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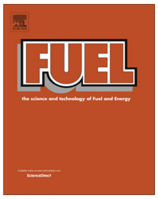

Experimental study of hydraulic fracturing for shale by stimulated reservoir volume

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HIGHLIGHTS

- Hydraulic fracturing simulation experiments of shale outcrops were first carried out.
- Fracture morphology was observed for the first time by high-energy CT scanning.
- The effects of multiple factors on fractures propagating in shale play were studied.
- CT scanning images were combined with internal fractures photographs for analysis.
- Hydraulic fracturing of horizontal well was simulated for shale specimens.

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ABSTRACT

"Stimulated reservoir volume" (SRV) makes it possible for commercial production of shale gas by means of multistage fracturing of horizontal wells. However, the formation mechanism of effective fracture network has not been well understood. The mechanism of fracture propagation in shale with hydraulic fracturing needs to be further explored, in order to realize the control on morphology of fracture network with SRV and increase the single well production of shale gas. In this article, the true triaxial test system was deployed for horizontal well hydraulic fracturing simulation experiments of shale outcrops for the first time. The effects of multiple factors on propagating rules of fractures of horizontal well in shale with SRV were studied, and the fracture morphology of post-fracturing rock cores was observed for the first time by high-energy CT scanning using the large-scale non-destructive testing system based on linear accelerator. The results show that the influence of flow rate (for SRV) on fracture complexity differs when its value falls in different intervals. When the horizontal in situ stress difference is less than 9 MPa, the hydraulic fracture easily propagates along the natural fractures, forming a fracture network. In this range, when the stress difference is increased, the appearance of the main hydraulic fracture contributes to interconnecting more natural fractures, forming a relatively more complex fracture system. Under the condition of the same horizontal stress difference, if the coefficient of stress difference $K_h > 0.25$, there is an obvious trend to form single main fracture. The effects of viscosity of fracturing fluid and flow rate on the fracture propagation can be expressed by the parameter $q \cdot \mu$. When the order of magnitude of $q \cdot \mu$-value is 10^{-9} N m, it is favorable to the generation of fracture network, but too small or too large values are both harmful. The development and cementing strength of depositional beddings seriously affect the propagating complexity of fracture network with hydraulic fracturing. Refracturing helps to produce some new fractures which are different from the initial ones, and better fracturing effect is achieved. The fracture initiation morphology in perforation fracturing is closely related to the distribution of natural fractures (depositional bedding) around the perforations. If the pressure curve fluctuates significantly, it is indicated that the shale core contains a large number of opened natural fractures or depositional beddings before fracturing, which causes the serious loss of fracturing fluid in the propagation process.

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1. Introduction

Shale matrix has very low porosity and permeability, and shale gas has different existential states [1,2], which brings great difficulties for the exploitation of shale. Hydraulic Fracturing by Stimulated Reservoir Volume (SRV) [3] is a major technology to achieve commercial development of shale gas. The in-depth understanding of propagation mechanism of fractures in shale with SRV can contribute to guide the design of fracturing operation, controlling the morphology of fracture network of shale with SRV, thus improving the single well production of shale gas. The key factors affecting the morphology of post-fracturing network include horizontal in situ stress difference, rock brittleness and natural fracture system (sedimentary bedding) [4–6]. In addition, the morphology of fracture network can also be affected by the fracturing operation factors (volume of fracturing fluid, flow rate, the spacing between fracturing segments [7,8]) and fracturing techniques (horizontal well multistage fracturing, synchronous fracturing, zipper fracturing and refracturing [9]).

The hydraulic fracturing simulation experiment is an important and accurate tool to study the mechanism of fracture propagation. So far, many fracturing simulation experiments of coals [10,11], cement blocks [11,13] and sandstones [14,15] have already been carried out globally. The propagation mechanisms of hydraulic fractures in relevant rocks under certain conditions have been revealed, and some studies have also been presented to analyze the effect of natural fractures on hydraulic fracture propagation [14,16–18]. However, lots of experimental studies under triaxial loading show that shale rock has its own unique physical and mechanical properties [19–21]. The propagation mechanism of fractures in shale with SRV is not yet clear [22,23], and the reports of true triaxial fracturing simulation experiments on shale cores are very rare [24], Zhang et al. [25] carried out the hydraulic fracturing simulation experiment on shale, but only a few factors had been investigated. Moreover, this experiment was not able to achieve the precise positioning of fractures propagation morphology. It is very difficult to obtain accurate structural information of complex fracture network of shale only by the conventional method of observing the fracture indicated by the tracer through rock breaking after hydraulic fracturing [16,17]. Due to the reasons of the large size, high clay content and abundant natural fractures in shale specimens, the acoustic emission energy is pretty weak during fracture propagation. Therefore, it is also difficult to locate complicated fractures by acoustic emission monitoring system [18,26].

In this article, the uniqueness of experiment was showed as follows. Firstly, the true triaxial horizontal well hydraulic fracturing simulation experiments were conducted for the large-size natural shale cores. Therefore, the experimental results could make more instructive value to the actual shale gas development. Secondly, the research factors were relatively comprehensive. The effects of horizontal stress, horizontal stress difference coefficient, flow rate, viscosity of fracturing fluid and perforation on fracture propagating morphology were explored for the fracturing of shale horizontal well. Thirdly, the large-scale “IPT4106D” non-destructive testing system based on linear accelerator was used for the first time to carry out high-energy CT scanning for observing the structure of complex shale fracture network after treatment. So, the analysis about fractures combined with internal fractures photographs was more accurate. The research findings would provide theoretical basis and technical support for the efficient development of shale gas reservoirs.

2. Experiments

2.1. Test apparatus and specimen processing

Experiment apparatuses included the large-size true triaxial hydraulic fracturing simulation system [16] and the large-scale “IPT4106D” non-destructive testing system (6 MeV) based on linear accelerator [27]. The latter provided high-energy computed tomography (CT) scanning and digital radiography (DR) scanning for large-size work pieces. CT scanning and DR scanning can provide tomographic images and integral perspective views of specimens, respectively.

Specimens were collected from Sichuan shale outcrops in China, belonging from the No. 5 layer of the Triassic Xujiahe Formation in Sichuan Basin. During sampling, the weathered rock layer was removed. The well-preserved fresh shale outcrops were obtained, and then they were processed into 30 cm × 30 cm × 30 cm cubes. By using a special chemical glue, the steel liquid injection tube with the length of 12.5 cm was fixed to eyehole to simulate the wellbore, and a 5 cm open hole section was formed. To simulate perforation fracturing, the steel tube was designed with a sealed bottom, a length of 17.5 cm and four perforations.

The shale mineral analysis showed that the average contents of carbonate, quartz and clay were 13.1%, 41.3% and 39.9%, respectively. As shown by the brittleness index calculated by Young’s modulus–Poisson’s ratio method [6] and the ratio of uniaxial compressive strength to tensile strength [28], the brittleness of the shale core is high.

2.2. Experiment design

In order to investigate the effects of horizontal stress, horizontal stress difference coefficient, flow rate, viscosity of fracturing fluid and perforation on the fracture propagating rules in the fracturing of shale horizontal well, the experiment program was designed as shown in Table 1.

Table 1
Experiment program for hydraulic fracturing simulation of shale.

Sample number	Triaxial stress (MPa) $\sigma_V/\sigma_H/\sigma_h$	Completion method	Displacement (ml/min)	Fracturing fluid viscosity (mPa s)
1#	25/15/12	Open hole	10	2.5
2#	25/15/12	Open hole	50	2.5
3#	25/15/12	Open hole	100	2.5
4#	25/18/12	Open hole	100	2.5
5#	25/18/12	Open hole	50	2.5
6#	25/18/6	Open hole	50	2.5
7#	25/18/9	Open hole	50	2.5
8#	25/18/9	Open hole	100	2.5
9#	25/9/6	Open hole	50	2.5
10#	25/12/6	Open hole	50	2.5
11#	9/12/6	Open hole	50	2.5
12#	25/15/12	Open hole	50	65
13#	25/14/8	Open hole	50	2.5
14#	25/15/12	Perforation	50	2.5