A multi-perforation staged fracturing experimental study on hydraulic fracture initiation and propagation

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Abstract

Hydraulic fracture initiation and propagation are extremely important on deciding the production capacity and are crucial for oil and gas exploration and development. Based on a self-designed system, multi-perforation cluster-staged fracturing in thick tight sandstone reservoir was simulated in the laboratory. Moreover, the technology of staged fracturing during casing completion was achieved by using a preformed perforated wellbore. Three hydraulic fracturing methods, including single-perforation cluster fracturing, multi-perforation cluster conventional fracturing and multi-perforation cluster staged fracturing, were applied and studied, respectively. The results clearly indicate that the hydraulic fractures resulting from single-perforation cluster fracturing are relatively simple, which is difficult to form fracture network. In contrast, multi-perforation cluster-staged fracturing has more probability to produce complex fractures including major fracture and its branched fractures, especially in heterogeneous samples. Furthermore, the propagation direction of hydraulic fractures tends to change in heterogeneous samples, which is more likely to form a multi-directional hydraulic fracture network. The fracture area is greatly increased when the perforation cluster density increases in multi-perforation cluster conventional fracturing and multi-perforation cluster-staged fracturing. Moreover, higher perforation cluster densities and larger stage numbers are beneficial to hydraulic fracture initiation. The breakdown pressure in homogeneous samples is much higher than that in heterogeneous samples during

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hydraulic fracturing. In addition, the time of first fracture initiation has the trend that the shorter the initiation time is, the higher the breakdown pressure is. The results of this study provide meaningful suggestions for enhancing the production mechanism of multi-perforation cluster staged fracturing.

Keywords
Multi-perforation cluster, staged fracturing, hydraulic fracturing, fracture propagation

Introduction
Tight sandstone is a reservoir with a low to ultra-low porosity and permeability (Becker et al., 2017; Lu et al., 2015; Zhou et al., 2018). Hydraulic fracturing is one of the most effective ways for enhancing oil and gas recovery and has been applied in tight sandstone oil and gas exploitation for years. As an important part of hydraulic fracturing, research on hydraulic fracture initiation and propagation has always been a topic of increased interest (Bohloli and Pater, 2006; Brudy and Zoback, 1999; Gale et al., 2007; Huang et al., 2017; Lee, 2015; Li et al., 2014; Liu et al., 2018). Based on observations from outcrops and core samples, Gale et al. (2007) agreed that natural fractures could divert hydraulic fracture propagation. A series of numerical simulations were carried out by Huang et al. (2017), and the results indicated that the value of the lateral stress coefficient determines the fracture initiation type. Moreover, hydraulic fracturing experiments on coalbed methane reservoirs were performed by Liu et al. (2018), and it was found that new hydraulic fractures prefer to propagate along the pre-existing fracture direction at a small approaching angle.

Many previous works have focused on conventional fracturing in vertical wells (Dehghan et al., 2015; Liu et al., 2014, 2018; Zhao et al., 2018; Zhou et al., 2008). Hydraulic fracturing experiments were conducted by Zhou et al. (2008) with a tri-axial fracturing apparatus to investigate the hydraulic fracture propagation behaviour in naturally fractured reservoirs, and the results indicated that the factors of the horizontal stress difference, approach angle and shear strength of pre-fracturing play dominant roles in the fracture propagation behaviour. The hydraulic fracture initiation mechanism of multi-perforation clusters remains unclear. Subsequently, similar experiments have been extensively conducted by many researchers (Jia et al., 2013; Kumari et al., 2018; Stanchits et al., 2015; Stoeckhert et al., 2015; Zou et al., 2016), and a full range of integrated surveillance techniques, including acoustic emission (AE) and industrial computed tomography (CT) technologies, were used to monitor the cracking behaviour during experiments. AE was applied to record hydraulic fracturing signals, and a special phenomenon was observed whereby the velocity increases in sandstones and decreases in shales when the P-wave velocity ray path is intersected by a hydraulic fracture (Stanchits et al., 2015). Recently, a series of large-scale tri-axial tests were conducted by Tan et al. (2017), and the propagation mechanism of hydraulic fractures in the vertical plane was specifically investigated. The results indicated five basic patterns in the vertical plane.

The above works on hydraulic fracturing experiments are mostly conducted using a single-perforation cluster, which is completely different from practical applications considering that multi-stage fracturing has been commonly used for unconventional oil and gas development (Guo et al., 2015a; Rahman and Abdulrazak, 2013; Ren et al., 2017, 2018;
Shen et al., 2017; Xie et al., 2018). Previous conventional hydraulic fracturing measures were adopted in the Changqing oilfield, Shanxi Province; however, hydraulic fracture detection results indicated that it was difficult to fully utilize the reservoir in the vertical direction by using conventional fracturing. When multi-stage fracturing was applied on a large scale, the exploitation of thick tight sandstone reservoirs was highly improved, and the oil recovery was very suitable (Li et al., 2008). Additionally, large numbers of multi-stage fracture-stimulated horizontal wells were applied in the Cardium Formation in the Pembina field of Alberta, Canada, in 2011, and oil production was extended to the upper limit of the economic recoverable volume compared to vertical well development (Klein et al., 2012).

Many studies related to multi-stage fracturing in thick tight sandstone reservoirs have been conducted (Karpov et al., 2017; Li et al., 2018; Lu et al., 2015; Olson and Taleghani, 2009). Olson and Taleghani (2009) suggested that hydraulic fractures could propagate across natural fracture planes without deviation and without additional leak-off under certain conditions. Based on surveillance data, Clark et al. (2013) held the view that multi-stage fracturing combined with horizontal completion technologies would highly increase reservoir contact and contribute to enhancing the potential of tight gas reservoirs. A 3D-FEM fracture propagation model was adopted by Guo et al., (2015b) to simulate multi-cluster staged fracturing, which proved that a small cluster spacing would affect stress changes more severely. In addition, multi-stage fracturing with multi-perforation clusters preferentially produces complex fractures compared to multi-stage fracturing with single-perforation clusters (Lu et al., 2015). Moreover, the fixed-point multi-stage fracturing technique was adopted by Li et al. (2018) to analyse the fracture propagation behaviour; based on the results, it was concluded that it is difficult to form a complex fracture system when the stress difference is higher than 6 MPa in the horizontal direction.

However, few works have specifically focused on studying the influence of reservoir heterogeneity on fracture propagation. Furthermore, multi-stage fracturing and conventional fracturing (single-stage hydraulic fracturing) with multi-perforation clusters were not considered simultaneously in the above studies. Therefore, it is very meaningful to investigate multi-perforation cluster staged fracturing (MPCSF), which will help to improve reservoir utilization and is critical in optimizing hydraulic fracturing design. This paper is mainly focusing on studying the following unclear mechanisms: (1) hydraulic fracture initiation and propagation characteristics of MPCSF and (2) the relationship between fracture propagation type and perforation cluster density. On the basis of the above topics, heterogeneous and homogeneous thick tight sandstone reservoirs were studied by using self-designed physical samples. Moreover, the technology of staged fracturing during casing completion was achieved with a preformed perforated wellbore. Hydraulic fracture initiation and propagation of SPCF, MPCCF and MPCSF have been investigated, respectively, and were demonstrated by comparative study. The results in this study can provide certain effective suggestions for applying the MPCSF method in oil and gas development and improving hydraulic fracturing design.

Experiments and methodology

Experimental apparatus and staged fracturing design

The hydraulic fracturing experiments are conducted with a true triaxial pressure system (Figure 1). When starting an experiment, the sample is surrounded by pressure plates,
which are controlled by a hydraulic voltage stabilizer, and the pressure on the pressure plates can be used to simulate the in situ stress of the reservoir. Fracturing fluids are injected into the samples, which are controlled by an MTS 816 instrument system.

Based on the principle of the sliding sleeve (Yang et al., 2014; Zhang et al., 2017; Li et al., 2018; Liu et al., 2018), the multi-stage fracturing technique has been achieved by a self-designed wellbore under experimental conditions. The process of three staged fractures is displayed in Figure 2. The three groups of the top perforation cluster, middle perforation cluster and bottom perforation cluster show a distinct hierarchical system from top to bottom for each wellbore. In first-stage fracturing, the top and middle perforation clusters are sealed by sliding sleeves (Figure 2(a)). Then, the top and bottom perforation clusters are sealed by sliding sleeves during second-stage fracturing (Figure 2(b)). Finally, only the top perforation cluster is employed in third-stage fracturing (Figure 2(c)). Similarly, double-perforation cluster-staged fracturing can be realized with the same principle. Casing completion perforation has been simulated by preformed perforation to ensure that the MPCSF experiments approximate the actual conditions. Therefore, MPCSF during casing completion has been applied in the laboratory environment. The test wellbores with a single-perforation cluster, double-perforation clusters and triple-perforation clusters are shown in Figure 3.

**Sample preparation and experimental conditions**

Experimental data were obtained by considering reservoir mechanics parameters and in situ stress. The data of the thick tight sandstone reservoirs in the Changqing oilfields, which are the largest oil and gas fields in China, are characterized by Young’s modulus (15–20 GPa), Poisson’s ratio (0.21) and tensile strength (4.2–5.2 MPa). The vertical stress ($\sigma_v$), maximum horizontal stress ($\sigma_H$) and minimum horizontal stress ($\sigma_h$) of the target reservoir are 36, 45
and 32 MPa, respectively; thus, the lateral pressure coefficient ($\kappa$) is 1.07 (Huang et al., 2017, 2019; Hoek and Brown, 1980).

The experimental samples are artificial (300 × 300 × 300 mm) because it is difficult to collect large numbers of rock samples from the target formation. The mechanical parameters, including the strength, Young’s modulus and Poisson’s ratio, are approximately equal to those of the reservoir when cement and fine quartz sand are mixed with water in specific proportions. After large numbers of tests, the cement and fine quartz sand proportions were

**Figure 2.** Schematic diagram of triple-staged fracturing, where the distance L between the three groups of perforation clusters is equally spaced along the wellbore.

**Figure 3.** (a) The test wellbores of staged fracturing and (b) the test wellbores of staged fracturing with preformed perforations.
determined as 1:2.00 and 1:1.88, and the corresponding tensile strength, Young’s modulus and Poisson’s ratio were 4.2 MPa, 13 GPa and 0.21 and 5.2 MPa, 17.3 GPa, and 0.21, respectively. Based on the principle of the similarity criterion applied by Liu et al. (2000) and Liu et al. (2018), the fracturing fluid injection flow rate was 0.50 mL/s during the experiments, corresponding to a value of 6.0 m³/min in field fracturing operations. The hydraulic fracturing curve appears a clear decline trend which can be considered as one of the judgement standards that the hydraulic fracturing experiment is finished. Therefore, the injection fluid volume was unlimited considering experiment end times are different under different conditions. Similarly, the injection time also cannot be fixed. The tri-axial stresses ($\sigma_v$, $\sigma_H$ and $\sigma_h$) applied in the fracturing experiments were 36, 45 and 32 MPa ($\kappa = 1.07$), respectively, considering the actual in situ stress conditions. The tri-axial stresses are relatively high; thus, the compression failure is more likely to occur. To avoid this situation, the loading process is very careful, the hydraulic fracturing experiment will not be conducted until the loading tend to be stable, and at the same time, the AE detector will be used to detect if there is any rock failure.

Based on the above proportions, the samples were made in the lab. The proportion of 1:2.00 was adopted to make homogeneous samples, which were made by injecting the mixture into a mould (Figure 4(a)). A septum was applied to separate different layers, and then the mixtures with proportions of 1:2.00 and 1:1.88 were injected into the different layers; thus, heterogeneous samples were prepared (Figure 4(b) and (c)). A sealing device was installed in the wellbore to avoid any pressure instability caused by poor sealing during hydraulic fracturing (Figure 4(d)).

**Figure 4.** (a) The preparation of a homogeneous sample; (b, c) the mould of a heterogeneous sample, where the septum is identified in the figures; (d) the sealing device is installed in the wellbore.
Hydraulic fracturing experimental design

A total of eight samples were manufactured in this study. These samples were divided into four groups to examine the influence of reservoir properties and fracturing type on fracture initiation and propagation (Table 1). Conventional fracturing with a single-perforation cluster (one cluster/300 mm) was applied in group one (1# and 4#), and the influence of reservoir properties on fracturing will be studied by comparing homogeneous sample 1# with heterogeneous sample 4#. The samples in group two (2# and 3# are homogeneous) and group three (5# and 6# are heterogeneous) had double-perforation clusters (two clusters/300 mm). Fracturing tests were conducted with conventional methods using 2# and 5#, while staged fracturing was applied to 3# and 6#. Therefore, the distinction between the effects of double-perforation cluster conventional fracturing and double-perforation cluster staged fracturing on fracture initiation and propagation can be shown according to result analysis. Group four (7# and 8#) contained triple-perforation clusters (three clusters/300 mm) that were both heterogeneous, similar to group three. This group aimed to study the difference between MPCCF and MPCSF. The details are shown in Figure 5 and Table 1.

Results and discussion

Fracture initiation and propagation characteristic of SPCF, MPCCF and MPCSF

Hydraulic fractures are divided into two types: type I, the major hydraulic fractures with a large size; type II, branched fractures of type I or fractures with a small size. For group one

| Schemes | Perforation cluster type | Sample number | Sample type | Fracturing type |
|---------|--------------------------|---------------|-------------|----------------|
| 1       | Single                   | 1# and 4#     | Homogeneous versus heterogeneous | Conventional |
| 2       | Double                   | 2# and 3#     | Homogeneous | Conventional versus staged |
| 3       | Double                   | 5# and 6#     | Heterogeneous | Conventional versus staged |
| 4       | Triple                   | 7# and 8#     | Heterogeneous | Conventional versus staged |

Figure 5. Hydraulic fracturing experimental design of the eight samples.
(1# and 4#), with the SPCF method, it can be seen from Figure 6 that the fractures are relatively simple in both the homogeneous and heterogeneous samples. For 1#, only a type I fracture is formed; however, the propagation direction of this main fracture is not parallel to the maximum horizontal principal stress (σ_H); in contrast, there is an \(~30^\circ\) angle between the fracture and σ_H directions (Figure 6(b)). In contrast to the 1# sample, the type I fracture in the 4# sample propagated along the direction of σ_H first and then slowly changed to an \(~30^\circ\) angle (Figure 6(d)). The propagation direction of hydraulic fractures tends to change in heterogeneous samples.

The samples in group two are both homogeneous, and MPCCF is applied (2# and 3#). It is clear that both type I and type II fractures can be seen in the 2# and 3# samples (Figure 7(a) and (c)). The type I fracture in the 2# sample propagated at an angle of \(~25^\circ\) to the σ_H direction, while the type II fracture is virtually parallel to the σ_H direction (Figure 7(b)). Previous studies conducted by Huang et al. (2017) and Liu et al. (2018) have the similar conclusion. The fracture propagation direction is not always along with σ_H in homogeneous reservoir during hydraulic fracturing; many factors like perforation direction, mechanical properties of the sample, fractures interference, etc., may affect the hydraulic fracture propagation (Li et al., 2018; Liu et al., 2018).

Figure 6. Fracture initiation and propagation in samples #1 and #4.
The fractures in the 3# sample are much more complicated. The type I fracture manifests three propagation stages despite a small type II fracture, and the propagation path of the type I fracture has a trend towards the \( \sigma_{HH} \) direction as the approaching angle decreases (Figure 7(d)). Furthermore, it is clear that the type I fracture in sample #3 is much longer than that in sample #2, which indicates that sample #3 is more likely to have a larger fracture area than sample #2. The results imply that staged fracturing is much more effective than conventional fracturing in homogeneous reservoirs considering the fracture length and area.

Although the samples in group three (5# and 6#) are heterogeneous, the propagation of hydraulic fractures is similar to group two. There is a main type I fracture at an angle of \( \sim 30^\circ \) to the \( \sigma_{HH} \) direction in the 5# sample (Figure 8(a) and (b)). Similarly, the type I fracture in the 6# sample shows a multi-propagation stage, and the fracture experiences a direction change several times. Quite a few type II fractures are created during staged fracturing (Figure 8(c) and (d)); moreover, two type II fractures are horizontal fractures, which are observed for the first time (Figure 8(c)). The results from groups two and three suggest that staged fracturing is conducive to producing complicated fractures, especially in heterogeneous reservoirs. In addition, fracture propagation during conventional fracturing, even for

\( \text{Figure 7. Fracture initiation and propagation in the 2# and 3# samples.} \)
double-perforation clusters, is still relatively simple regardless of whether the sample is homogeneous or heterogeneous.

The samples in group four (7# and 8#) are heterogeneous, and the fractures become even more complex than group three. Unlike the 2# and 5# samples, the hydraulic fractures in the 7# sample are relatively complex. The angle between the type I fracture propagation and $\sigma_H$ directions is $\sim45^\circ$, which is much higher than 2# ($25^\circ$) and 5# ($30^\circ$) (Figure 9(a) and (b)). In addition, a type II fracture intersects the main fracture in an X shape. Similar to the 3# and 6# samples, the type I fracture in the 8# sample presents multi-propagation stages. The right side of the fracture is approximately parallel with the $\sigma_H$ direction, whereas the fracture clearly shows a two-fold change in the propagation direction on the left side (Figure 9(c) and (d)). Furthermore, the main fracture and a type II fracture are intersected by a small fracture near the wellbore; thus, the connectivity of the fractures has been greatly improved. The above results indicate that optimizing the perforation cluster density would help to augment the fracture complexity.

**The fracture propagation section shape and size**

The fracture shape is generally like a flake circular, and the fracture surface is uneven (Paluszny and Zimmerman, 2011). After the experiment finished, the hydraulic fracture

![Figure 8. Fracture initiation and propagation in the 5# and 6# samples.](image)
shape and surface were displayed to illustrate the fracturing effect. Fracture propagation characteristics and fracture areas are shown in Figure 10. The fracture in sample #1 roughly propagates along the $\sigma_H$ direction at an angle of 30°, which is basically in the form of a symmetric double-winged shape. The propagation area of the fracture is mainly focused around the perforation, and fracture propagation exhibits a priority in the lateral direction compared to the longitudinal direction. However, it is clearly observed that the fracture fails to extend to the top. The maximum propagation length of the measured fracture is 30 cm, and the expansion area is approximately 792 cm$^2$. Therefore, the fracture expansion area accounts for 44% of the cross-sectional area (1800 cm$^2$). The fracture in the 2# sample is clearly a typical two-stage fracture. The fracture section is approximately elliptical, and the fracture propagation area of the first perforation section is larger than the second perforation section. The maximum extension length of the measured fracture is 26 cm, and the total fracture expansion area is 1022 cm$^2$; thus, the fracture expansion area accounts for 56.8% of the cross-sectional area.

The fractures formed in the 5# heterogeneous sample under conventional fracturing with double-perforation clusters are connected to each other. The fractures are basically distributed in a symmetrical bifurcation shape, and the fractures are approximately circular. The maximum extension length of the measured fracture is 25 cm, and the fracture

Figure 9. Fracture initiation and propagation in the 7# and 8# samples.
propagation area is approximately 876 cm². Therefore, the fracture expansion area accounts for 48.7% of the cross-sectional area. In contrast to the 5# sample, with the MPCSF method applied in the 6# heterogeneous sample, it can be seen that the fractures are well connected to each other and asymmetrically distributed. The fracture propagation area is approximately 1190 cm², which accounts for 66.1% of the cross-sectional area of the sample. The fracturing effect is better than that of conventional fracturing under the same conditions.

Fracture propagation in the heterogeneous 7# sample occurs under the condition of triple-perforation cluster conventional fracturing. The fractures roughly propagated along the horizontal maximum principal stress. After fracturing was completed with the three perforation clusters, the fractures are connected to each other and basically distributed in a symmetrical bifurcation form, presenting an elliptical profile. The surface of the fracture is rough and uneven, which is likely caused by the heterogeneity of the sample. The fracture propagation area is approximately 1218 cm² and accounts for 67.7% of the cross-sectional area of the sample. The fracturing effect of 8# is better than that of conventional fracturing under the same conditions.

Fracture propagation in the heterogeneous 8# sample takes place under the condition of triple-perforation cluster staged fracturing. The fractures are basically distributed symmetrically. The fracture propagation area is approximately 1356 cm², which accounts for 75.3% of the cross-sectional area of the sample. The fracturing effect of 8# is better than 7#, and the propagation area of the fracture is clearly improved.

Figure 10. Fracture propagation section shape and size of the 1#, 2#, 5#, 6#, 7# and 8# samples.
The perforation cluster density and fracturing effect are evaluated in this section. The hydraulic fracture length and width have a very positive impact on the hydraulic fracturing effect; therefore, the fracture area is also a very important parameter. For a more in-depth analysis, the hydraulic fracture area is measured and divided by the cross-sectional area (1800 cm²) to obtain the fracture area ratio. Samples 4# (SPCF), 5# (MPCCF), 7# (MPCCF), 6# (MPCSF) and 8# (MPCSF) were chosen to analyse the fracturing effect between conventional fracturing and staged fracturing (Figure 11). The fracture area clearly increased with increasing perforation cluster density in MPCCF and MPCSF. Moreover, the fracture area ratio of staged fracturing is much higher than that of conventional fracturing. This result indicates that the method of staged fracturing is much better than conventional fracturing under the same reservoir conditions (Omara et al., 2016).

**Relationship between the hydraulic fracturing curve and fracture propagation**

Fracturing fluid is driven by the oil pressure and then injected into the sample during hydraulic fracturing; therefore, the oil pressure can be used to represent the hydraulic fracturing pressure (Huang et al., 2019). The fracturing pressure will reach a peak value and then decrease rapidly after a new fracture is initiated (Li et al., 2014; Liu et al., 2018). The peak value of the fracturing pressure is defined as the breakdown pressure, which is marked by red points. As shown in Figure 12, the hydraulic fracturing curves of the eight samples were displayed and analysed. The 1# and 4# samples (both SPCF) have similar hydraulic fracturing curves, which clearly show that the fracturing pressure first rapidly reaches the breakdown pressure and then decreases rapidly to a lower value, after which the pressure fluctuates slightly and nearly remains constant at 10 and 8.5 MPa, respectively. We hold the opinion that this kind of hydraulic fracturing curve belongs to the stable type, which means that the fracturing curve will tend to stabilize once a new fracture is formed. The 2#, 5# and 7# samples are MPCCF test samples. It is clear that the 2# and 5# samples...
have experienced two fracture initiation times, and then the pressure value fluctuates over a wide range, in contrast to that of 1# and 4#. Similarly, the pressure curve of the 7# sample has the same trend as 2# and 5#; however, much more fracture initiation events occur in the 7# sample. Therefore, the hydraulic fracturing curves of 2#, 5# and 7# belong to the fluctuating type; in other words, there is still the possibility of forming other fractures after the first fracture. The 3#, 6# and 8# samples are MPCSF test samples. The 3# sample is homogeneous with double-perforation clusters, and the two peak values of 15.80 and 14.50 MPa correspond to two-staged fracturing times, which is quite different from the 6# sample in

**Figure 12.** Hydraulic fracturing curves of the eight samples.
which four peaks appear, and the peak values have a large gap, which is likely because the mechanics of the upper and lower layers are different. The 8# sample is heterogeneous and has triple-perforation clusters, and the pressure distribution curve is a typical three-staged fracturing curve. Similar to 6#, the different mechanics of the sample are responsible for the difference between the three peak values of 8, 12.90 and 9.70 MPa. The 3#, 6# and 8# samples belong to the fluctuating disturbance type, which is based on curve characterization.

It can be concluded from the analysis that it is difficult to form a complex fracture system in SPCF considering the relatively few new fracture initiations regardless of whether the sample is homogeneous or heterogeneous (1# and 4# in Figure 12), which is also shown in Figure 6(a) and (c), where only simple fractures are formed. In addition, for fluctuating types 2#, 5# and 7#, when the fracturing fluid flows from the multi-perforation clusters at the same time, the fracturing pressure will change the stress field around the perforation cluster. Moreover, fracture initiation and propagation from the different perforation clusters would merge together, thus causing stress disturbances at the fracture tips, which would lead to new secondary fractures by stress coupling, as shown in Figures 7(a), 8(a) and 9(a). It is clear that all the curves are typical multi-stage curves for the fluctuating disturbance types of 3#, 6# and 8#, and the propagation direction of the main hydraulic fractures (type I) accordingly shows two or three distinct periodic variation characteristics (Figures 7(c), 8(c) and 9(c)), which suggests a complex fracture system with a large fracture area.

Two kinds of reservoirs are applied in the experiments; we define homogeneous and heterogeneous reservoirs such as #1 and #2, respectively. For the homogeneous samples, it is quite clear that the average breakdown pressure is approximately 14.63 MPa, which is much higher than the value of 11.34 MPa for the heterogeneous samples, as shown in Figure 13(a). The time of first fracture initiation for the eight samples is obtained, and fracture initiation times have the trend whereby the shorter the initiation time is, the higher the breakdown pressure is (Figure 13(a)). The numerical simulation conducted by Wang (2016) indicated that the fracture width increases with the long lasting time of injection. Based on experimental results, it can be illustrated that the longer the initiation time is, the lower the breakdown pressure is and the bigger fracture width is.

There are a total of three kinds of perforation clusters, including single-perforation clusters, double-perforation clusters and triple-perforation clusters. It is observed that a higher number of perforation clusters has a negative influence on the breakdown pressure; similarly, the stage number also has the same effect on the breakdown pressure (Figure 13(b)), which means that
a high perforation cluster density and stage number are beneficial to fracture initiation. We hold the view that the in situ stress around the wellbore would change when new hydraulic fractures are created during first-stage fracturing; thus, fracture initiation during second- or third-stage fracturing occurs much easier. The numerical investigation by Huang et al. (2017) revealed that a vertical fracture will form for a lateral pressure coefficient ($\kappa$) of 1.05–1.10. Coincidentally, the value of $\kappa$ is 1.07 in this paper, and almost all hydraulic fractures are vertical fractures during the hydraulic fracturing experiments.

Conclusions

A series of hydraulic fracturing experiments in thick tight sandstone reservoirs have been conducted in this paper. The effects of SPCF, MPCCF and MPCSF on hydraulic fracture initiation and propagation were compared and examined. The conclusions are shown below:

1. The hydraulic fracture propagation characteristics of SPCF are relatively simple, namely, it is difficult to form complex fracture systems regardless of whether the sample is homogeneous or heterogeneous. In contrast, MPCSF can lead to a complex fracture system, especially in heterogeneous samples. Optimizing the perforation cluster density would help to augment the complexity of the fracture network.

2. In MPCSF, the fractures formed during first-stage fracturing will change the stress state near the wellbore; therefore, the newly formed fractures during second-stage hydraulic fracturing would propagate in a different direction, thus leading to a multi-directional hydraulic fracture network. The propagation direction of hydraulic fractures tends to change in a heterogeneous sample.

3. The fracture area greatly increased with increasing perforation cluster density in MPCCF and MPCSF, while the fracture area in MPCSF was much larger than those in SPCF and MPCCF. The interference of vertical fractures can lead to complicated hydraulic fractures during MPCSF, and the fracture area is greatly increased.

4. A higher perforation cluster density and larger stage number are beneficial to fracture initiation. The breakdown pressure in homogeneous samples is much higher than that in heterogeneous samples. The time of first fracture initiation has the trend whereby the shorter the initiation time is, the higher the breakdown pressure is.

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