Large-scale Physical Simulation of Hydraulic Fracturing under True-triaxial Conditions and Analysis of Fracture Propagation

Fan Zhang1*, Geng Ma1,2,3, Yunqi Tao1,2,3, Xiao Liu1, Rui Li4 and Dan Feng5

1School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454003, P.R. China
2Research Institute of Henan Energy Resource and Chemical Industry Group Co., Ltd., Zhengzhou, Henan 450046, P.R. China
3Henan Engineering Research Center of Simultaneous Extraction of Coal and Gas with Low Permeability & Outburst Coal Seam, Zhengzhou, Henan 450046, P.R. China
4Applied Technical College, China University of Mining and Technology, Xuzhou, Jiangsu 221008, P.R. China
5State Key Laboratory for Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, P.R. China

Abstract

In order to study the effect of in-situ stresses and natural fractures in coal seam on fracture initiation, fracture propagation, fracture morphology and fracture width, a large-scale sample made of similar materials with inner artificial fracture was applied to conduct large-scale true triaxial hydraulic fracturing simulation experiment. Initial angle and final angle of fractured sample were measured by protractor. Fracture width in fracturing process was tested by displacement meter timely. The experimental results indicated that fracture initiation, fracture propagation path and fracture morphology are affected greatly by in-situ stresses and natural fractures in coal reservoir, in-situ stresses is the major influencing factor. Initial angle of hydraulic fracture is mainly affected by the angle between perforations and maximum horizontal stress. Natural fracture is an important factor influencing fracture propagation, which results in leak-off of fracturing fluid and formation of fracture network, but hydraulic fractures gradually turn to the direction of perpendicular to minimum horizontal stress. When vertical stress and minimum horizontal stress are constant, fracture width decreases and fracture length increases with the increasing of maximum horizontal stress. The research results are consistent with existing fracturing theory (fracture width reduces with the increasing of horizontal stress difference) and would provide reference for the improvement of hydraulic fracturing technology and theory.

Key Words: Hydraulic Fracturing, Fracture Propagation, True Triaxial, Simulation Experiment, Fracture Width

1. Introduction

Coalbed methane (CBM) in China has characteristics of low permeability, low porosity and different complex stress, while the CBM reserves are abundant and rank third in the world. The characteristics of low permeability and porosity make it hard to extract CBM from coal seam [1]. How to extract gas from coal seam of low permeability becomes an important topic for modern scholars at home and abroad [2–5]. Hydraulic fracturing is an important method for gas drainage, which is of great significance for coal seam of low permeability and has been applied to coal mine in China [6–8]. The effect of hydraulic fracturing is influenced by mechanical properties of coal rock, natural fracture in coal seam, in-situ stresses, fracturing fluid, flow rate and fracturing techniques [9–14]. For so many influencing factors, the rule of fracture propagation and fracture morphology in coal seam is not clear. However, fracture initiation and propagation affect the formation of fracture network and effect of industrial

*Corresponding author. E-mail: 379591198@qq.com
field tests directly, which is of great importance for hydraulic fracturing theory [15].

True triaxial hydraulic fracturing simulation experiment is an effective and accurate method to study the rule of fracture initiation, fracture propagation and fracture morphology [16]. So far, lots of experiments were conducted by using coal rock, sandstone and samples made of similar materials [17–19]. Patel et al. [17] conducted hydraulic fracturing experiment by using sandstone (4 inch in diameter and 5.5 inch in length) and pre-breakdown cyclic injection under triaxial stress conditions. They found that damage generated around hydraulic fracture by cyclic injection hydraulic fracturing is approximately twice that generated by conventional injection. The breakdown pressure is lower and varies more than two standard deviations from that of conventional injection. Lin and Du [18] conducted hydraulic fracturing experiment by using samples made of similar materials (50 mm in diameter and 100 mm in length) and hydraulic fracturing experimental devices. The results indicated that crack always propagates along the in-situ stress’s biggest direction and the character of crack surface has the important influence on the fracturing fluid flowing in the seam. C.J. et al. [19] performed acoustic measurements in a time-lapse sequence to separate the fracture response from the background signal by scaled laboratory tests. They could detect the hydraulic fracture and characterize the geometry in fracturing though compressional and shear waves. The rule of fracture propagation and morphology has been demonstrated through relevant experimental results, which is of great significance for the study of hydraulic fracturing theory [20]. However, report of large-scale hydraulic fracturing experiment is rare globally. For the complex condition of CBM in China, it is necessary to conduct large-scale hydraulic fracturing experiment to study fracturing mechanism. As known, fracture width is of great significance for CBM drainage, relevant study is still at stage of theoretical analysis. It is difficult to observe fracture width in fracturing process. In addition, natural fractures in coal reservoir can make fracture propagation complex [21]. Experimental reports of precast fracture have not been revealed clearly yet by using natural rock sample.

In this article, the feature of hydraulic fracturing simulation experiment was showed as follows. Firstly, large-scale true triaxial apparatus was applied to conduct hydraulic fracturing experiment. Secondly, fracture width was tested quantificationally timely in fracturing process. Last but not least, large-scale sample contained precast fractures was applied to simulate natural fracture in coal seam. The research results would provide reference for the improvement of hydraulic fracturing technology and theory.

2. Experiment

2.1 Materials and Experimental Apparatus

It is not easy and cost a lot to collect large raw coal from coal mine and carry them to laboratory. Similar material has been applied to study the mechanism of engineering widely in the world. After reading a lot of papers, cement, gypsum and pulverized coal are applied to simulate the characteristics of raw coal selected from No. 4 coal seam of Xintian Coal Mine in Guizhou Province. The mechanical properties of raw coal are tested in laboratory, its compressive strength is 8.53 MPa, tensile strength is 0.63 MPa, elastic modulus is 0.82 GPa, Poisson’s ratio is 0.28, firmness coefficient (Protodayakovon’s coefficient) is 0.80. When ratio of cement, gypsum and pulverized coal is 2, 1, 2, the mechanical properties of similar materials (its compressive strength is 5.36 MPa, tensile strength is 0.71 MPa, elastic modulus is 0.95 GPa, Poisson’s ratio is 0.25, firmness coefficient is 0.82) are close to the ones of raw coal [22]. When making sample, precast fractures are placed to the direction of parallel to maximum horizontal stress. Precast fractures can absorb fracturing fluid and weaken their original strengths after being soaked, which can simulate natural fractures in raw coal. The sample is shaped into size of $600 \times 600 \times 450$ mm (length × width × height) and angle between maximum horizontal stress and perforations is 45°, as shown in Figure 1. The diameter of steel injection tube is 20 mm, its length is 390 mm and fracturing perforations’ length is 100 mm. Steel injection tube is fixed into the eyehole by epoxy resin adhesive to simulate fracturing wellbore, as shown in Figure 1. The directions of maximum horizontal stress ($\sigma_{x1}$, $\sigma_{x2}$), vertical stress ($\sigma_{z1}$, $\sigma_{z2}$) and minimum horizontal stress ($\sigma_{z0}$) are shown in Figure 1.

Experimental apparatuses are multi-field coupling test system for coalbed methane exploitation [23] and
fracturing pump, as shown in Figure 2. The former apparatus includes three-phase four-pole stress system, displacement meter, data acquisition system and sample fixing device. Three-phase four-pole stress system (Figure 3) has nine hydraulic rods to simulate in-situ stresses accurately and stresses can be loaded step by step, the maximum loaded stresses are 10 MPa in horizontal and vertical directions. When the stresses are loaded to certain values at the same time, the experimental stresses are loaded to another target value meanwhile until the experimental stress values are finally reached. The displacement meters (Figure 3) are fixed beside hydraulic rob independently, which can collect the deformation data of experimental sample in fracturing process. Its measurement accuracy is 0.1 mm. The working principle of displacement meter is shown as follows. Because experimental stresses are constant, the hydraulic fracture opens firstly under the effect of fracturing fluid and then closes under stresses. When new fracturing fluid is pumped into steel injection tube, closed hydraulic fracture opens again and fracture width increases at the same time. The data collected by displacement meter can reflect the trend of fracture width in real time. In fracturing process, all stresses are constant and fracturing fluid is pumped at constant flow rate. The flow rate of fracturing fluid can be controlled by software entitled “True triaxial testaid”, which is a part of multi-functional true triaxial fluid-solid coupling test system. The data of flow volume and water pressure can be recorded by data acquisition system of multi-field coupling test system for coalbed methane exploitation [23,24].

2.2 Methods
To study the effect of in-situ stresses and natural fractures on fracture initiation, fracture propagation and relationship between fracture width and horizontal stress difference (the difference between $\sigma_{1h}$ and $\sigma_{6h}$), the experimental program is designed as Table 1. The stress loading stage is shown in Figure 4.

2.3 Experimental Procedure
According to designed similar material ratio, cement, gypsum and pulverized coal are applied to make sample,
as shown in Figure 5a. The mould is taken off after five days and sample is used to conduct hydraulic fracturing experiment after thirty days. When sample is set upon true-triaxial test station, high presser water pipe is connected with steel injection tube (Figure 5b). Then experimental stresses are loaded step by step upon steel plates. With the pumping of fracturing fluid, initial hydraulic fracture generates and propagates in sample. As fracturing fluid flows out from sample, it is indicated that fractures have passed through sample. The rule of fracture initiation and propagation can be observed by breaking fractured sample. For constant pumping of fracturing fluid, the curve of fracture width with time is recorded by displacement meter timely.

### 3. Experimental Results and Analysis

#### 3.1 Result and Analysis of Fluid Pressure

Figure 6 is the curve of fluid pressure with time recorded by data acquisition system in fracturing process. It shows that when fracturing fluid is pumped into steel injection tube, fluid pressure increases sharply because the volume of pumped fracturing fluid is bigger than the one of leak-off. Initial fracture does not generate until fluid pressure increases to breakdown pressure. With the continuous pumping of fracturing fluid, new fracturing fluid is pumped into hydraulic fracture, the fluid pressure decreases and hydraulic fracture stops propagating. When the volume of new fracturing fluid increases to certain volume that bigger than the one of leak-off and generated fracture, the fluid pressure increases again and new hydraulic fracture propagates in sample. The curve of fluid pressure with time fluctuates up and down, hydraulic fractures open and close again and again. The fracturing pump is shut down until fracturing fluid flows out

<table>
<thead>
<tr>
<th>$\sigma_{11}$/MPa</th>
<th>$\sigma_{12}$/MPa</th>
<th>$\sigma_{v1}$/MPa</th>
<th>$\sigma_{v2}$/MPa</th>
<th>$\sigma_{h}$/MPa</th>
<th>Flow rate (L/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
<td>2.2</td>
<td>1.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1. Experimental parameters for hydraulic fracturing experiment

![Figure 4. Experimental stress loading stage according to experimental program.](image)

![Figure 5. Experimental sample and steel injection tube.](image)

![Figure 6. Curve of fluid pressure with time.](image)
from the surface of fractured sample, hydraulic fractures pass through fractured sample. In Figure 6, fluid pressure mainly fluctuates among 2.3 min to 3.2 min. The reason is that hydraulic fracture propagating path is affected by natural fractures. For leak-off of fracturing fluid, main hydraulic fracture does not propagate along the direction of maximum horizontal stress and secondary fractures propagate to different directions in sample, which is proved by fractures upon broken sample.

3.2 Result and Analysis of Fracture Initiation and Propagation

To study the effect of in-situ stresses on fracture initiation and fracture propagation, complex stresses are loaded upon sample. When sample is fractured, final angles are measured by protractor. From Figure 7, it is seen that hydraulic fractures propagate to the direction of perpendicular to minimum horizontal stress. The direction of perforations is shown as dotted line in Figure 7, the initial angles between perforations and maximum horizontal stress at side A and B are all 45. While the cracking angle between initial fracture and maximum horizontal stress is 45 at A side, the one at B side is 30.

When fracturing fluid flows out from sample, the final angle changes at the same time. The final angle between hydraulic fracture and maximum horizontal stress reduces to 15 at the edge of A side, as shown in Figure 7. It is proved that hydraulic fractures propagate gradually to the direction of maximum horizontal stress though the cracking angle between initial fracture and maximum horizontal stress is 45, which indicates that hydraulic fracture is affected greatly by in-situ stresses.

While the final angle increases to 45 at the edge of B side, the reason is that hydraulic fracture can propagates easily to the direction of small force when propagating in fractured coal reservoir. For the size of precast fracture and direction of hydraulic fracture, hydraulic fracture does not encounter precast fracture at B side.

Figure 8 reveals that the shape of hydraulic fracture is oval at A side and hydraulic fracture propagation path is complex around precast fracture. Compared different colors upon sample in Figure 8a and b, we can see that precast fractures visibly affect fracture propagation path.
hydraulic fracture passes through precast fracture and continues propagating to the direction of parallel to maximum horizontal stress, as shown in Figure 8a. Besides, we can see that the color degree of fracturing fluid is different around precast fractures. Because of powerful flowing energy of fracturing fluid, partial fractures firstly propagate along the surface of precast fracture and then continue to propagate to the direction of parallel to maximum horizontal stress after they propagate to the edge of precast fracture. Partial fractures propagate along precast fracture at some distance and then fracturing fluid is absorbed by it, which is consistent with the property of natural fracture. For the size of precast fracture, partial fractures do not pass through precast fracture and stop propagating, as shown in Figure 8b.

From what have been discussed above, we learn that natural fractures in coal reservoir can affect hydraulic fracture propagation path locally. Hydraulic fracture finally propagates to the direction of perpendicular to minimum horizontal stress and has some angle with maximum horizontal stress. Therefore, hydraulic fracture propagation path is easily influenced by natural fracture locally and final fracture propagates to the direction of parallel to maximum horizontal stress. Initial angle, fracture morphology and fracture propagation are greatly influenced by in-situ stresses, direction of perforation, natural fracture and maximum horizontal stress.

3.3 Result and Analysis of Fracture Width

In fracturing process, fracture width changes when fracturing fluid is pumped into steel injection tube, fracture width reduces or even closes under the effect of constant stresses, as shown in Figure 9. With the continuous pumping of fracturing fluid, closed fracture opens and fracture width increases. Figure 9 shows that the order of fracture width is \( \text{Sv1, Sv2, Sh, SH2, SH1} \). In experimental program, the difference between \( \sigma_{v1} \) and \( \sigma_{H1} \) is bigger than the one between \( \sigma_{v2} \) and \( \sigma_{H2} \). It is seen that fracture width reduces with the increasing of horizontal stress difference, which is accordance with the result of what has been studied in reference 24 (fracture width reduces with the increasing of horizontal stress difference). Since fracturing fluid is steadily pumped to make fracture propagating, so fracture width does not produce a peak. Therefore, when vertical stress and minimum horizontal stress are constant, the flowing energy of fracturing fluid increases, fracture width reduces and fracture length increases with the increasing of maximum horizontal stress.

4. Conclusions

Large-scale physical simulation of hydraulic fracturing under true-triaxial conditions was conducted by multi-field coupling test system for coalbed methane exploitation, fracture width was tested by displacement meter quantificationally, initial and final angle of hydraulic fracture were measured by protractor. The experimental results are as follows.

1. Initial angle of hydraulic fracture is affected greatly by the angle between perforations and maximum horizontal stress. Hydraulic fracture gradually turns to the direction of parallel to maximum horizontal stress. Fracture propagation path is influenced by natural fracture locally and the direction of overall fracture is determined by in-situ stresses.

2. Natural fracture in coal seam is one of the main points affecting fracture propagation. The size and number of natural fractures make fracture propagation path complex. The angle between natural fracture and maximum horizontal stress influences fracture propagation locally.

3. Fracture width reduces or even closes under the effect of constant stresses. With the pumping of fracturing fluid, closed fracture opens and fracture width increases. When vertical stress and minimum horizontal

![Figure 9. Fracture width tested from each direction of experimental stress.](image-url)
stress are constant, fracture width reduces and fracture length increases with the increasing of maximum horizontal stress.

Acknowledgements

The authors would like to thank the Major Work on Innovation Methods of the Ministry of Science and Technology of China in 2016 (No. 2016IM010400); National Natural Foundation of China in 2014 (No. 71472171) for financial support of this work.

Author Contributions

Fan Zhang, Geng Ma, Xiao Liu conceived the experiments. Fan Zhang, Dan Feng performed the experiments. Fan Zhang, Yunqi Tao, Rui Li analyzed the experimental results and prepared the manuscript. All authors reviewed the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References


*Manuscript Received: Nov. 27, 2017*  
*Accepted: Jun. 27, 2018*