displayed in Table 1. A total of ten samples was prepared for the experimental study. To further investigate the impact of neighboring perforations on the change in brittleness affecting hydraulic fracture behavior, the difference between zone A and zone B in rock mechanical strength increase, the Young's modulus in zone A is set to 36.5 GPa while the Young's modulus in zone B is still 16.5 GPa for the sample No. 7. As for a comparison, the similar rock mechanical properties are set for the zone A and zone B for sample No. 8 (Table 2).

2.2. Experimental apparatus

The true tri-axial fracturing system is composed of a framework, a confining load pump, an ISCO pump, a servo control system, an oil–water separator, and data acquisition and monitoring devices (see Fig. 2). Three principle in-situ stress can be loaded at different independent directions with three movable plates along the *X*, *Y*, and *Z* directions in the Cartesian coordinate. The maximum tri-axial stress can reach 70 MPa, and the range of stress load is 0.1 MPa. The maximum fluid injection pressure is 50 MPa, and the accuracy of the injection flow rate is ±0.5 mL/min. Two different fracturing fluids with different viscosities are applied in the experiment. To highlight the effect of viscosity, the viscosity of slickwater is 10 mPa s while the gel fracturing fluid has a viscosity of 80 mPa s, which is used for most cases.

2.3. Experimental scheme

Tri-axial horizontal fracturing tests on a rock with lateral heterogeneous mechanical properties were conducted using six essential phases. (1) Set up the devices and place the prepared samples in the real tri-axial loading framework. (2) Apply the tri-axial stress loading to the in-situ stress circumstances. The minimal horizontal stress value was simultaneously loaded in three directions to prevent the stress underbalanced scenario. The vertical stress was increased to the maximum horizontal stress value gradually before the maximum horizontal stress was reached. (3) Using a pump to inject the fracturing fluid into the sample until a hydraulic fracture. (4) While the fracturing process is underway, continuously record the injection pressure curve. (5) Each sample was carefully opened along the hydraulically-induced fracture after fracturing and was then slowly divided into two parts with a hammer and chisel. (6) A thorough fracture morphology and pressure response analysis would be conducted. Fracture spacing, cluster count, fracturing fluid viscosity, and in-situ stress were the four key characteristics used to analyze the fracture behavior of heterogeneous rock with many in-plane perforation clusters. In tests 1–3, the effect of perforation number and in-situ stress was investigated. Test 4 looked at how fluid viscosity affected things. The influence of perforation spacing on the fracture behavior was studied for test 5. The impact of the pump rate was studied in test 6. Tests 7 and 8 investigated the rock lateral heterogeneity on the propagation of numerous hydraulic fractures. Test 9 investigated the effect of the variable density perforations on ununiform hydraulic fracturing propagation. Test 10 focused on the application of a temporary plugging agent for ununiform hydraulic fracturing propagation improvement on the horizontal well. The minimum horizontal principal stress was fixed at 37 MPa, while the maximum horizontal principal stress was set at 45 MPa and the overburden stress was 50 MPa. Table 2 shows the detail of this tri-axial fracturing experiment.

3. Experimental results and analysis

The hydraulic fracturing experiments were conducted based on

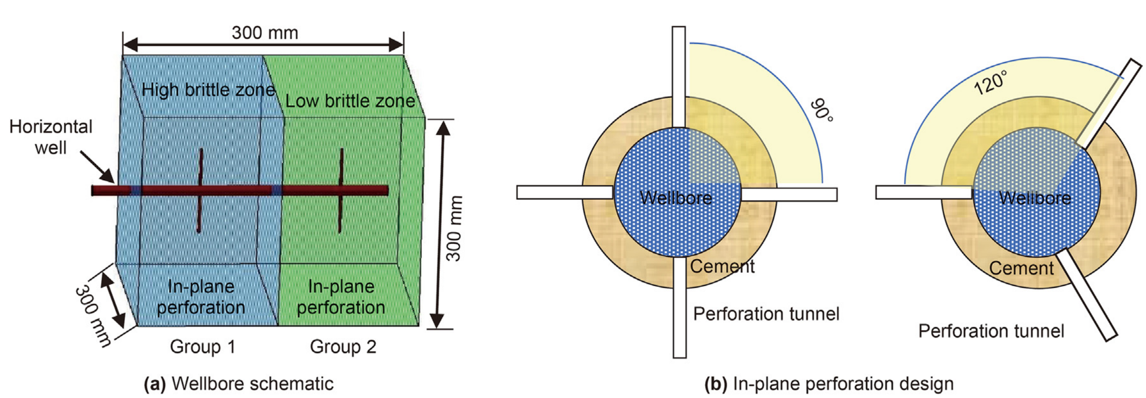

Fig. 1. Schematic of the wellbore and in-plane perforation design for large scale fracturing experiment.

Table 1
Basic mechanical properties of two layers of concrete samples.

Layer	Young's modulus, GPa	Poisson's ratio	Unconfined confining strength, MPa	Tensile strength, MPa
High brittle layer	26.5	0.23	112	3.8
Low brittle layer	16.5	0.25	95	3.2

Table 2
Tri-axial fracturing experimental parameters.

Model	Shot phase between perforations, °	Shot interval, m	Perforation number in one perforation cluster	Treatment type	Pump rate, mL/min	Fracturing fluid viscosity, mPa s	Horizontal stress difference, MPa	Young's modulus difference for different zones, GPa
No. 1	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	80	8	10
No. 2	90	0.1	Perforation group 1:4 Perforation group 2:4	Constant density perforations	15	80	8	10
No. 3	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	80	3	10
No. 4	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	200	8	10
No. 5	120	0.15	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	80	8	10
No. 6	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	30	80	8	10
No. 7	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	80	8	20
No. 8	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations	15	80	8	0
No. 9	120	0.1	Perforation group 1:4 Perforation group 2:3	Variable density perforations	15	80	8	10
No. 10	120	0.1	Perforation group 1:3 Perforation group 2:3	Constant density perforations + temporary plugging	15	80	8	10

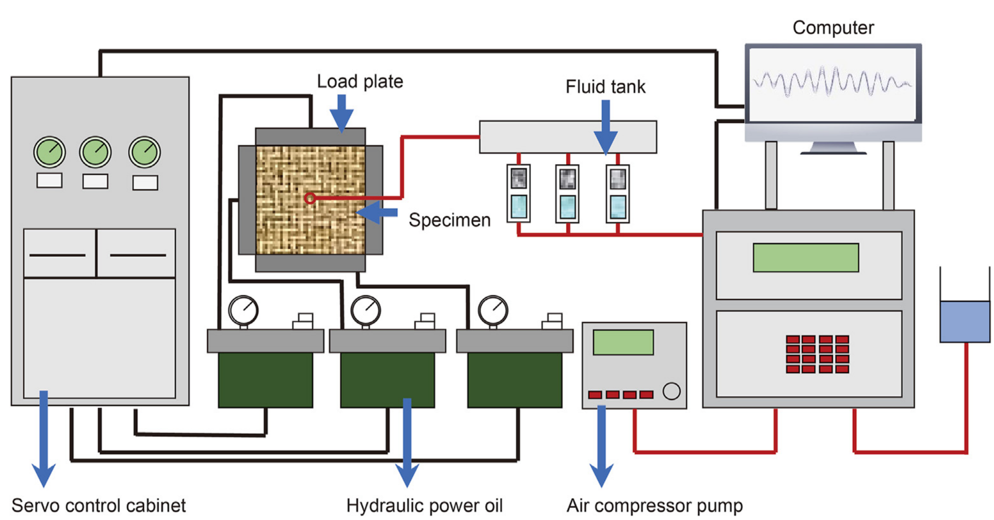

Fig. 2. Experimental equipment and flowchart.

a heterogeneous sample with the experimental scheme using multiple in-plane-perforations in the horizontal well. The hydraulic fracture traces on the heterogeneous sample was carefully observed. It shows multiple parallel non-planar transverse fractures can be seen clearly for almost all samples while local micro-fractures can be seen. The fracture morphology is composed of main transverse fractures and multi-branch fractures.

3.1. Effect of perforation number on hydraulic fracture geometry

Perforation density is an important parameter of the final fracture geometry of a horizontal well. Fig. 3 shows the fracture morphology of sample No. 1 with four perforation tunnels in one defined plane. According to the fracture morphology, both perforation clusters can create an effective fracture propagation path. The increase in the perforation number and misalignment of the perforation tunnel with the orientation of the maximum horizontal principal stress can successfully initiate hydraulic fractures from all

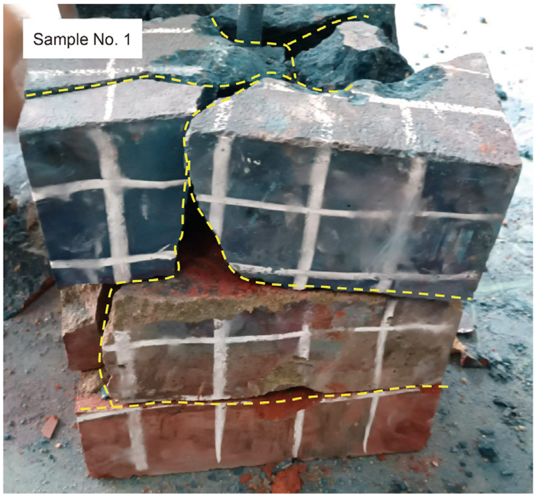

Fig. 3. Fracture morphology of sample No. 1.

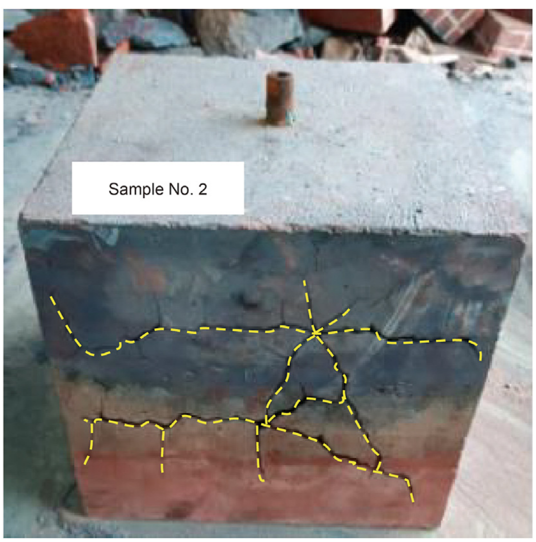

Fig. 4. Fracture morphology of sample No. 2.

perforations. The fracture in the perforation cluster of the sandstone part does not appear to generate a straight transverse fracture, which might result from the relatively high mechanical properties and strong stress interference between neighboring perforations. Fig. 4 shows the fracture morphology of sample No. 2 with three perforation tunnels in one defined plane. Two relatively straight transverse fractures were observed in each cluster. Due to the fracturing fluid's fierce competition, this sample exhibited curved fracture paths. More perforation tunnel guides were produced as a result of the creation of more branch fractures in the main multiple parallel transverse fractures. Therefore, the complexity of fractures benefits from an increase in the perforation density. The attractiveness of high-brittleness zones for hydraulic fracture propagation is shown by a study of fracture morphology in several zones with varying mechanical properties. In particular, for sample No. 1, the curved transverse fracture eventually spreads into the brittleness zone despite initially propagating along the direction of the maximum horizontal stress. The local in-situ stress field and mechanical characteristics determine how the fracture route changes depending on the fracture orientation.

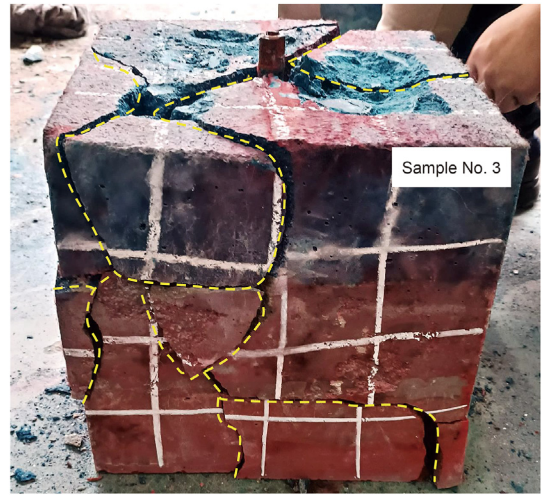

Fig. 5. Fracture morphology of sample No. 3.

3.2. *Effect of the horizontal stress difference on hydraulic fracture geometry*

The minimum horizontal principal stress was fixed at 37 MPa, while the maximum horizontal principal stress was set at 40 MPa to explore the impact of the stress differential on the geometry and propagation course of numerous fractures. The fracture morphology of sample No. 3 demonstrates how a reduction in the horizontal stress can cause a curve in the propagation paths of the fractures (see Fig. 5). Furthermore, the rock segment with the highest rock brittleness exhibited more branched fractures. The fluid is not uniformly dispersed into each fracture owing to the stress shadowing effect between the nearby fractures. Fractures in the zone of high brittleness receive more injection of fracturing fluid because the fracture propagation in the zone of low brittleness is strongly controlled by the fracture geometry. Because of the decrease in the horizontal principal stress difference, transverse fractures can be created, and an axial fracture can be generated. Transverse hydraulic fractures usually propagate in the direction of the maximum horizontal principal stress under normal stress conditions, but tend to extend along the horizontal direction, which is influenced by local stress. The most likely reason for this is the different perforation tunnel direction. Under the low-principle horizontal stress direction, the initial perforation guide tends to be more important for hydraulic fracture propagation. Influenced by multiple perforation clusters, hydraulic fractures reoriented after initiation, propagated vertically along the main hydraulic fracture surface, and eventually propagated towards the sample boundary.

3.3. *Effect of fracturing fluid on hydraulic fracture geometry*

The impact of the fracturing fluid on the fracture geometry was also investigated using large-scale true triaxial fracturing experiments. As shown in Fig. 6, the final fracture morphology of sample No. 4 resembled the two main transverse fracture morphologies with a large viscous fracturing fluid. In addition, except for the two induced transverse fractures that can be observed at the rock surface, local branch hydraulic fractures can be found. More induced fractures were connected in the section with high rock brittleness; thus, this fracture type had a complex fracture shape. Compared to a sample with a low-viscosity fracturing fluid, the created main fracture can still follow the highest horizontal principal stress

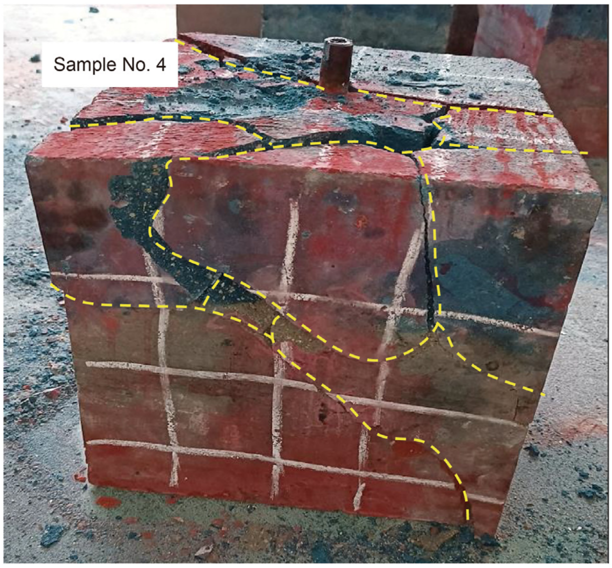

Fig. 6. Fracture morphology of sample No. 4.

direction, even though the induced fracture gradually veered away from the nearby hole. Because a high-viscosity fracturing fluid tends to build an adequately high fracturing energy for primary transverse fracture propagation, the stress interactions between nearby perforations appear to be reduced when it is utilized. Numerous branch hydraulic fractures only started from inside a small area rather than spreading into the sample boundary, owing to the reduction in fluid leak-off.

3.4. Effect of cluster spacing on hydraulic fracture geometry

The morphology of the fractures with a large fracture cluster spacing is depicted in Fig. 7 (sample No. 5). The initiation and propagation of hydraulic fractures from perforations are affected by perforation cluster spacing. The fracturing energy owing to the very small perforation cluster spacing can induce a more complex fracture geometry. This phenomenon is a result of the stress shadow effect. Moreover, a more intense stress interaction can be observed near the perforation part, whereas no large branch fractures can be observed for the two main transverse fractures. The branch fracture only extended into a limited area, indicating that the stress activation area controlled the limited area. The transverse fractures deviated at the end of the fracture, indicating a local stress field surrounding the fractures from the original. This stress perturbation affects nearby fractures, causing them to develop dissimilarly to some fractures propagated along the maximum horizontal stress direction, thus yielding a complex fracture path. In addition, the deviation in the fracture path demonstrates that the effect of the stress shadow along the fracture path decreases.

3.5. Effect of pump rate on hydraulic fracture geometry

The change in the pump rate can also alter the fracture geometry during multicluster fracturing. When the pump rate increased, a more complex fracture geometry was easily observed for sample No. 6 (see Fig. 8). In this case, two distinct transverse fractures were created and several axial fractures were generated. Compared to the sample using a low pump rate, the transverse fracture path was almost straight, while the fracture direction was perpendicular to the minimum horizontal principal stress direction. Thus, an increase in the pump rate also decreases the stress interaction between the fracture clusters. Furthermore, fracture reorientation only occurs at the sample boundary, which indicates a decay of the fracturing energy. Under a large pump rate background, the expansion distance of the hydraulic fractures in the vertical and horizontal directions was significantly increased. Such non-planar fracture propagation is affected by the fracturing energy, whereas a high pump rate provides high energy for fracture propagation. However, there was no significant difference in the fracture paths for the two fracture clusters in different zones with different rock brittleness. This implies that a high fracturing energy can also diminish the influence of rock brittleness on the fracture path.

3.6. Effect of lateral rock mechanical properties on hydraulic fracture geometry

The fracture geometries of samples No. 7 and No. 8 are shown in Figs. 9 and 10, respectively, to discuss the impact of the rock mechanical parameters on fracture initiation and propagation. In the case of sample No. 7, axial fractures were formed in addition to planar transverse fractures. The induced fracture develops into a more substantial and intricate area as the brittleness in the brittle zone increases. In addition, a complex fracture system can be

Fig. 7. Fracture morphology of sample No. 5.

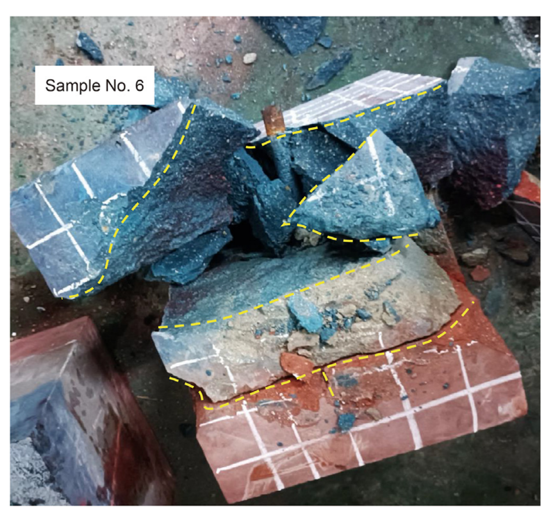

Fig. 8. Fracture morphology of sample No. 6.

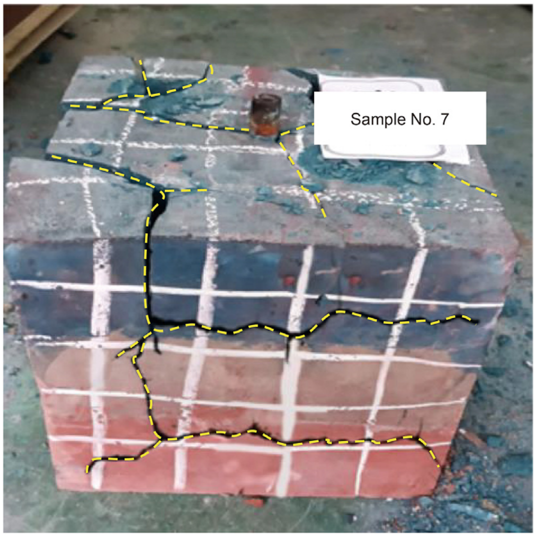

Fig. 9. Fracture morphology of sample No. 7.

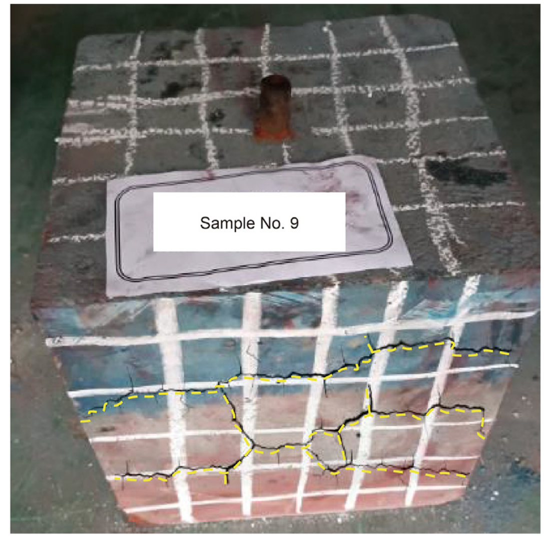

Fig. 11. Fracture morphology of sample No. 9.

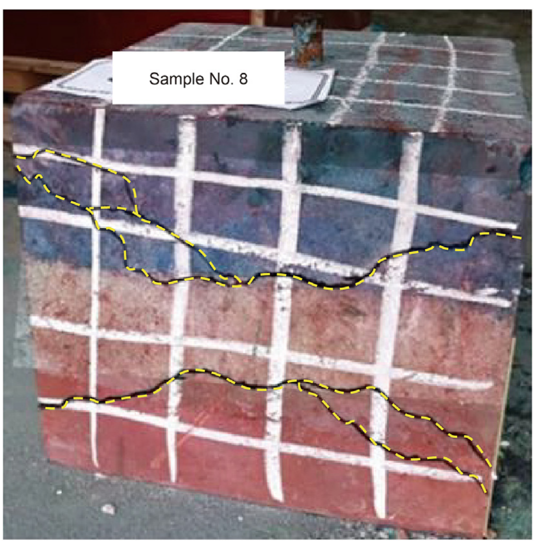

Fig. 10. Fracture morphology of sample No. 8.

successfully formed via reoriented and branched fractures. The two created hydraulic fractures alter the in-situ stresses in the vicinity of the sandstone section, causing the branch fracture to deviate towards the highly brittle area. This fracture deviation may be explained by the stress shadow. The fracture in the brittle zone has a greater propagation area than that in the low brittle zone owing to the significant difference in the mechanical characteristics of the rock. The mechanical characteristics of sample No. 8 are homogeneous. Two planar transverse fractures appear to make up the entire fracture because the mechanical characteristics of the rocks are the same. A similarity in the fracture geometry was apparent. Branch fractures also diverge from the initial principal stress direction and can be observed at the tips of the transverse fractures. In this instance, the fracture attraction is more clearly visible close to the perforation position, whereas the fracture deviation is visible farther from the perforation zones.

3.7. Effect of treatment parameter on hydraulic fracture geometry

Fig. 11 shows the fracture geometry of sample No. 9 with the variable density perforations treatment. According to the experimental results, two transverse fractures were successfully created. Moreover, due to the variable density perforations set, the two transverse fractures can keep a parallel path toward the boundary. However, there are still some micro fractures that can be found along the fracture path and these fractures mainly develop from the perforation position. One great reason is the variable density perforations already only guide the fracture near the wellbore. Unlike the other sample, because more perforations were set on the weak zone and more complex fractures can be observed although these fractures are also more likely distributed near the perforation positions. Fig. 12 illustrates the fracture geometry with the application of a temporary plugging agent (sample No. 10). The experimental result indicates non-uniform transverse fracture path can be obtained while the two fractures can keep a relatively straight path while almost no distinct micro fractures can be seen. However, an axial fracture still can be found, which relates to the temporary

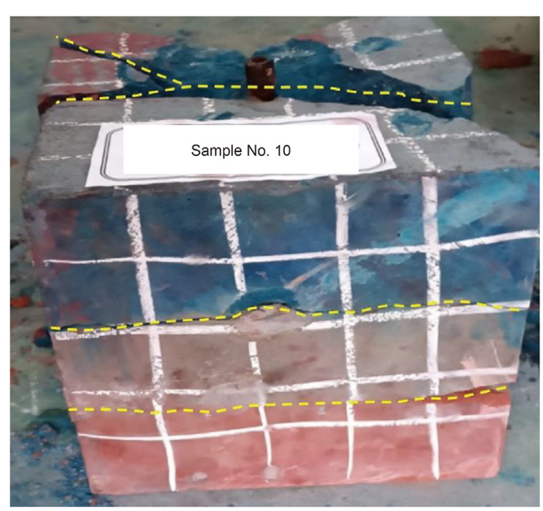

Fig. 12. Fracture morphology of sample No. 10.

plugging effect. Compared to the other samples, the injection of a plugging agent greatly balanced the fluid competition and stress shadowing effect between perforations. However, if the temporary plugging volume cannot be calculated carefully, new fractures might create in new direction. By regulating the injection control of fracturing fluid through the plugging effect of temporary plugging agent, the stress interference phenomenon between cluster spacing is reduced, which makes it easier for uniform fracture initiation and extension.

3.8. Injection pressure curves

The changes in the lateral mechanical properties and development of hydraulic fractures caused by the action of the fracturing fluid may be reflected in the injection pressure curves. All injection pressure curves can be divided into three stages. (1) Rapid injection pressure growth before reaching the fracturing breakdown pressure: the fracturing pressure increased quickly when the fracturing fluid was injected. (2) The fluctuating injection pressure stage initiates when the fracture starts spreading. This could be caused by a small amount of fracturing fluid inside the fracture, which was lower than the initial fracturing breakdown pressure, and several rupture points were generated. (3) Sharp injection pressure decline stage: with the continued injection of fracturing fluid, the fracturing pressure continued to leak off from the fracture surface.

Owing to the lateral mechanical property difference, the fluctuation of the injection pressure refers to the secondary or tertiary fracture initiation and propagation from multiple clusters in the horizontal well. Fig. 13 depicts the variations in injection pressure curves for samples No. 1 through No. 10. Fig. 13 indicates the breakdown pressure of sample No. 1 is approximately 60.12 MPa. The breakdown pressure of sample No. 2 is approximately 62.26 MPa, which is higher than that with a small number of perforation clusters. The curves show more fluctuation in sample No. 3 because the low horizontal principle stress is beneficial to complex fracture geometry, while the breakdown pressure is approximately 65.19 MPa, which is the highest for all samples. A complex fracture propagation path corresponds to a complex pumping curve; thus, fluctuations in the injection pressure can be observed for all three stages, indicating a complex fracture geometry. When a high pump rate and highly viscous fracturing fluid are utilized, the breakdown pressures of samples No. 4 and No. 6 are 65.09 and 62.02 MPa, respectively. The energy required to encourage further fracture propagation after initiation is provided by an increase in the fracturing pump rate and fracturing fluid viscosity in the wellbore. Owing to the small amount of fracturing fluid flowing out of the specimens, the sample curves typically provide a simple fracture geometry. The breakdown pressure of sample No. 5 is approximately 58.55 MPa, which decreases by slightly more than 4.5 percent in the case of a dense cluster of perforations. A comparison of the injection pressures for samples No. 7 and No. 8 indicates that the increase in rock mechanical heterogeneity can increase the breakdown pressure. The breakdown pressure of heterogeneous rock sample No. 7 has the lowest value, which is approximately 58.65 MPa. In contrast, the breakdown pressure of sample No. 8 is approximately 65.09 MPa. This is

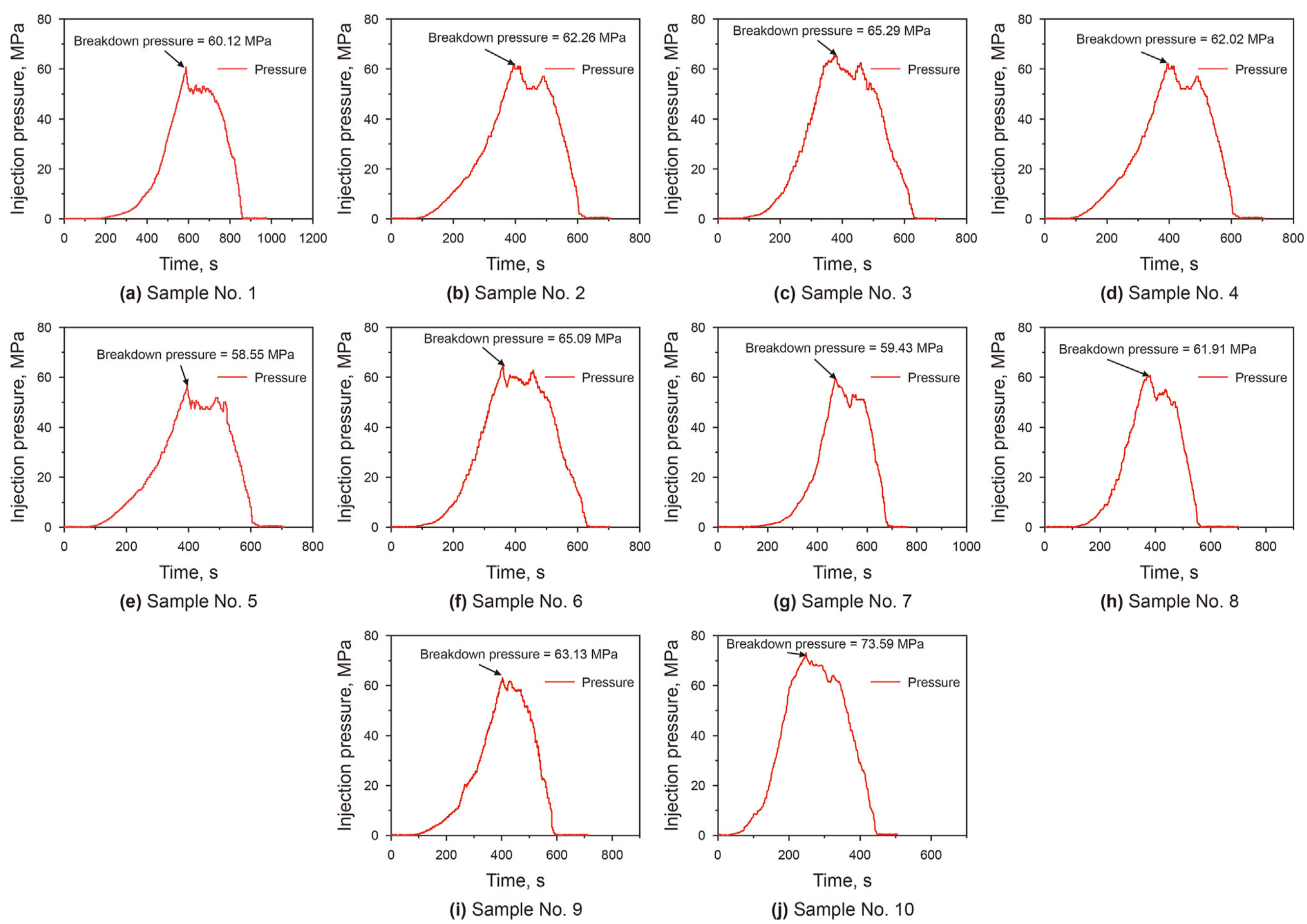

Fig. 13. Injection pressure curves change for samples under different conditions.

because more intersection patterns are observed when encountering the interface between the high brittle and low brittle zones, including slipping, crossing, and vertical fracture extension. The injection pressure of sample No. 9 refers to sample with varying perforation number in each perforation cluster, and the breakdown pressure of this sample is about 63.13 MPa.

The axial fracture and transvers fracture increase the breakdown pressure, thus the breakdown pressure of sample No. 10 is about 73.59 MPa, which is the highest of all samples. The largest breakdown pressure of this sample result from the plugging effect, the balance of fracturing fluid distribution in each perforation cluster prevent un-uniform fracture propagation but also increase the fluid flow resistance.

4. Discussion

Although in-plane perforations can have more chances to reduce the near-wellbore tortuosity and make a clean and bigger fan structure fracture, two types of complex fracture geometry namely parallel transverse fractures and parallel transverse fractures with non-planar axial fractures. More specifically, transverse fractures can be classified into single curved transverse fractures and transverse fractures with branch fractures. Moreover, with the decrease of fracturing fluid energy towards the sample boundary, more branch fractures can be observed at the fracture tip, which belongs to the hierarchical branching. At the same time, fracture attraction can be seen in the middle part of the fracture while fracture repulse can be found at the fracture tip, which controls by the stress shadowing effect degree. Due to their stress interference, the two main transverse fractures always tend to diverge apart gradually along the fracture path. Additionally, numerous branch fractures can be seen outside of the perforation-controlled zones. Fig. 14 illustrates the fracture morphology types with multiple perforation clusters for the horizontal well in the heterogeneous rock.

Hydraulic fracture propagation through a heterogeneous rock from multiple perforation clusters exhibits a complex fracture path, thus it is important to understand the impact of the treatment and completion variables on the multiple fractures created per stage. To further compare the fracturing stimulation effectiveness, the fracture stimulated area (FSA) in the brittle zone and weak zone is calculated with the help of the laser scanning and reconstruct modelling by the Geomagic Studio software. In addition, the non-uniform fracture propagation parameter is used to justify the even fracture path in different zones. Table 3 summarizes the triaxial fracturing experimental results of all samples. The total FSA of sample No. 1 is about 1257.65 cm^2 using four perforations in one plane. With the reduction of perforation number, the total FSA of sample No. 2 is about 1083.29 cm^2. More perforations allow for a smaller pressure drop across each perforation tunnel. Except for the perforation number, the decrease of principal horizontal stress difference and increased pump rate and can increase fracture complexity. The total FSA of sample No. 3 is about 1594.42 cm^2 under the small principle horizontal stress difference, resulting from complex fracture network. In a comparison, the total FSA of

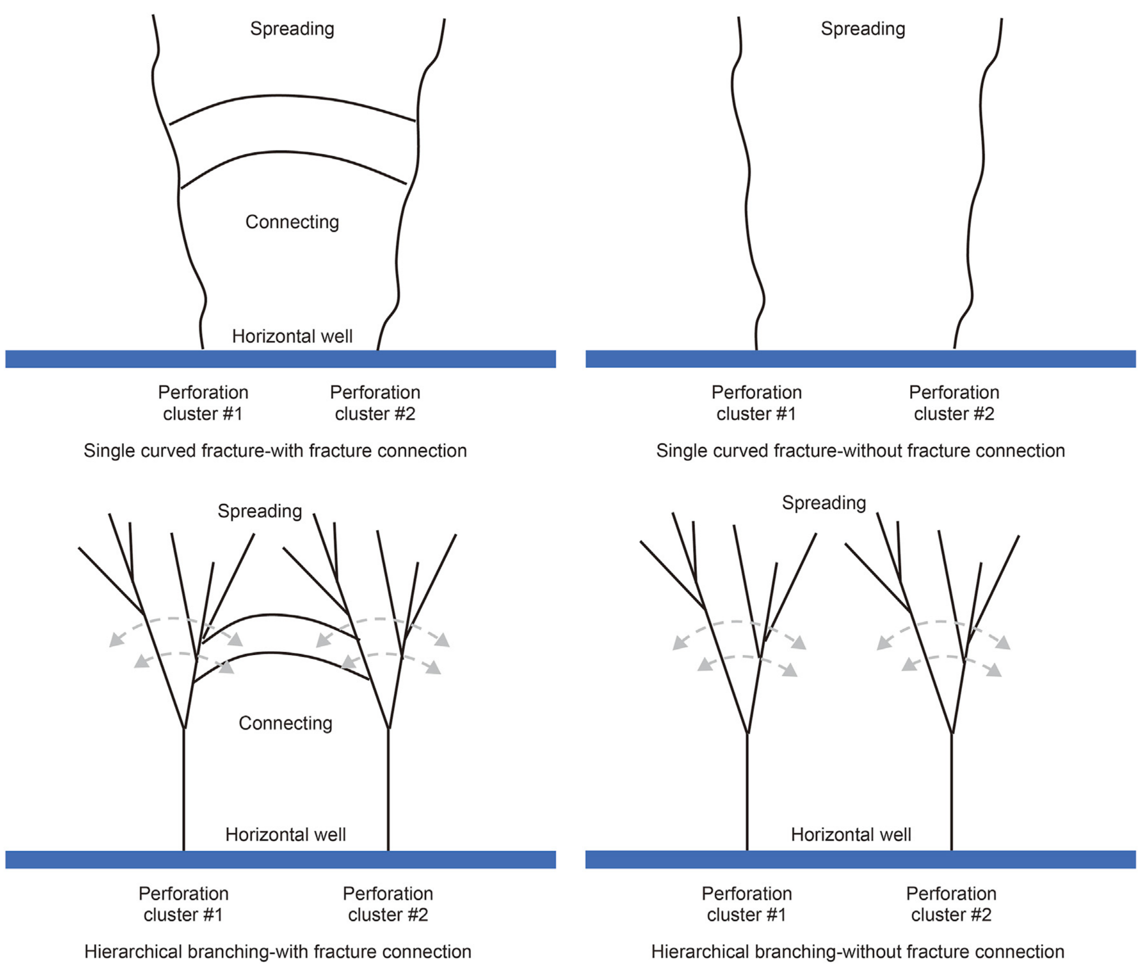

Fig. 14. Transverse fracture morphology types with multiple perforation clusters for the horizontal well in the heterogeneous rock.

Table 3
The summary of experimental results for the FSA.

Sample No.	Zone 1	Zone 2	Uniform fracture propagation parameter	FSA, cm^2
1	752.15	505.5	1.49	1257.65
2	694.28	389.01	1.78	1083.29
3	964.35	630.07	1.53	1594.42
4	533.48	391.9	1.36	925.38
5	632.86	450.58	1.40	1083.44
6	1184.91	561.87	2.11	1746.78
7	1015.55	680.14	1.49	1695.69
8	648.68	493.45	1.31	1142.13
9	623.62	484.85	1.29	1108.47
10	928.13	834.72	1.11	1762.85

sample No. 4 is about 925.38 cm^2 using slick water fracturing fluid, which is the smallest of all samples. The main reason is that the low fracturing fluid is sometimes inadequate to create enough high fracturing fluid penetration energy to open or slide the layer interface, thus the fracture path is restricted. The total FSA of sample No. 5 with large perforation spacing is about 1083.44 cm^2. When spacing increases between neighboring perforations, less tense fluid completion for each perforation can increase the non-uniform propagation parameter was presented to signify the fracture propagation.

The large of perforation spacing can decrease the stress interaction between neighboring perforations but also sacrifice the fracture complexity. The fracture pressure will have a greater influence over the fracture fluid flow, which tends to result in more equal fluid injection into each cluster if no distinct stress interaction exists. Fracture complexity can be increased by increasing the pump rate of the fracturing fluid. Increased pump rate can result in sufficient high fracturing energy and a minimal likelihood of stress re-orientation. Regardless of the stress shadowing effect's existence. The total FSA of sample No. 6 using large pump rate is 1746.78 cm^2, which is the largest for all samples. High viscosity fracturing fluid, large perforation spacing and low injection rate can prevent fluid filtration and decrease the possibility of shear slide of fracture, thus reducing the possibility of activation of layers, resulting in less complex fracture system. The change of the rock mechanical properties can also affect the fracture path, the total fracture areas are about 1695.69 and 1142.13 cm^2 for samples No. 7 and 8, respectively. The temporary plugging method and the variable density perforation method were used to control the propagation path. The purpose of both two methods is the adjustment of the flowrate distribution into each perforation cluster by balancing flow resistance within the fractures. Thus, increasing the number of perforations in weak zone can reduce the flow resistance into the weak zone and thus promote more fractures to propagate. The total FSA of sample No. 9 using the variable density perforations is 1108.47 cm^2. The total FSA of sample No. 10 using the temporary plugging fracturing method. Clear straight parallel fracture geometry and less stress interactions between multi-stage hydraulic fractures inside the rock mass can be obviously observed for sample No. 10. Because of the straight fracture path, the proppants are transported a long distance by fracturing fluids. Moreover, an axial fracture also can be seen for this sample, thus large fracture area can be also ensured. This is because the plugging agent can affect the fracturing fluid flow, the better the fracture reorientation performance will be. We separately calculate the stimulated fracture area for the brittle and weak zones, and the uniform fracture propagation parameter is used to represent the even fracture propagation. The higher of this parameter predict largely different fracture path between different zones. According to the calculated results, the uniform fracture propagation parameter is about 2.11 for sample No. 6 with large pump rate. The temporary plugging fracturing and variable density perforation, the uniform fracture propagation parameter are about 1.11 and 1.29, respectively. Thus, with the help of plugging agent, uniform fracture propagation and large FSA can be meet the field demand.

Most fractures propagate asymmetrically away from the wellbore due to differences in the fracture geometry at the two sides of a horizontal well. When fracture geometry is compared to various rock brittleness, it is implied that rock heterogeneity may have a greater impact on the fracture's ability to propagate. Greater stress interference between numerous propagating fractures from contiguous perforations can be caused by higher Young's modulus and brittleness. In other words, more complex fracture geometry can be used to shatter the high rock brittleness zones. Additionally, this indicates that the stress shadow will be layered with considerable rock heterogeneity. Additionally, a high degree of brittleness can draw fractures from nearby perforations, leading to the overlaying of complicated fractures. Thus, most of the generated fractures can be classed into the fishbone type fracture in heterogeneous rock. Fig. 15(a) shows sketch of fracture morphology differences from zones with different lateral rock heterogeneity. Fig. 15(b) illustrates the fracture morphology differences with no lateral heterogeneity and large lateral heterogeneity. The cutting fracture geometry of sample No.7 was complex but a transverse fracture with branch fracture in the weak brittle zone still can be observed. In a comparison, complex fracture can be seen in the high brittle zone. The two parallel transverse fracture can be found for sample No. 8 with no lateral heterogeneity. As for this case, only stress shadowing between perforations can affect the fracture geometry. Moreover, the hydraulic fracture morphology is not torturous with the help of an in-plane perforation guide for this case.

An interface can be thought of as the connection between two layers having distinct mechanical properties. The weak interface is always the initiation position in all samples due to the interface's reduced mechanical strength, even though the perforation position is not entirely fixed at the interface. The generated fracture from the low brittle zone with low rock brittleness may modify the fracture course after passing through the bond contact due to variances in the lateral rock characteristics. These mechanisms can function as another mechanism for complicated fracture geometry in addition to the contrast in the mechanical properties of the rock. However, because of sufficient high fracturing energy, hydraulic fractures skip the interface directly and no identifiable shear fractures can be seen there. Hence, to achieve desirable fracture behavior, hybrid fracturing can be used in strong heterogeneous formations. The high viscous fracturing fluid should be injected during the early fracturing period to keep the fracture extending straight near the

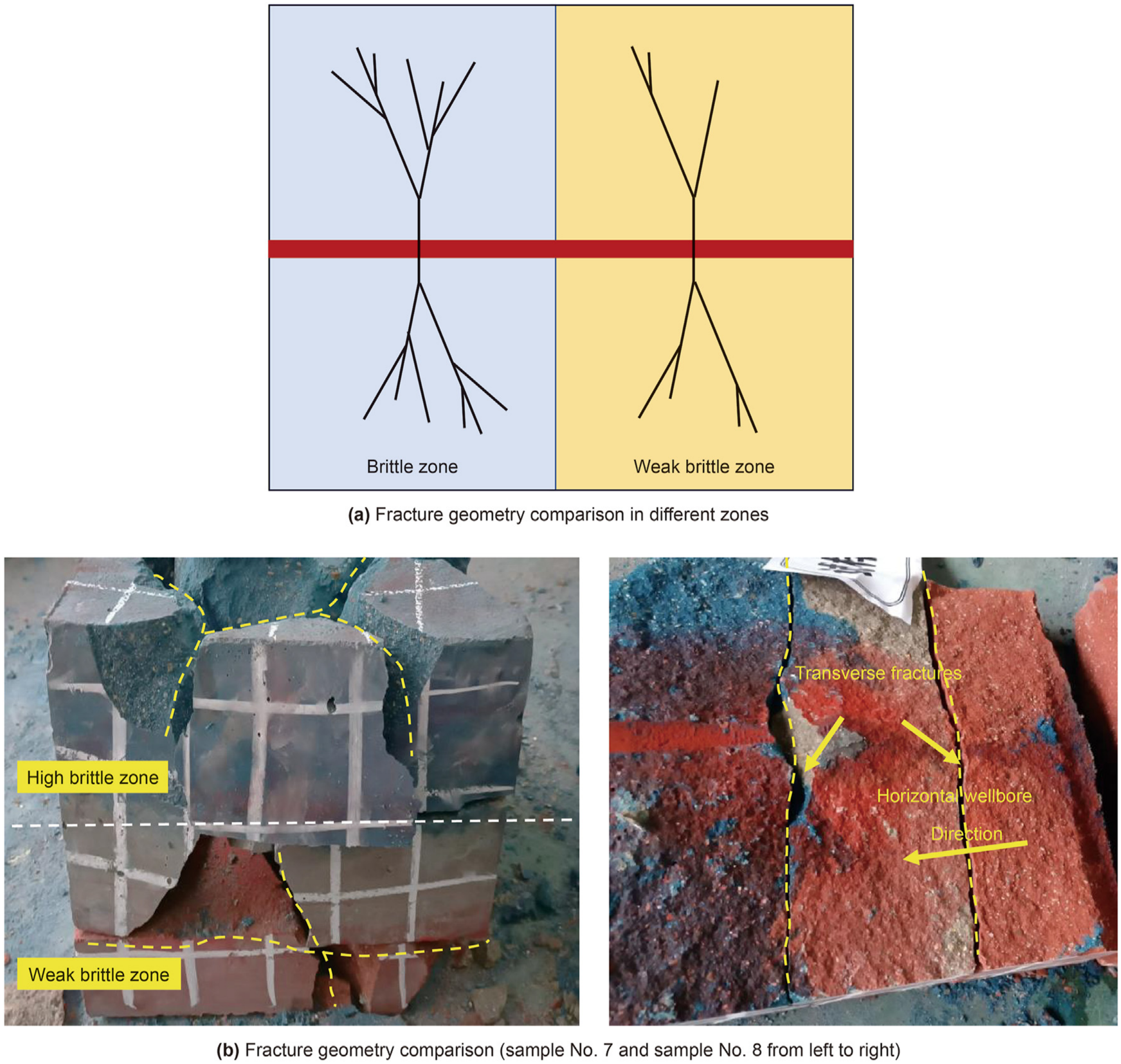

Fig. 15. Fracture morphology differences from zones with different lateral rock heterogeneity.

wellbore and low viscous fracturing fluid injection can make the fracture propagate into the far field, which balances the fracture complexity and fracture extend the area. Fracture arresting in the interface makes the propagation pressure rise. The pumping injection pressure curve fluctuation in the propagation stage shows complex fracture behavior, such as fracture diversion, penetration, and cross. Especially when the hydraulic fracture comes from the low brittle zone to the high brittle zone, the curve will show an obvious rising. The fracture propagation from different mechanical zones will not only lead to an increase in fracture pressure and extension pressure but also to complex fracture geometry. with the help of an in-plane perforation guide, a near-flat fracture surface can be created for majorities of testing samples.

The complex reservoir properties and various scales of petrophysical heterogeneity exists within distinct rock fabrics along the horizontal well. The existence of later heterogeneity not only result from stratigraphic cyclicity but also relates to facies distribution and diagenesis. In general, the heterogeneity of rock quality not only includes brittleness but also can include in-situ stress, pore pressure, and reservoir properties such as porosity and permeability. Thus, there is a critical variability in heterogeneity above which the stress shadow effect becomes insignificant and heterogeneity governs the simulated fracture trajectories. Thus, the lateral fracability estimation of horizontal well on target formation is necessary. The most important parameters that the operators can control to increase the number of fractures created per stage are the number of clusters per stage, cluster spacing, and perforation parameters. Therefore, selecting and controlling the corresponding perforation and treatment parameters is the most concerning issue in the field of hydraulic fracturing design. The variation of perforation parameters for the various clusters in a stage can increase the stimulation efficiency. Otherwise, it is necessary to use the intense density perforation to guarantee the fracture complexity in each stage.

5. Conclusions

Based on the true tri-axial experiments of the heterogeneous rock sample using the in-plane perforation technique on the horizontal well, the fracture propagation behavior and pumping injection pressure curve were mainly investigated under different rock mechanical properties and perforation conditions. Some of the main conclusions were drawn as follows.

(1) Because of the stress shadowing effect, both parallel transverse fracture and parallel transverse fracture with non-planar axial fracture can be found. As for the transverse fracture, single curved transverse fracture and transverse fracture with branch fractures still can be found. Depending on the geological and treatment parameter difference, fracture attraction, branch, connection, and repulsion can be observed.
(2) Hydraulic fractures tend to divert and be complex with low horizontal principle stress differences and high pump rates. The increase in perforation number or decrease in the cluster spacing could provide more chances to increase the complexity of the target stimulated zone, thus affecting the pressure fluctuation. In a contrast, the increase of fracturing fluid viscosity can reduce the multiple fracture complexity.
(3) The lateral rock mechanical properties and in-situ stress both on the horizontal well have an impact on the multiple fracture propagation, causing the fracture deviation and attraction around the perforations. The rock mechanical properties in the lateral direction increase the fracture stress shadowing and promote the extension of the fracture. Thus, the overlap of fracture and fishbone type fracture in heterogenous rock can be commonly seen. Moreover, fracture morphologies after hydraulic fracturing and pressure curves of high brittle and low brittle zones have significant differences.
(4) Even when it develops in a direction that is perpendicular to the main horizontal stress direction, the hydraulic fracture always starts at the interface bond. When a hydraulic fracture comes into contact with an interface, the fracture geometry becomes complex in three dimensions, and lateral heterogeneous rock properties frequently cause the hydraulic fracture to bypass the interface. The experimental results show how the modification in lateral rock mechanical factors affects the complexity of multiple cluster fracturing on the horizontal well. The modification of perforation parameters in line with the lateral well fracability is a workable alternative to induce the growth of multiple fractures.

CRediT authorship contribution statement

Xian Shi: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Yuan-Yuan Yang:** Writing – original draft, Supervision, Investigation, Data curation. **Xiang-Wei Kong:** Project administration, Methodology. **Qi Gao:** Validation, Supervision, Resources. **Shu Jiang:** Resources, Project administration, Conceptualization. **Hai-Jun Mao:** Visualization, Investigation.

Declaration of competing interest

The authors declare no competing financial interest.

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