



Understanding hydraulic fracture propagation behavior in tight sandstone–coal interbedded formations: an experimental investigation

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Abstract

Whether hydraulic fractures could connect multiple gas zones in the vertical plane is the key to fracturing treatment to jointly exploit coalbed methane and tight sandstone gas through integrative hydraulic fracturing in tight sandstone–coal interbedded formations. Laboratory true triaxial hydraulic fracturing experiments were conducted on layered specimens with different combination types of natural sandstone and coal to simulate the propagation behavior of hydraulic fractures. The effects of the fracture initiation position, fracturing fluid viscosity and injection rate were discussed. The results showed that different fracture morphologies could be found. When initiating from coal seams, three patterns of fracture initiation and propagation were obtained: (1) The main hydraulic fracture initiated and propagated along the natural fractures and then diverged due to the effects of in situ stress and formed secondary fractures. (2) The hydraulic fracture initiated and propagated in the direction of the maximum horizontal stress. (3) Multiple fractures initiated and propagated at the same time. With the same fracturing fluid viscosity and injection rate, the hydraulic fractures initiating in sandstones had greater chances than those in coal seams to penetrate interfaces and enter neighboring layers. Excessively small or large fracturing fluid viscosity and injection rate would do harm to the vertical extension height of the induced fracture and improvement of the stimulated reservoir volume. Compared with operation parameters (fracturing fluid viscosity and injection rate), the natural weak planes in coals were considered to be the key factor that affected the fracture propagation path. The experimental results would make some contributions to the development of tight sandstone–coal interbedded reservoirs.

Keywords Hydraulic fracturing · Fracture propagation · Sandstone–coal interbed · Layered formation

1 Introduction

Coal-bearing strata consist of interbedded coal seams and tight sandstones deposited and jointly preserved in the vertical direction. Due to the effects of the characteristics of shallow burial depth, multiple gas zones and poor permeability, it is very difficult to develop one type of gas resource separately from the coal-bearing strata (Qin et al. 2014). Great attention has been paid to comprehensive research and development of the unconventional gases in coal-bearing strata (Li et al. 2014; Qin et al. 2014; Shen et al. 2017). Some pilot tests with integrative hydraulic fracturing were conducted in some areas (such as the Surat Basin in Australia (Shen et al. 2017) and Xuanhua Basin in China (Li et al. 2014)) and achieved great progress. To realize co-exploitation of many types of gas successfully, it is necessary to make hydraulic fractures effectively connect different production layers in the vertical direction

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and to communicate with natural weak planes in coal seams to form an optimized fracture network.

With regard to the vertical propagation of hydraulic fractures in layered media, many studies have been carried out including laboratory experiments and numerical simulations. In aspects of laboratory research, Anderson (1981) and Hanson et al. (1981) studied the effect of interfacial friction on fracture height growth and found that the lower the friction coefficient, the greater the normal stress required for hydraulic fracture to cross the interface. Based on laboratory experiments and field tests, Warpinski et al. (1982), Teufel and Warpinski (1983) and Teufel and Clark (1984) revealed that mechanical property differences between layers were not sufficient to prevent the propagation of hydraulic fractures at the interface, whereas the minimum in situ stress difference was critical for the fracture propagation path. Roundtree and Miskimins (2011) performed experiments combined with acoustic emission monitoring to analyze hydraulic fracture propagation patterns in layered media. The results showed that a penny-shaped fracture plane would be formed when a layered interface was well cemented. Liu et al. (2016) studied the influences of different deviation angles, borehole azimuths, perforation parameters and in situ stress on multi-fracture propagation from layered formations in inclined well hydraulic fracturing. AlTammar and Sharma (2017) used digital image correlation to resolve full-field displacement and strain when fracturing layered formations.

In respect of numerical simulations, Fung et al. (1987) studied the influences of stress difference and elastic modulus contrast on the fracture height growth based on a semi-analytical and finite element method. The results showed that the modulus contrast between layers had little effects on fracture height growth. However, the minimum horizontal stress difference was the main factor when the extension height was low with large stress differences. Smith et al. (2001) indicated that fracture widths could be affected by differences in the elastic modulus between different layers. Barriers with large elastic modulus produced narrow fractures and a high fluid pressure, and thus, fractures easily penetrated the interface. Zhao and Chen (2010) revealed that a critical fracture length exists when fracturing ceases. Hydraulic fractures would extend along layer interfaces or break into adjacent layers when the fracture length exceeds a certain critical value. Zhao et al. (2015) and Chuprakov and Prioul (2015) took into account the stress change around the layer interface, analyzing the mechanical behavior when the hydraulic fracture came across the interface. Ouchi et al. (2017) established a peridynamics-based hydrodynamic fracturing model and studied the propagation behavior of hydraulic fractures in the vertical plane. His study showed that three types of hydraulic fracture geometries (including turning, kinking and branching) near the layer interface

were explored, which were consistent with the experimental results of AlTammar and Sharma (2017).

However, the above studies focused on homogeneous layered media, and the theoretical models were based on the assumption of linear elasticity, ignoring the effect of natural fractures on fracture propagation. Previous studies showed that, under the influences of natural fractures and cleats, hydraulic fracture geometries in coal seams were complex, which were different from those in tight sandstone reservoirs (Fan et al. 2014; Tan et al. 2017a). Therefore, when naturally fractured coals and homogeneous sandstones are fractured jointly, hydraulic fracture geometries may exhibit great differences with traditional homogeneous layered formations (Hou et al. 2016; Tan et al. 2018). To understand the propagation of hydraulic fractures in tight sandstones–coal interbedded reservoirs, this paper used natural coal and tight sandstone samples to produce different combinations of layered media (including three and five layers) to carry out true triaxial fracturing experiments. Due to the low availability of reservoir cores, fresh outcrop samples are selected from Baode County in the northeast of the Ordos Basin in Shanxi Province, China (see Fig. 1). The propagation behavior of hydraulic fractures initiating from different rocks is discussed. In addition, the effects of engineering parameters (including fracturing fluid viscosity and injection rate) on fracture propagation in the vertical direction are studied.

2 Experimental setup and procedures

2.1 Experimental equipment

All sets of hydraulic fracturing experiments were conducted using a true triaxial hydraulic fracturing test system (see Fig. 2). All external stresses were applied via a voltage stabilizer, and the injection pressure was supplied using a servo-controlled voltage pump, a mechanical testing and simulation 816 (Zhou et al. 2008). Stresses of up to 28 MPa and injection pressures of up to 140 MPa were applied to a cubic specimen with an edge length of 40 cm. The injection system can pump up to 800 mL of fluids continuously. Experimental control and data acquisition were conducted using customized software running on a desktop computer. This system was used successfully to initiate and to propagate hydraulic fractures in a variety of materials using different fracturing fluids.

2.2 Experimental preparation and scheme

The mechanical parameters were measured by the triaxial fracturing system under a confining pressure of 15 MPa. The compressive strength, elastic modulus and Poisson's ratio of the coal rock are 98.6 MPa, 4.39 GPa and 0.26, respectively.

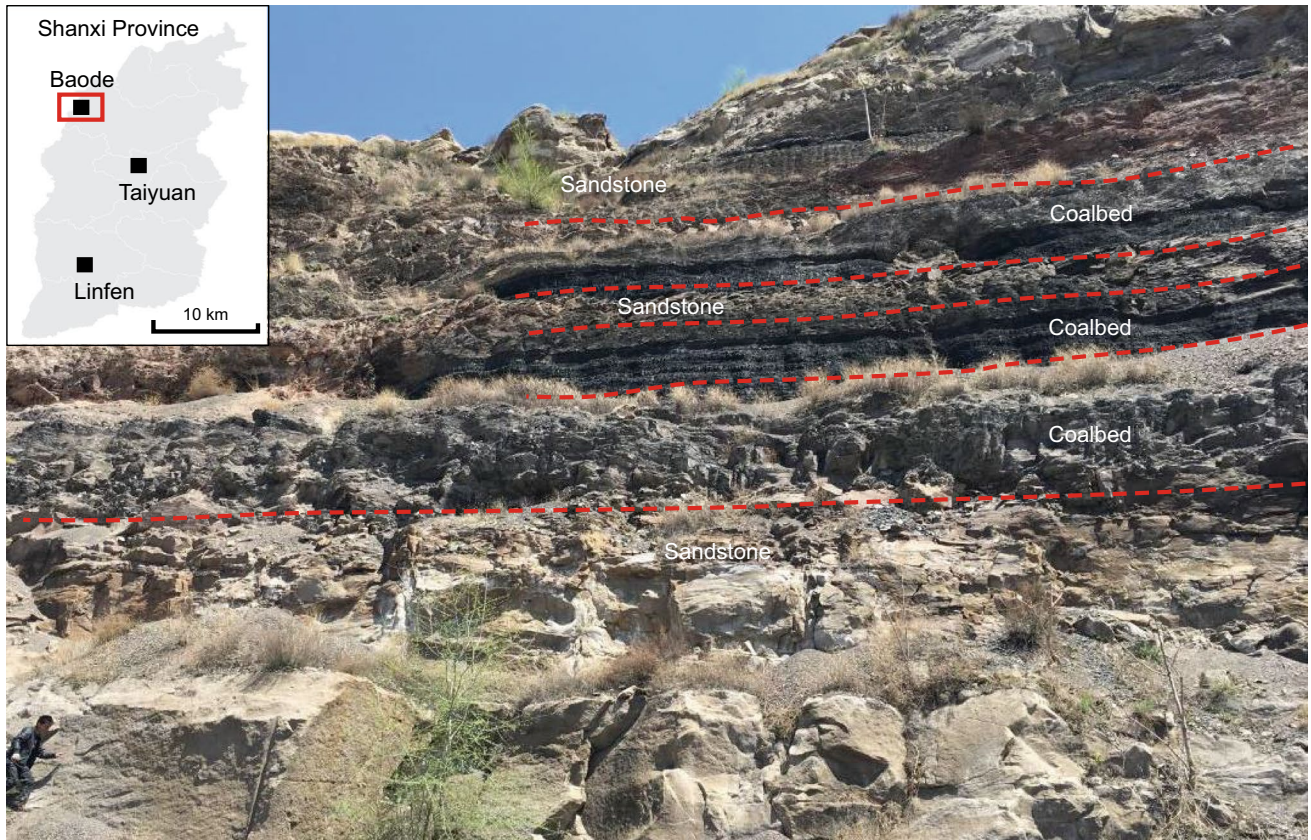


Fig. 1 The sampling location and outcrops section

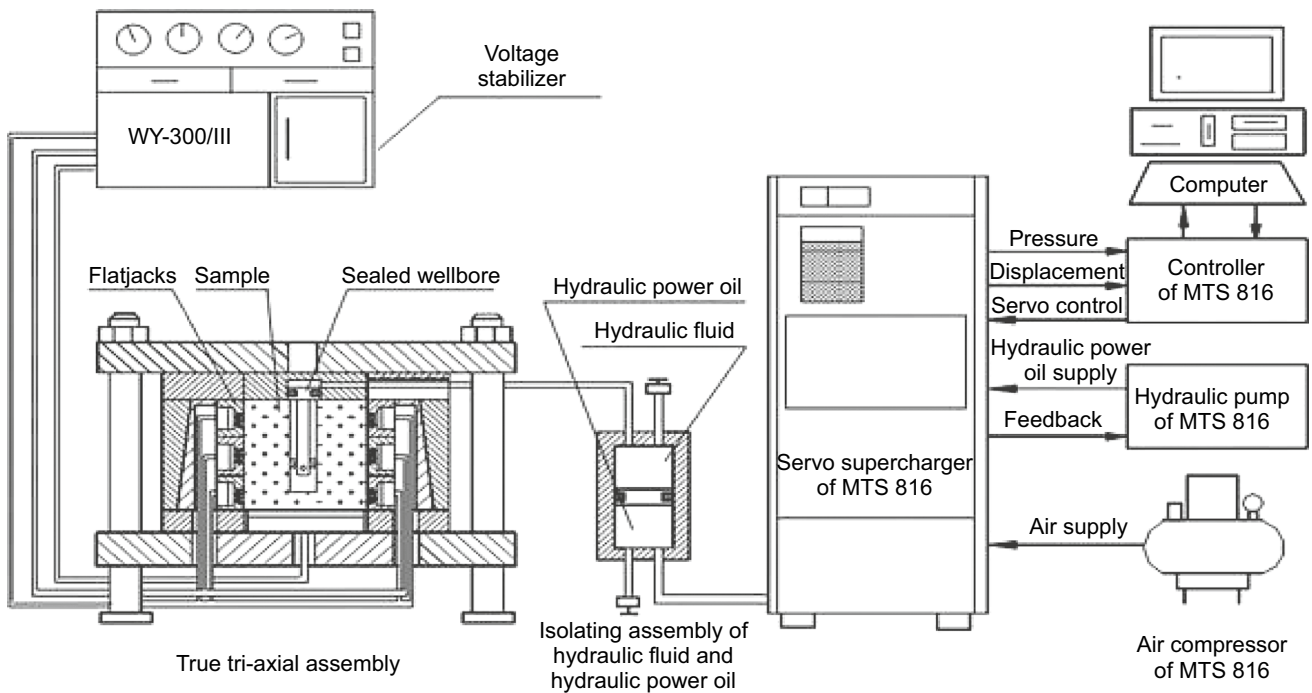


Fig. 2 Schematic of true triaxial fracturing system (Zhou et al. 2008)

The compressive strength, elastic modulus and Poisson’s ratio of the tight sandstone are 162.8 MPa, 12.3 GPa and 0.17, respectively.

In this study, combined specimens with three or five layers had a similar processing method. The preparation of a five-layer specimen was described as follows: (1) A piece of irregular outcrop was cut into a cuboid (dimensions: 5 cm × 30 cm × 30 cm, 10 cm × 30 cm × 30 cm or 15 cm × 30 cm × 30 cm) by a CNC wire-cut machine. It is important to note that the bedding planes were parallel to the large face of the cuboid, so as to ensure that the vertical stress was applied perpendicularly to the bedding plane. (2) Epoxy resin was used to cement sandstone and coal layers, forming a block with dimensions of 35 cm × 30 cm × 30 cm. (3) The bonded block was placed at the bottom of a special mold (Zhou et al. 2008) and then wrapped by concrete uniformly to form a testing block with a side length of 40 cm. (4) Specimens were allowed to cure in air for 1 month to be completely solidified. Subsequently, by using a hollow boring bit, a 16-cm-deep counter bore was drilled parallel to the layer interface at the center of the sample surface. (5) A steel pipe, with dimensions of 0.6 cm in inner diameter, 1.6 cm in outer diameter and 12 cm in length, was fixed with a high-strength adhesive in the borehole. A 4-cm open hole was reserved below the wellbore. Detailed procedure is shown in Fig. 3. The final testing specimen is shown in Fig. 4.

The specific experimental parameters are listed in Table 1. Test sample 1# to sample 3# were tri-layered media, and sample 4# and sample 5# were five-layered media. The stress conditions were the same for all samples: the vertical

stress is 27 MPa, the maximum horizontal stress 22 MPa, and the minimum horizontal stress 16 MPa.

2.3 Experimental procedure

Spiral perforation instead of open hole completion is always adopted in oilfields. Limited by the scale of indoor experiments, it is difficult to perform such operations as casing cementing and helical perforation. Therefore, complex near-wellbore fractures induced by helical distribution of perforations were neglected. Instead, the fracture propagation from only one perforation hole along the direction of the maximum horizontal stress was investigated. In the experiments, the maximum horizontal stress was applied along the simulated perforation hole axis, the vertical stress perpendicular to the interface and the minimum horizontal stress perpendicular to the direction of maximum horizontal stress and vertical stress (Fig. 4a). To avoid the unbalanced loading of triaxial stresses, the 3D stresses were first loaded to the value of the minimum horizontal stress at the same time (16 MPa), and then the maximum horizontal stress and vertical stress were slowly increased to the set maximum horizontal value (22 MPa). Eventually, the vertical stress was again slowly increased to the designed value (27 MPa) to finish the 3D stress loading. Once the stresses reached their desired values, a delay of approximately 15 to 30 min was allowed to establish a stress equilibrium around the hole prior to the fracturing test. After experiments, we observed fracture geometries based on the tracer distribution of the luminous yellow fluorescent dye added to the fracturing fluids.

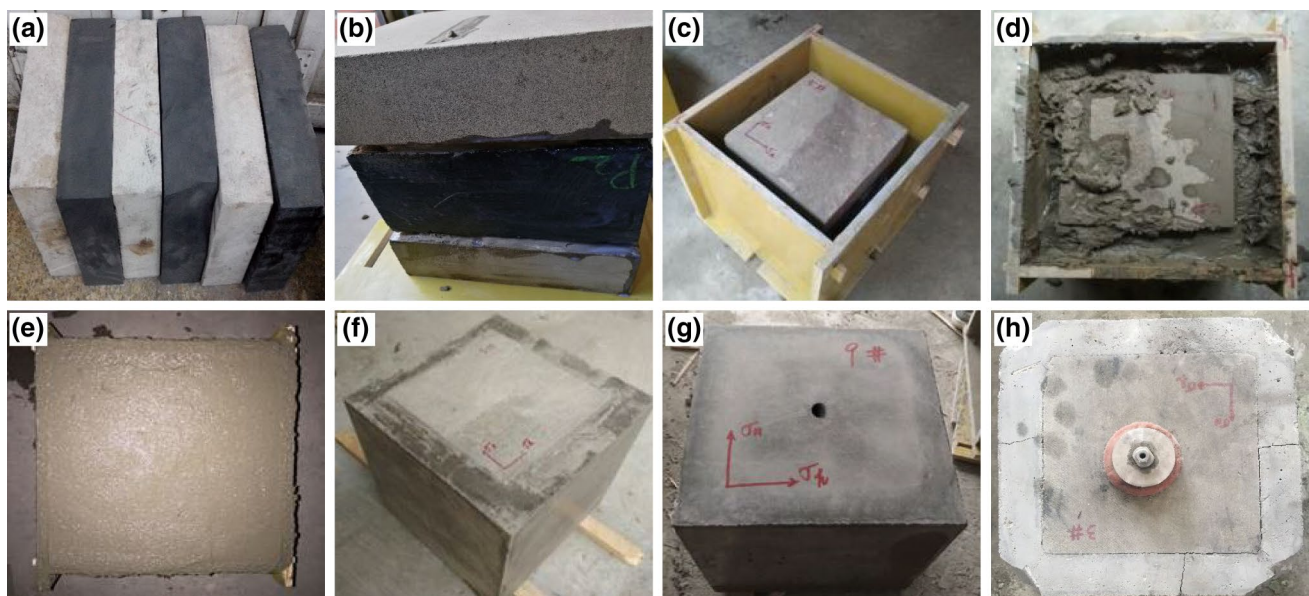


Fig. 3 Specimen preparation. **a** Prepared rock slice. **b** Cemented rock slice. **c** Waiting for concrete pouring. **d** Concrete pouring. **e** Maintenance for concrete setting. **f** Combined specimen. **g** Hole drilling. **h** Steel pipe fixing

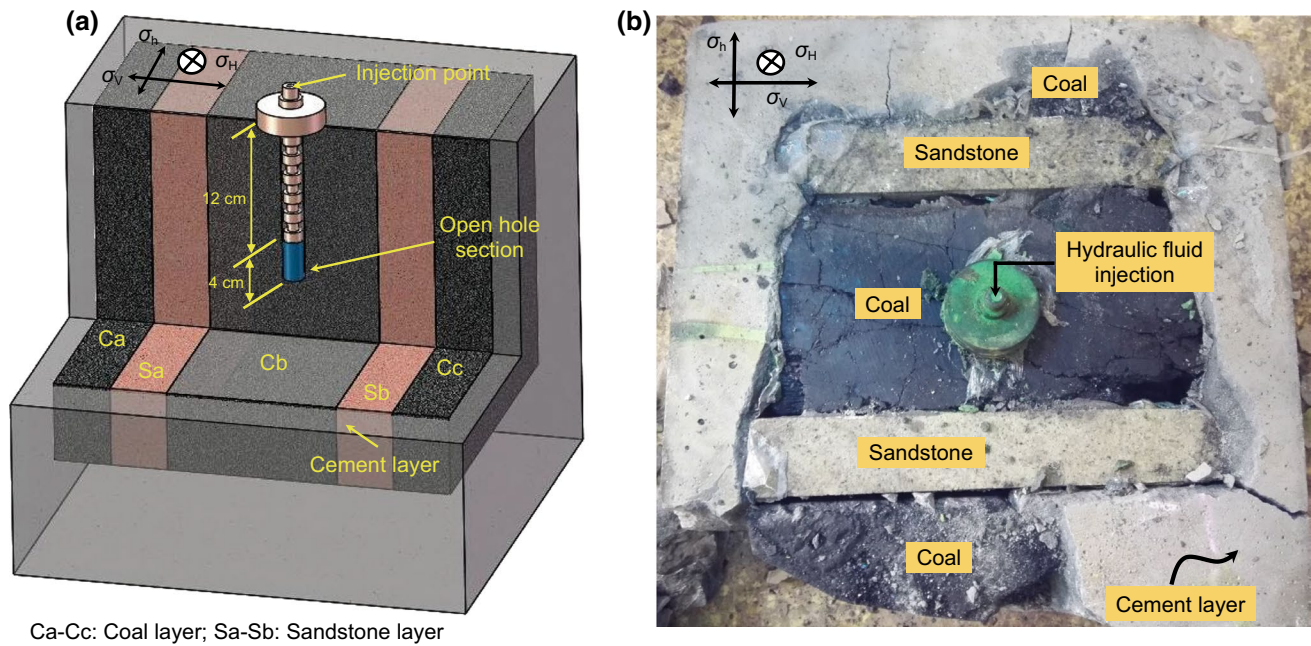


Fig. 4 Illustration of the testing specimen. **a** Schematic diagram. **b** Real fracturing specimen

Table 1 Summary of experimental parameters

Specimen number	Rock combination	Thickness of the rock slice, cm	Fracture initiation position	Injection rate, mL/min	Viscosity, mPa s
1#	S1-C1-S2	10-15-10	Coal	10	3
2#	S3-C2-S4	10-15-10	Coal	30	16.5
3#	C3-S5-C4	10-15-10	Tight sandstone	10	16.5
4#	C5-S6-C6-S7-C7	5-5-15-5-5	Coal	20	33.5
5#	C8-S8-C9-S9-C10	5-5-15-5-5	Coal	20	3
6#	S10-C11-S11-C12-S12	5-5-15-5-5	Tight sandstone	20	3
7#	S13-C13-S14-C14-S15	5-5-15-5-5	Tight sandstone	20	16.5

The symbol of C1 to C14 and S1 to S15 indicated different coal slices and sandstone layers, respectively

3 Experimental results and analysis

3.1 Experimental results

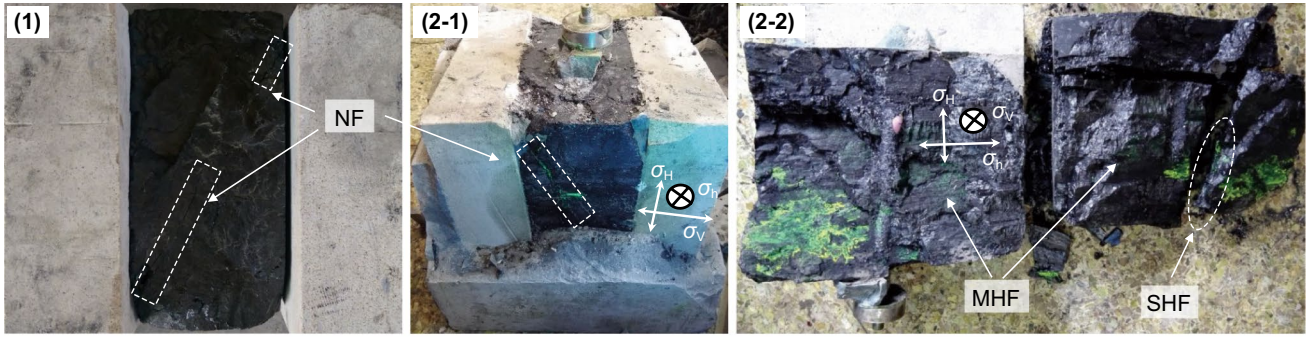
After experiments, the specimen was split along the fracture surface to observe the initiation and propagation of hydraulic fractures. The post-fracture morphology is shown in Figs. 5 and 6. The results show that hydraulic fracture geometries initiating from coal are significantly different from those from sandstone. Instead of initiating a simple fracture perpendicular to the direction of the minimum horizontal stress from the sandstone slice, multiple fractures in coal blocks may be produced with cleats or natural fractures opening.

3.1.1 Initiation from the coal

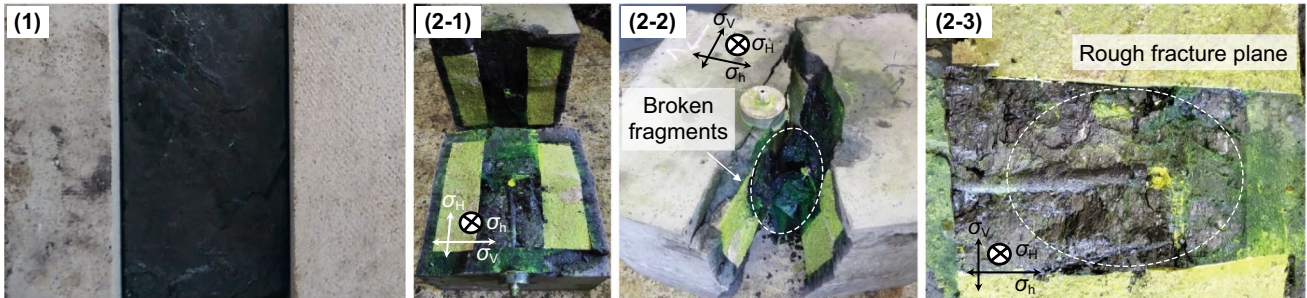
When the fracture initiation position was located in the coal seam, the initiation and propagation of hydraulic fractures exhibited the following three patterns.

(1) *Pattern I*: The main hydraulic fracture initiated and propagated along the direction of natural fractures with some secondary fractures due to the effect of in situ stress (specimen 1#, specimen 4# in Fig. 5. For specimen 1#, there was an inclined natural fracture crossing the borehole. Although diverting partially along the vertical stress direction, the main hydraulic fractures propagated along the natural fracture inside the coal seam and failed to extend to the sandstone layer. For specimen 4#, the main

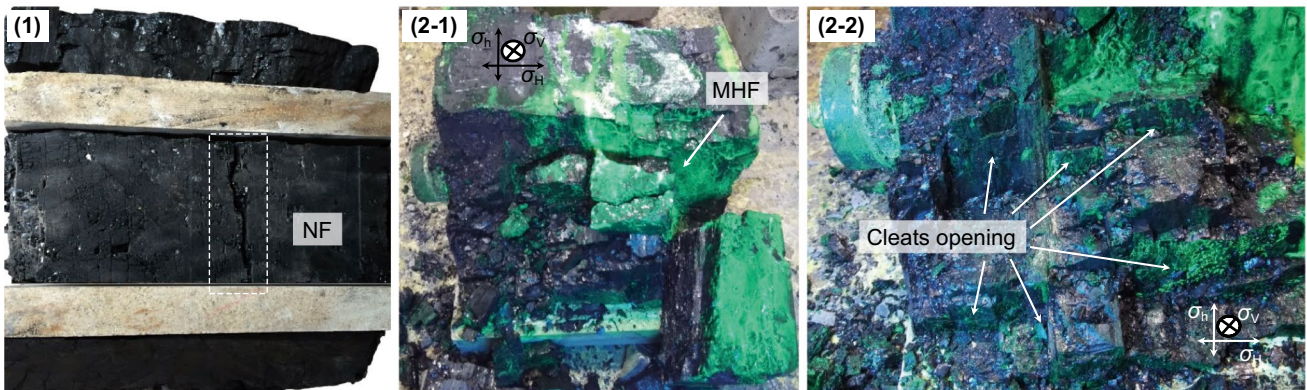
(a) Specimen 1# (S1-C1-S2)



(b) Specimen 2# (S3-C2-S4)



(c) Specimen 4# (C5-S6-C6-S7-C7)



(d) Specimen 5# (C8-S8-C9-S9-C10)

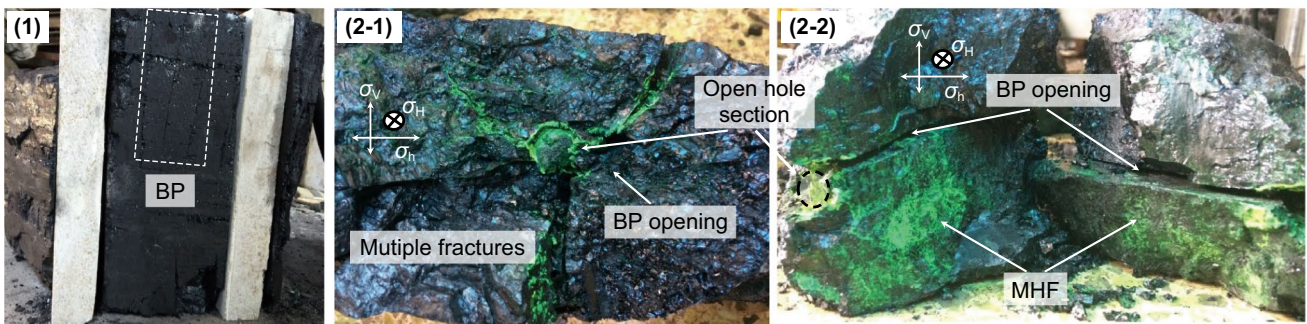
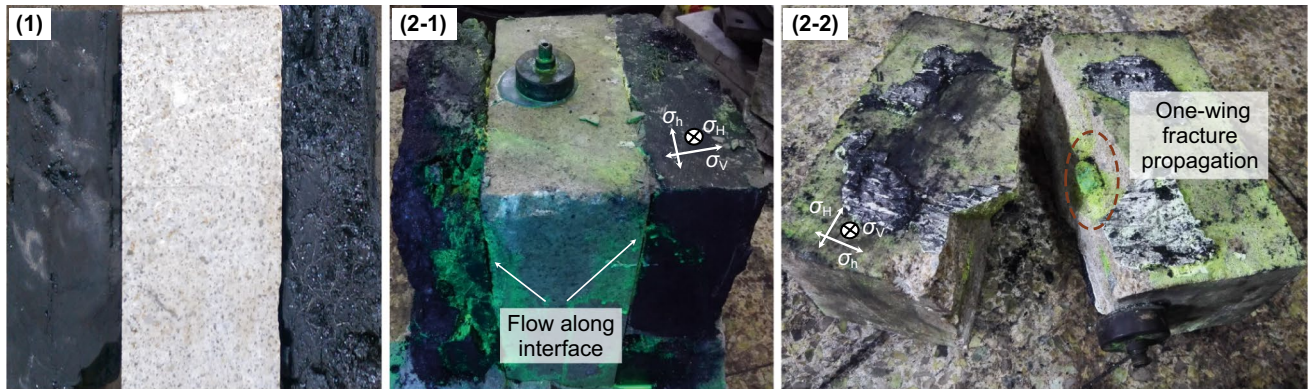
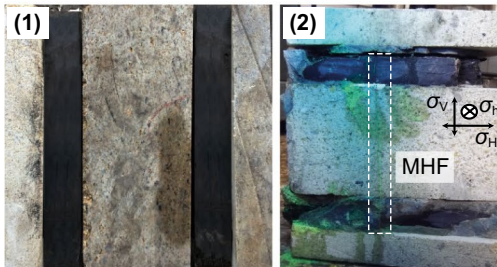


Fig. 5 Fracture geometry before and after test from **a** to **d**: (1) before test; (2–1) to (2–3) after test. *NF* indicates natural fracture; *BP* indicates bedding plane; *MHF* indicates main hydraulic fracture; and *SHF* indicates secondary hydraulic fracture

(a) Specimen 3# (C3-S5-C4)



(b) Specimen 6# (S10-C11-S11-C12-S12)



(c) Specimen 7# (S13-C13-S14-C14-S15)

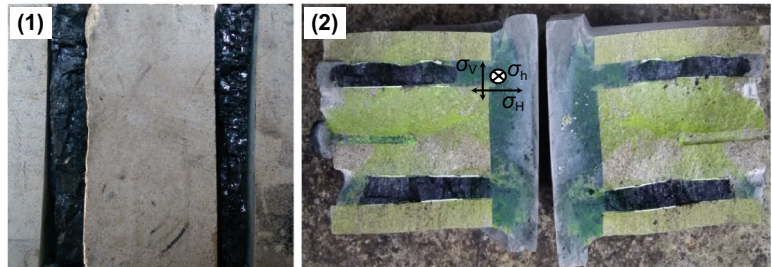


Fig. 6 Fracture geometry before and after test from (a)–(c)

hydraulic fractures also initiated and propagated along the natural fracture with a large aperture in the vertical direction. In the process of fracture propagation, the fracturing fluid was completely filtered along coal seams to form complex fractures. The hydraulic fractures eventually did not penetrate the layer interface.

(2) *Pattern II*: The hydraulic fracture initiated and propagated along the vertical direction perpendicular to the minimum horizontal stress (specimen 2# in Fig. 5). In specimen 2#, the coal block had a relatively complete structure and no obvious cracks were observed in the surface. Under high injection conditions (30 mL/min), the hydraulic fracture crossed the layer interface and connected the neighboring layers. In addition, due to the low strength and brittleness of coal, rock collapse occurred near the wellbore, and the main fracture surface was rough.

(3) *Pattern III*: Multiple fractures initiated and propagated simultaneously (specimen 5# in Fig. 5). Affected by the multiple factors of the developed bedding planes and in situ stress, the fracture geometry near the wellbore was complex in specimen 5#. Hydraulic fractures including both vertically and horizontally were finally formed and did not propagate into the neighboring sandstone layers.

3.1.2 Initiation from the tight sandstone

When the initiation position was located in the tight sandstone layer, hydraulic fractures primarily initiated and propagated along the direction perpendicular to the minimum horizontal stress, and the vertical extension distance of the hydraulic fractures was related to the operation parameters (fracturing fluid viscosity and injection rate) and the mechanical properties of the coal block. Experiment results are shown in Fig. 6.

At a low injection rate (10 mL/min), the hydraulic fracture propagated unilaterally to the layer interface and then diverted along the layer interface, forming a simple “T”-shaped fracture geometry in sample 2# (see Fig. 6a).

When the injection rate was increased to 20 mL/min, the hydraulic fracture penetrated the interface and communicated with the coal seam (see Fig. 6b, c). Since a low-viscosity fracturing fluid (3 mPa s) was injected into specimen 6# (see Figs. 6b and 7), a complex fracture network with many beddings and cleat opening was formed after the hydraulic fractures entered the coalbed. Massive fracturing fluid loss via the natural fracture systems in coal resulted in a limited height growth, preventing fractures penetrating the top and bottom sandstone layers. In specimen 7# a high-viscosity fracturing fluid (16.5 mPa s) was used; to a certain extent, this reduced

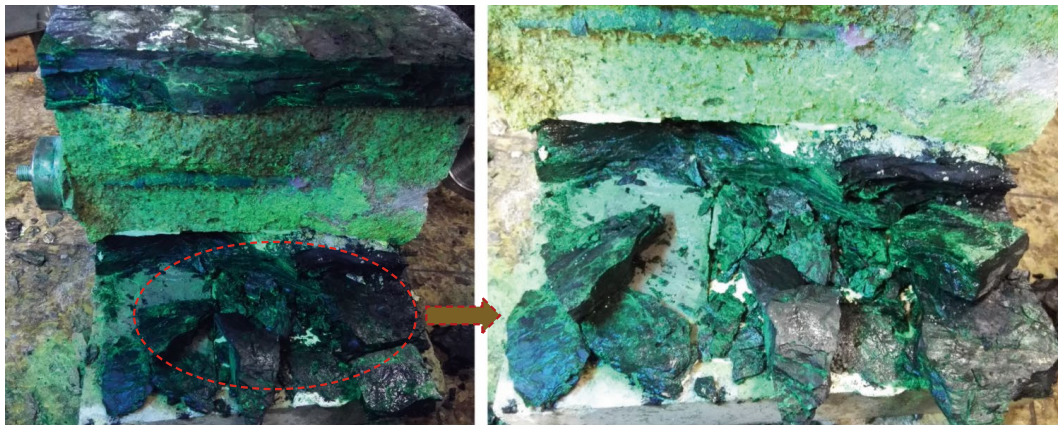


Fig. 7 Fracture geometry of specimen 6# after test

the complexity of hydraulic fractures in coal seams. A single vertical fracture penetrating all the layers was finally formed (see Fig. 6c).

The above results indicated that the features of hydraulic fractures in coal blocks exhibited a great difference from what is observed in sandstone. Due to the influences of the natural fracture system, when the initiation position was located in the coal seam, the hydraulic fractures initiated and propagated with complexity, and hydraulic energy was distributed to multiple fractures and reduced the probability of connecting the sandstone. However, with identical fracturing fluid viscosity and injection rate, hydraulic fractures initiating in sandstones had greater chances than those in coal seams to connect to neighboring layers. Therefore, it was suggested that the initiation position in the naturally fractured coal seam should be avoided for the integrative hydraulic fracturing in tight sandstone–coal interbedded formation, whereas the adjacent sandstone layer could be selected to improve the operation effects. If it could not be avoided, probability of penetration could be improved by increasing the injection rate. In this situation, it should be noticed that collapse and coal powder might occur near wellbore.

3.2 Experimental analysis

3.2.1 Effects of fracturing fluid viscosity and injection rate

The viscosity and injection rate of the fracturing fluid are two important controlling parameters in fracturing designs, which have important influences on the initiation and propagation of hydraulic fractures. In this paper, three groups of liquid viscosity and injection rate were investigated. The results showed that when the viscosity of the fracturing fluid was low (3 mPa s), the fracturing fluid was easy to seep via the bedding plane and shear slip occurred, which led to an excessive opening of weak planes in coal, thus increased

the complexity of hydraulic fractures in coal and limited the vertical propagation (specimen 1#, 5# and 6#). As shown in sample 6# in Figs. 6b and 7, after hydraulic fractures extended to coal seams, the low-viscosity fracturing fluids were fully infiltrated along the weak planes, resulting in a high fragmentation degree. When reaching the layer interface, the hydraulic fractures failed to enter the top and bottom sandstone layers. Compared with sample 6#, the fracturing fluid viscosity in sample 7# increased to 16.5 mPa s, which ensured the formation of complex fractures in the coal seam to a certain extent. At the same time, the fluid loss reduced and higher fracture pressure promoted hydraulic fractures to connect all layers, resulting in larger fracture height (see Figs. 6c and 8).

Figure 9 shows the combined effects of fluid viscosity and injection rate. It could be found that when the fracturing fluid injection rate was small (10 mL/min), the hydraulic fractures tended to propagate along natural fractures and cleats, reducing the probability of penetrating the layer interface (specimens 1# and 3# in Fig. 9). An appropriate increase in injection rate could improve the fracture pressure and fracture penetration capacity (specimen 7# in Fig. 9). However, too high injection rate (30 mL/min in specimen 2#) would reduce the fracturing fluid filtration effect, thereby reducing the complexity of hydraulic fractures. From the above analyses, it could be seen that an appropriate injection rate or fracturing fluid viscosity (specimen 7# in Figs. 8 and 9) should not only meet the requirement of fracture height, but also promote the formation of secondary fractures in the coal seam and increase SRV. Too high an injection rate and too low a fracturing fluid viscosity are not conducive to improving the final fracturing effect. Beugelsdijk et al. (2000) and Guo et al. (2014) used the product of fracturing fluid viscosity and displacement ($q \cdot \mu$) to comprehensively analyze the effect on the complex fracture propagation in naturally fractured formations. The results showed that the

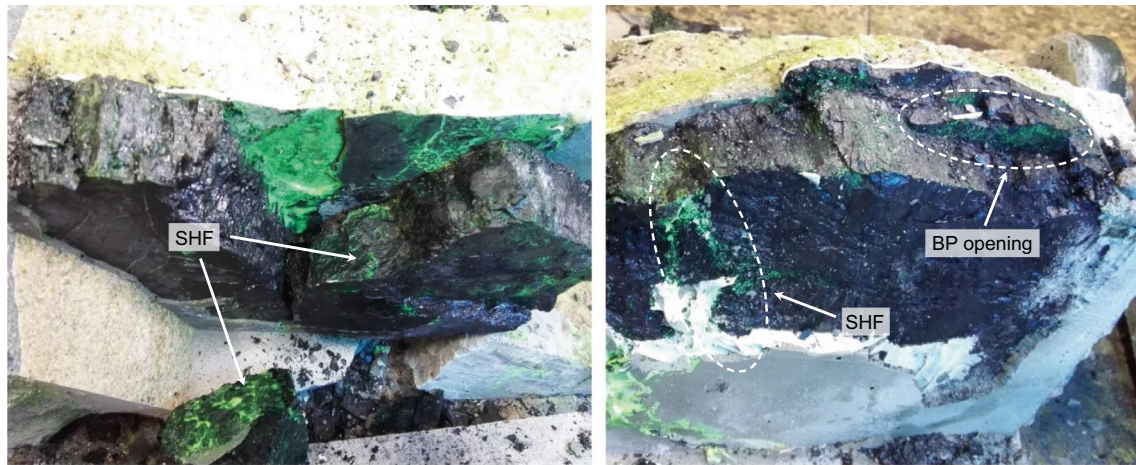


Fig. 8 Fracture geometry of specimen 7# after test

values excessively high or low were not favorable for the formation of complex fracture networks, which was consistent with the conclusions of this study. However, a short fracture height limited in the coal was formed in specimen 4# (see Fig. 5c) with high fluid viscosity and large injection rate. Analysis indicated that it is mainly due to the effects of developed natural fractures and cleats in the coal (see Fig. 5c). Compared with operation parameters (fracturing fluid viscosity and injection rate), properties of natural

fractures in the coal were the key factors influencing fracture propagation.

3.2.2 Effects of cleats in coal seam

The propagation of hydraulic fractures in coal would be influenced by beddings, cleats and other natural weak planes in addition to the impact of operation parameters (Fan et al. 2014; Tan et al. 2017b). The experimental results

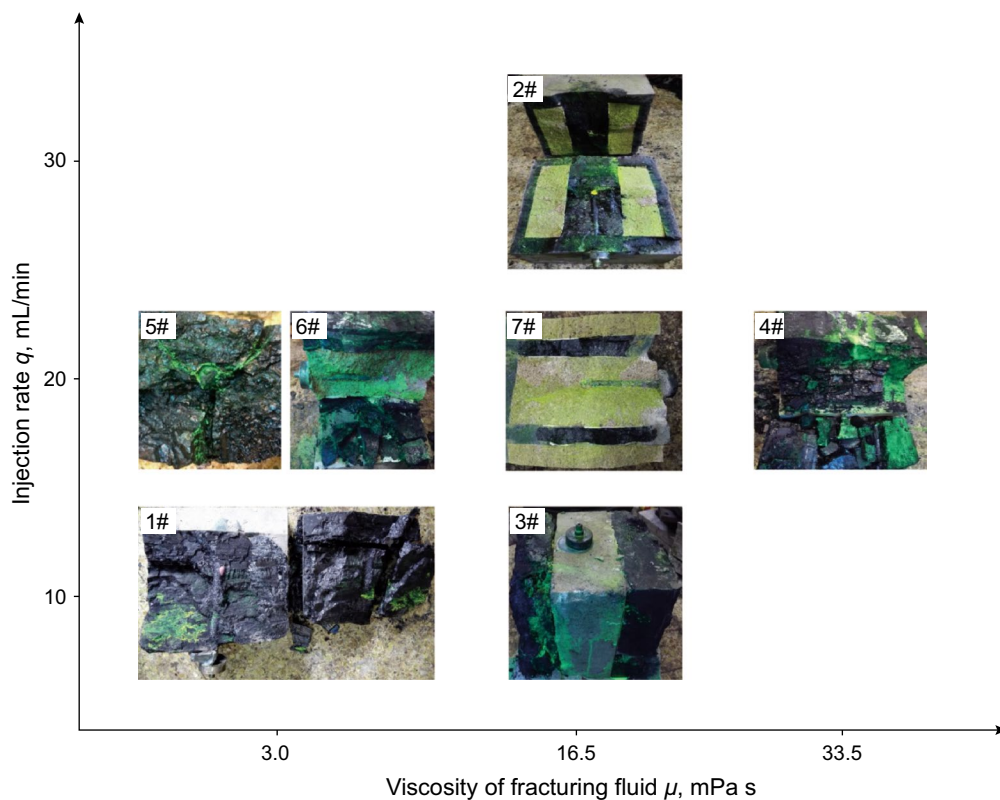


Fig. 9 Fracture geometry under different operating parameters

(experimental results of this study or of Fan et al. 2014; Tan et al. 2017b) showed that the development degree, distribution and aperture of natural weak planes had important influences on fracture initiation and propagation. Influenced by cleats, the fracture surfaces are rough and tortuous. In specimen 1# (Fig. 5c) and specimen 4# (Fig. 5c), the main hydraulic fracture initiated and propagated along the pre-existing natural fractures, although the secondary fractures locally diverted or bifurcated along the vertical stress direction. In contrast, the natural fractures in sample 2# (Fig. 5b) were not well developed and the hydraulic fractures began to propagate along the vertical minimum stress direction to form a single main fracture.

Many researchers (Li et al. 2017a, b; Warpinski and Teufel 1987; Zhou et al. 2008) have found that the approach angle between the hydraulic fracture and the natural fracture had an important effect on the propagation path of hydraulic fractures. When the approach angle was less than 30°, the hydraulic fracture would deflect along the natural fracture. When the approaching angle was between 30° and 60°, the hydraulic fracture would be arrested and shear slip of the natural fractures would occur. When the approaching angle was more than 60°, the hydraulic fracture could penetrate into the natural fractures. However, the experimental results in this study showed that the fracturing fluid could seep into natural weak planes in a variety of angles and mutually communicate with each other. Therefore, except for the angle of the natural weak plane, the natural fracture aperture and the cement strength also had significant impacts on the fracture morphology. During the process of hydraulic fracturing, the fracturing fluid might flow or seep along the natural fracture system in the coal, reducing the friction properties and the cement strength of the fracture surface. Based on the

cross-criterion (Gu et al. 2012; Li et al. 2017a, b), when the friction coefficient or cohesion of fracture surface decreases, the surface will undergo shear slip, and thus, the natural fracture system will open or be activated.

3.2.3 Response characteristic of fracturing pressure

Figure 10 shows the fracturing curves of each sample initiated from different positions. The curves could reflect the occurrence of hydraulic fractures under the action of fracturing fluid and the changes in the natural weak surface. Proper analyses and explanations of the curves are helpful to understand some fracture features that could not be observed directly.

Comparing Fig. 10a with Fig. 10b, when the initiation position was located in the sandstone layer, the fracture initiation pressure was significantly higher than the pressure at the time of initiation from the coal seam. Furthermore, affected by coal cleats and natural fractures, the initiation pressure of each specimen displayed a great difference when fracturing from the coal seam.

From the aforementioned analyses, it could be seen that when the fracture initiated from the coal layer, there would be three types of fracture propagation patterns, that is, along the natural fractures, along the direction perpendicular to the minimum horizontal stress and along multiple directions simultaneously.

(1) When the hydraulic fracture extended along the natural fractures near the wellbore, the fracturing fluid mainly flowed along these weak surfaces. The fracturing curve exhibits a low breakdown pressure, a low breakdown pressure drop and a low extension pressure (specimen 1# and 4# in Fig. 10a). In particular, for specimen 4# (Fig. 5c), when

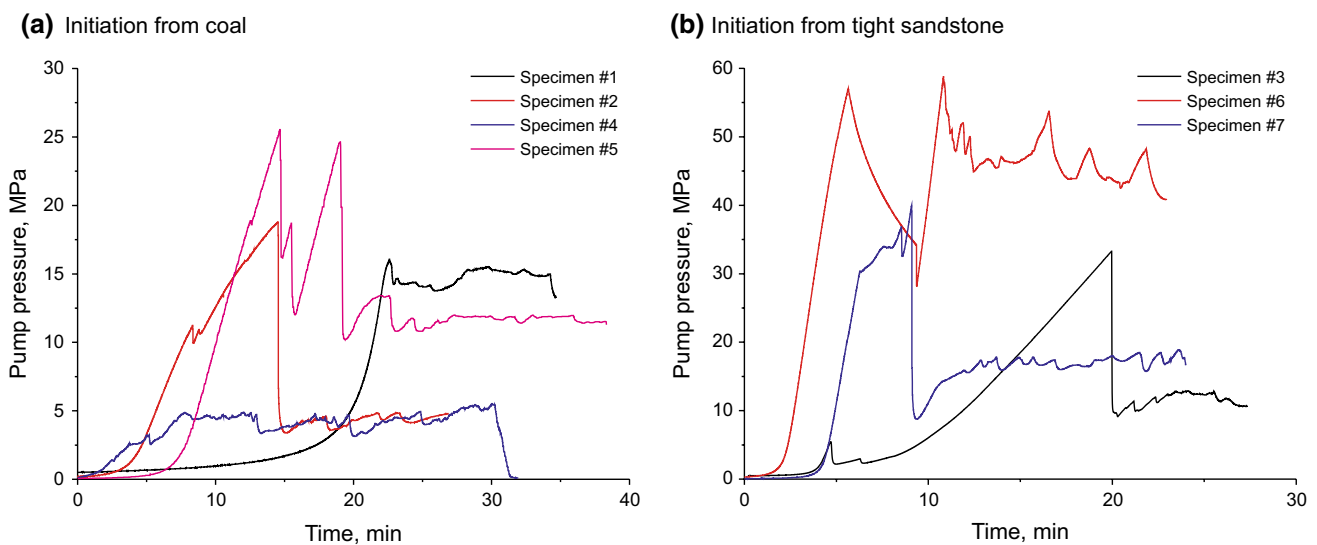


Fig. 10 Experimental pressure profile

the aperture of natural fractures near the wellbore was large, the breakdown pressure was extremely low and almost no significant breakdown characteristics exist in the fracturing curve. As the fracturing fluid flowed along the cleat system during the fracturing process, a saw-toothed fluctuation characteristic in the fracturing pressure profile showed (specimen 4# in Fig. 10a).

(2) When the hydraulic fracture initiated and propagated along the direction perpendicular to the minimum horizontal stress, the fracturing curve displayed high breakdown pressure and high breakdown pressure drop (such as specimen 2# in Fig. 10a).

(3) When the hydraulic fracture initiated and propagated along multiple directions simultaneously, the pressure curves showed multiple breakdown pressures and significant fluctuation characteristics. As in specimen 5#, multiple fractures extended simultaneously, and the injected hydraulic energy was dispersed, thus increasing the fracture extension pressure (specimen 5# in Fig. 10a).

When the fracture initiated from the sandstone, the fracture initiation would not be affected by natural fractures, and the fracture geometry was simple near the wellbore, which was perpendicular to the minimum horizontal stress direction. The fracturing curve was characteristic of high breakdown pressure and distinct breakdown pressure drop. In addition, the curve characteristics were closely related to the post-fracture geometry in coal. Compared with specimen 6# and specimen 7#, it could be found that the more complex the post-fracture geometry, the greater the fluctuation of pressure curve (specimen 6# and 7# in Fig. 10b).

4 Discussion

Different from the concept of fracturing development in a single coal seam, it is not only desirable to obtain complex fractured networks in the coal seams, but also to require hydraulic fractures to extend in the vertical direction to communicate gas-bearing layers as much as possible in the co-exploitation of tight sandstone–coal reservoirs. It was found that when the initiation position was located in the coal, it is considerably easier to form complex fractures near the wellbore, which reduces the fracture penetration. At the same time, the formation of coal powder would hamper proppant migration. When the initiation position is located in the sandstone layer, the hydraulic fracture propagated almost along the direction perpendicular to the minimum horizontal stress and connected the neighboring layers more easily. Fracturing practice in the Xuanhua coal field in Hebei Province, China (Li et al. 2014), showed that the hydraulic fracture initiated from a sandstone layer with higher elastic modulus contributes to long fracture height and complex fracture network, effectively reducing the formation of coal

powder and multiple fractures near the wellbore and improving the single well gas production.

Results showed that the viscosity and injection rate of the fracturing fluid had important influences on the fracture propagation and penetration. Appropriate viscosity and injection rate could ensure large vertical fracture propagation height and formation of complex fracture networks in the coal seam. When the viscosity or injection rate of the fracturing fluid was too small, leakage would occur along the weak plane, forming multiple fractures, which is not conducive to fracture height. When the viscosity or injection rate of the fracturing fluid was too high, a single fracture was formed and the stimulated reservoir volume would be smaller. In the stimulated coalbed gas well, in order to reduce the formation damage caused by high-viscosity guanidine gum fracturing fluid, low-viscosity slickwater or clean fracturing fluid was used. However, for coal seams with well-developed natural fractures, low-viscosity fracturing fluid may easily cause leakage, thus forming multiple fractures hampering the main fracture propagation, also inducing tip screening out. Xiao et al. (2013, 2017) improved the anti-filtration and sand carrying capacity of the fracturing fluid by incorporating biodegradable fiber material in the active water fracturing fluid and fracturing stimulation of the coalbed methane well was enhanced as a result. Therefore, in the process of co-fracturing of a tight sandstone–coal interbedded reservoir, the method of mixed fracturing can be used. In the initial stage of fracturing, a high-viscosity fracturing fluid (such as cleaning fracturing fluid) is used to form a wide main fracture, reducing the complexity of the near-wellbore fracture and improving the effect of fracture penetration; then a biodegradable fiber active water fracturing fluid is used in the coal seam to effectively improve the communication of hydraulic fractures and natural fractures, and at the same time to reduce the amount of filtration, and to improve fracture growth propagation, so as to optimize the fracture morphology. In addition, due to higher breakdown pressure in the sandstone layer, optimization of perforation parameters in advance is needed in order to reduce operation difficulty.

5 Conclusions

Based on several true triaxial hydraulic fracturing experiments, fracture initiation and propagation behavior were studied for tight sandstone–coal interbedded formations. Conclusions were summarized as follows.

Fracture morphology differed when the fracture initiated from sandstone or coal. The fracture geometry was simple when the fracture initiated from the sandstone layer; in most cases, the fracture propagated perpendicular to the direction of the minimum horizontal stress. When the fracture

initiated from the coal layer, the fracture morphology was more complex with three main patterns: (1) The hydraulic fracture initiated and propagated alongside the natural fracture, partially diverging due to in situ stress and forming secondary fractures. (2) The hydraulic fracture initiated and propagated in the direction of the maximum horizontal stress. (3) Multiple fractures initiated and propagated simultaneously.

Operation parameters (fracturing fluid viscosity and injection rate) would significantly affect the fracture propagation and penetration behavior. Appropriate viscosity as well as injection rate would ensure a large vertical propagation distance of the fracture and increase the possibility of a fracture network forming. Too low a viscosity or injection rate of fluids would cause leakage through weak planes and as a result forming multiple fractures with limited fracture height. Too high a viscosity or injection rate of fluids would lead to forming a single fracture with lower SRV. Additionally, comparing with operation parameters, the natural weak plane characteristics (such as development of weak planes and distribution) of coal were the main controlling factor.

Pressure curves differed markedly when the fracture initiated from different layers. The fracture initiation pressure was high in the sandstone comparing to that in the coal layer. Affected by natural fractures, the breakdown pressure varied in a wide range when the initiation position was located in the coal. Also, the more complex the connection between main fractures and secondary fractures, the more severe the curve fluctuation would be.

During the process of co-exploitation, not only complex fracture networks were required in the coal seam, but also enough vertical propagation distance of the main fractures was needed to connect multiple gas layers. When the natural fractures were well developed in the coal layer, it was recommended to fracture tight sandstone layers first to improve the stimulation effects. At the same time, a mixed fracturing method can be used: a high-viscosity fracturing fluid was adopted first to form wide main fractures and followed by a degradable fiber active water fracturing fluid to increase SRV, lowering leakage and increasing fracture height.

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References

- AlTammar MJ, Sharma MM. Effect of geological layer properties on hydraulic fracture initiation and propagation: an experimental study. In: SPE hydraulic fracturing technology conference, 24–26 January, The Woodlands: Texas, 2017. <https://doi.org/10.2118/184871-MS>.
- Anderson GD. Effects of friction on hydraulic fracture growth near unbonded interfaces in rocks. SPE J. 1981;21(1):21–9. <https://doi.org/10.2118/8347-PA>.
- Beugelsdijk LJJ, de Pater CJ, Sato K. Experimental hydraulic fracture propagation in a multi-fractured medium. In: SPE Asia Pacific conference on integrated modelling for asset management, 25–26 April, Yokohama: Japan, 2000. <https://doi.org/10.2118/59419-MS>.
- Chuprakov DA, Prioul R. Hydraulic fracture height containment by weak horizontal interfaces. In: SPE hydraulic fracturing technology conference, 3–5 February, The Woodlands: Texas, 2015. <https://doi.org/10.2118/173337-MS>.
- Fan TG, Zhang GQ, Cui JB. The impact of cleats on hydraulic fracture initiation and propagation in coal seams. Pet Sci. 2014;11:532–9. <https://doi.org/10.1007/s12182-014-0369-7>.
- Fung RL, Vilayakumar S, Cormack DE. Calculation of vertical fracture containment in layered formations. SPE Format Eval. 1987;2(4):518–22. <https://doi.org/10.2118/14707-PA>.
- Gu H, Weng X, Lund JB, Mack MG, Ganguly U, Suarez-Rivera R. Hydraulic fracture crossing natural fracture at nonorthogonal angles: a criterion and its validation. SPE Prod Oper. 2012;27(1):20–6. <https://doi.org/10.2118/139984-PA>.
- Guo TK, Zhang SC, Qu ZQ, Zhou T, Xiao YS, Gao J. Experimental study of hydraulic fracturing for shale by stimulated reservoir volume. Fuel. 2014;128:373–80. <https://doi.org/10.1016/j.fuel.2014.03.029>.
- Hanson ME, Shaffer RJ, Anderson GD. Effects of various parameters on hydraulic fracturing geometry. SPE J. 1981;21(4):435–43. <https://doi.org/10.2118/8942-PA>.
- Hou XW, Zhu YM, Fu CQ. Fracture distribution in the Qinshui Basin and its indicative significance to unconventional gas co-exploration in coal measures. J China Univ Min Technol. 2016;45(4):729–38. <https://doi.org/10.13247/j.cnki.jcumt.000446> (in Chinese).
- Li DQ, Zhang SC, Zhang SA. Experimental and numerical simulation study on fracturing through interlayer to coal seam. J Nat Gas Sci Eng. 2014;21:384–96. <https://doi.org/10.1016/j.jngse.2014.08.022>.
- Li SB, Zhang DX, Li X. A new approach to the modeling of hydraulic-fracturing treatments in naturally fractured reservoirs. SPE J. 2017a;22(04):1064–81. <https://doi.org/10.2118/181828-PA>.
- Li Y, Deng JG, Liu W, Feng YC. Modeling hydraulic fracture propagation using cohesive zone model equipped with frictional contact capability. Comput Geotech. 2017b;91:58–70. <https://doi.org/10.1016/j.compgeo.2017.07.001>.
- Liu ZY, Jin Y, Chen M, Hou B. Analysis of non-planar multi-fracture propagation from layered-formation inclined-well hydraulic fracturing. Rock Mech Rock Eng. 2016;49:1747–58. <https://doi.org/10.1007/s00603-015-0872-1>.
- Ouchi H, Foster JT, Sharma MM. Effect of reservoir heterogeneity on the vertical migration of hydraulic fractures. J Pet Sci Eng. 2017;151:384–408. <https://doi.org/10.1016/j.petro.2016.12.034>.
- Qin Y, Liang JS, Shen J, Liu YH, Wang CW. Gas logging shows and gas reservoir types in tight sandstones and shales from the southern Qinshui Basin. J China Coal Soc. 2014;39(8):1559–65. <https://doi.org/10.13225/j.cnki.jccs.2014.9003> (in Chinese).

- Roundtree R, Miskimins JL. Experimental validation of microseismic emissions from a controlled hydraulic fracture in a synthetic layered medium. In: SPE hydraulic fracturing technology conference, 24–26 January, The Woodlands: Texas, 2011. <https://doi.org/10.2118/140653-MS>.
- Shen J, Zhang CJ, Qin Y, Zhang B. Effect factors on co-mining of sandstone gas and coal bed methane in coal series and threshold of parameter in the Linxing block, Ordos Basin. *Nat Gas Geosci.* 2017;28(3):479–87. <https://doi.org/10.11764/j.issn.1672-1926.2017.02.018> (in Chinese).
- Smith MB, Bale AB, Britt LK, Klein HH, Siebrits E, Dang X. Layered modulus effects on fracture propagation, proppant placement, and fracture modeling. In: SPE annual technical conference and exhibition, 30 September–3 October, New Orleans, Louisiana, 2001. <https://doi.org/10.2118/71654-MS>.
- Tan P, Jin Y, Hou B, Han K, Zhou YC, Meng SZ. Experimental investigation on fracture initiation and non-planar propagation of hydraulic fractures in coal seams. *Pet Explor Dev.* 2017a;44(3):1–7. [https://doi.org/10.1016/S1876-3804\(17\)30054-X](https://doi.org/10.1016/S1876-3804(17)30054-X).
- Tan P, Jin Y, Han K, Hou B, Chen M, Guo XF, et al. Analysis of hydraulic fracture initiation and vertical propagation behavior in laminated shale formation. *Fuel.* 2017b;206:482–93. <https://doi.org/10.1016/j.fuel.2017.05.033>.
- Tan P, Jin Y, Hou B, Zhou YC, Zhang RX, Chang Z et al. Laboratory investigation of shale rock to identify fracture propagation in vertical direction to bedding. *J Geophys Eng.* 2018;15:696–706. <https://doi.org/10.1088/1742-2140/aaa5d6>.
- Teufel LW, Warpinski NR. In-situ stress variations and hydraulic fracture propagation in layered rock-observations from a mine-back experiment. In: International society for rock mechanics and rock engineering 5th ISRM congress, 10–15 April, Melbourne, Australia, 1983.
- Teufel LW, Clark JA. Hydraulic fracture propagation in layered rock: experimental studies of fracture containment. *SPE J.* 1984;24(1):19–32. <https://doi.org/10.2118/9878-PA>.
- Warpinski NR, Schmidt RA, Northrop DA. In-situ stresses: the predominant influence on hydraulic fracture containment. *J Pet Technol.* 1982;34(3):653–64. <https://doi.org/10.2118/8932-PA>.
- Warpinski NR, Teufel LW. Influence of geologic discontinuities on hydraulic fracture propagation. *J Pet Technol.* 1987;39(2):209–20. <https://doi.org/10.2118/13224-PA>.
- Xiao B, Zhang SC, Zhang J. A novel nano-composite fiber laden viscoelastic fracturing fluid for coal-bed methane (CBM) reservoir stimulation: laboratory study and test. In: SPE Asia Pacific oil and gas conference and exhibition, 22–24 October, Jakarta, Indonesia, 2013. <https://doi.org/10.2118/165862-MS>.
- Xiao B, Jiang TX, Zhang SC. Novel nanocomposite fiber-laden viscoelastic fracturing fluid for coal bed methane reservoir stimulation. *J Energy Res Technol.* 2017;39(2):022906. <https://doi.org/10.1115/1.4034548>.
- Zhao HF, Chen M. Extending behavior of hydraulic fracture when reaching formation interface. *J Pet Sci Eng.* 2010;74:26–30. <https://doi.org/10.1016/j.petrol.2010.08.003>.
- Zhao JZ, Peng Y, Li YM, Xiao WL. Analytical model for simulating and analyzing the influence of interfacial slip on fracture height propagation in shale gas layers. *Environ Earth Sci.* 2015;73(10):5867–75. <https://doi.org/10.1007/s12665-015-4360-4>.
- Zhou J, Chen M, Jin Y, Zhang GQ. Analysis of fracture propagation behavior and fracture geometry using a tri-axial fracturing system in naturally fractured reservoirs. *Int J Rock Mech Min Sci.* 2008;45(7):1143–52. <https://doi.org/10.1016/j.ijrmm.2008.01.001>.