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Experimental Study of Perforation Parameters Impact on Oil Shale Hydraulic Fracturing

SHUAI GAO[1, 2], CHEN CHEN[1, 2] AND WEI WANG[3]

[1]*College of Construction Engineering, Jilin University, Changchun 130021 China*
[2]*Key laboratory of ministry of land and resources on complicated conditions drilling technology, Changchun 130021 China*
[3]*Daqing Oilfield Production Engineering & Research Institute, Daqing 163000 China*
Email: *shuaigao90@126.com*

Abstract: At present, Most of the oil shale in-situ heating technology need to hydraulic fracturing in oil shale formation. Nearly all hydraulic fracturing is carried out after the casing perforation. Perforation parameters play an important role among hydraulic fracturing construction parameters, which even affect effect of oil shale in-situ heating. The hydraulic fracturing process of indoor physical simulation experiment is carried out with the same formation conditions and different perforation parameters. The effect of perforation diameter, perforation orientation (the angle between the direction of perforation and the direction of maximum horizontal stress) and perforation density to fracturing pressure and fracture propagation are researched. The experimental results show that fracturing pressure reduces with perforation diameter increasing, but the effect is not obvious. Fracturing pressure increases obviously with perforation orientation increasing, and fracture becomes more complex. Fracturing pressure decreases obviously with perforation density increasing, which has a very small impact on fracture propagation.

Keywords: *oil shale, hydraulic fracturing, perforation parameters, fracturing pressure，fracture propagation*

1. Introduction

Oil shale is an important source of backup energy, and its global reserves are large. Broadly, there are two basic oil shale retorting processes: in situ (underground) and ex situ (aboveground). Oil shale retorting process aboveground can cause many environmental pollution problems, such as waste water, waste gas and waste residue. However, oil shale retorting process in situ is a relative economic and environmental protection technology which can avoid above problems. And, most oil shale retorting technology need plenty of fractures that can improve the permeability in oil shale formation generated through hydraulic fracturing[1,2]. Hydraulic fracturing is one of the main stimulation techniques to enhance recovery from oil and gas reservoirs. Many researchers have study the process of hydraulic fracturing by different research methods. Zhang Guangqing et studied the hydraulic fracturing process by established three-dimensional finite element model, which think perforation orientation and perforation density effect fracturing pressure primarily and perforation diameter effects weakly[3]. Jiang Xu et researched perforation orientation play a very important role on fracturing pressure though hydraulic fracturing experiments[4,5]. CHENG Wan，Ali Naghi Dehghan, GUO Chaohua et studied initiation and extension of fractures in shale or sandstone under different factors[6-11]. L.A. Behrmann, EI Rabaa W, R.G.van de ketteij et have researched impact of some perforation parameters on hydraulic fractures[12-14]. Yan Xuanchen, Liu Xinpeng et have tested the mechanical parameters of oil shale related to hydraulic fracturing[15,16]. Sun Keming et conducted theoretical and numerical research on oil shale hydraulic fracturing. And Yuan Guangjin et have a research on oil shale hydraulic fracturing optimization design [17].

However, most researches were about oil and gas wells hydraulic fracturing, and little research was about perforation parameters of oil shale hydraulic fracturing for in situ retorting. At present, design of perforation parameters in oil shale hydraulic fracturing for in situ retorting were conducted according to experience of oil and gas wells hydraulic fracturing.

Thus, this paper researches the influence of perforation parameters to fracturing pressure and fracture propagation when oil shale hydraulic fracturing through replaced oil shale with cement blocks. Perforation diameter, perforation orientation, perforation density were changed in the same in-situ stresses in order to obtained the effect to fracturing pressure and fracture propagation through simulate experiments.

2. Experimental Set Up and Test Procedure

2.1 Experimental equipment

The simulate experiments were conducted using the synthetic samples and the three axis hydraulic fracturing simulation system with (Fig.1). The size of the model blocks were 300mm×300mm×380mm, and height is 380mm. The model blocks were placed in the center of three axis assembly. The pressure plates put pressure on the surfaces of model blocks for simulating in-situ stresses conditions (the vertical, maximum and minimum horizontal principal stresses). The maximum pressure on every pressure plate can be up to 15MPa. The vaseline was plastered between the model blocks and the pressure plates to prevent shear stress. The hydraulic fluid was injected by the high pressure pump with a maximum capacity of fluid injection pressure of 60 MPa.

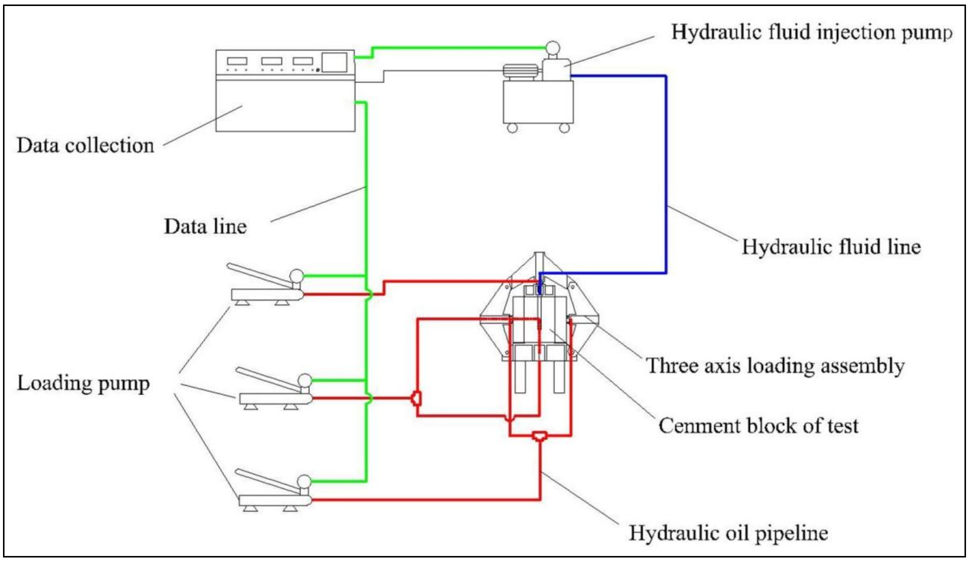

Fig.1 *Sketch map of three axis hydraulic fracturing simulation system*

2.2 Sample preparation

The size of outcrop oil shale in the field cannot satisfy experiments due to outcrop oil shale in the field break into thin sheet because of weathering. Thus this paper used cement blocks replace oil shale block. Plane sketch of synthetic samples is presented in Fig.2.

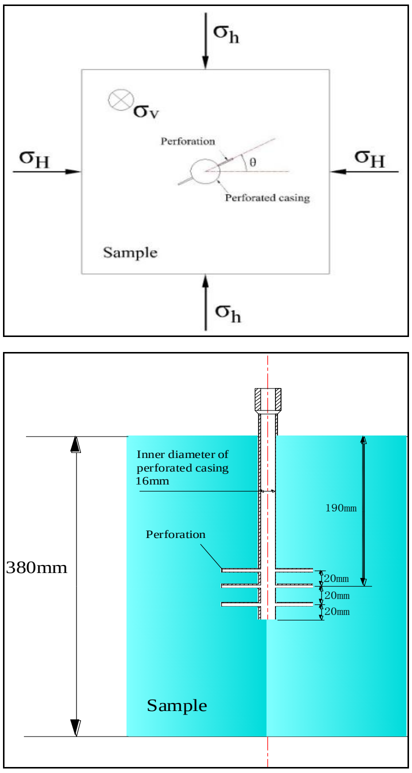

Fig.2 *Plane sketch of synthetic sample*

Firstly, the mixture of Chinese Portland cement No.425 and fine sand which were sieve by a fine-screen shaker were fixed with water. The mass ratio of cement: sand: water is 1:1:0.5. Then, the perforated casing was placed in the metal mold that the size of was 300mm×300mm×380mm, height is 380mm, and the final mixture was poured into the metal mold. At last, the sample was cured in an environment at room temperature and more than 95% humidity for 28 days. Inner diameter of the perforated casing was 16mm, and outer diameter was 20mm. Symmetrical branch pipes simulating perforations along radial direction of perforated casing were welded on the perforated casing, which the length was 40mm and diameter was 16mm, as shown in Fig. 3. The rock mechanic were conducted in order to determine synthetic sample's geomechanical properties(Table 1).

Table 1 : *Geomechancal properties of sample*

Parameters	Units	Value
Elastic modulus	GPa	8.49
Poisson's ratio	_	0.215
Unconfined compressive strength	MPa	31.94
Tensile strength	MPa	3.81
Permeability	mD	0.10
Porosity	ø	1.73

2.3 Experiment design

8 laboratory hydraulic fracturing experiments were conducted in a normal-faulting stress regime to investigate the effect of different perforation diameter, perforation orientation and perforation density on the fracturing pressure and fracture propagation, as

showed in table 2. The constant value of in-situ stresses were σ_V =3.4MPa(the vertical principal stress), σ_H =2.6MPa(the maximum horizontal stress), σ_h =1.7MPa(the minimum horizontal stress) respectively in consideration of that oil shale formation is shallow in Jilin Province.

Table 2: *Parameters for hydraulic fracturing experiments*

Sample number	Perforation diameter/mm	Perforation orientation /(°)	Perforation density
1	6	0	1
2	8	0	1
3	10	0	1
4	6	30	1
5	6	60	1
6	6	90	1
7	6	0	2
8	6	0	3

2.4 Experiment procedure

The sample was placed in the three axis loading assembly after that the sample was cured in an environment at room temperature and more than 95% humidity for 28 days. The in-situ stresses were increased up the value of design and then they were held for a while. After the above operations, the hydraulic fluid was injected into the perforated casing by hydraulic fluid injection pump, and the hydraulic fluid was added red tracer for observed the hydraulic fractures. The flow rate of hydraulic fluid was 6.0×10^{-6} m^3/S.

3. Experiment Results and Analysis

2.1 Effects of perforation diameter on hydraulic fracturing

Table 3 shows the fracturing pressures when the perforation diameter was 6mm, 8mm, 10mm respectively. It can be known from the experiment data, the fracturing pressure reduced with perforation diameter increased. And the fracturing pressure reduced from 8.34MPa to 7.96MPa (reduced by 4.6%) when the perforation diameter increased from 6mm to 10mm. The change of the fracturing pressure was very small.

Table 3: *Test results with different perforation diameter*

Sample number	Perforation diameter/mm	fracturing pressure /MPa
1	6	8.34
2	8	8.25
3	10	7.96

After finishing hydraulic fracturing experiments, the samples were took out from the three axis loading assembly for observing the hydraulic fractures. The hydraulic fractures initiated along the direction of perforation as well as maximum horizontal stress(σ_H) and formed a symmetrical main crack on both sides of wellbore in sample 1, as shown in Fig 3(a). The same situation appeared in the other two samples in addition to that some secondary fractures appeared with the increase of perforation diameter.

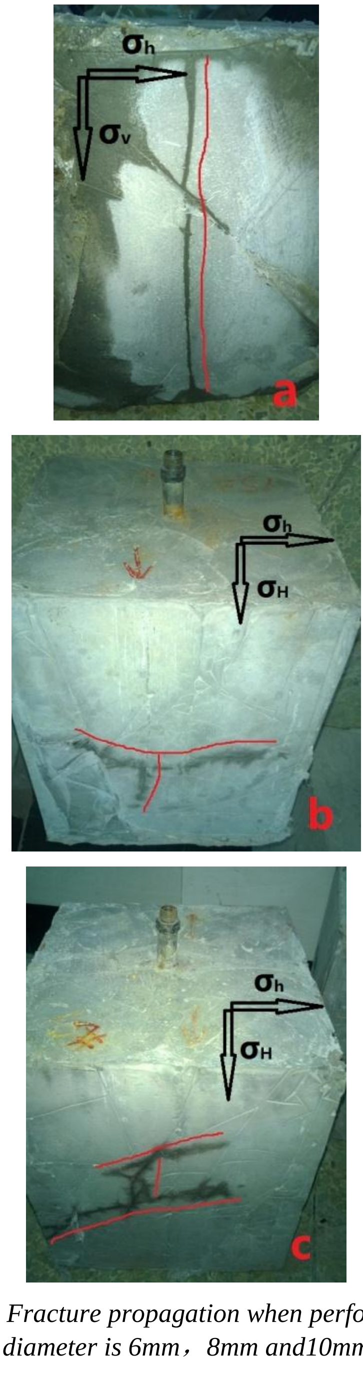

Fig.3 *Fracture propagation when perforation diameter is 6mm，8mm and10mm*

According to tensile strength criterion, hydraulic fractures always extended along the direction of maximum horizontal stress [18]. But fractures perpendicular to the vertical principle stress took place when the perforation diameter was 8mm and 10mm, which accounted for by the geomechanical properties of sample(tensile strength＞three in-situ stresses). Also, there were more micro cracks in the end of perforations when perforation diameter increased that leaded to forming more secondary fractures.

2.2 Effects of perforation orientation on hydraulic fracturing

Table 4 showed the results on hydraulic fracturing experiment when the perforation orientation were 0°, 30°, 60°, 90°. The fracturing pressures increased from 8.34 MPa to 11.13 MPa, 33.4% increase, with the perforation orientation changed from 0°to 90°. It showed that perforation orientation has a greatly effect on fracturing pressure on hydraulic fracturing.

Table 4: *Test results with different perforation orientation*

Sample number	Perforation orientation/°	Fracturing pressure/MPa
1	0	8.34
4	30	8.79
5	60	9.80
6	90	11.13

Perforations connect the wellbore and stratum in perforation completion. Fracturing fluid flows into and fractures stratum through perforations. Rock will fracture when the largest tensile stress effectively on the wall of well reach the tensile strength of the rock on the basis of tensile strength criterion. The mathematical formula can be derived on the fracturing pressure of perforation as follow[4].

$$P_f = \frac{1}{4}\{\sigma_h[3+6\cos 2\theta]+\sigma_H[3-6\cos 2\theta] -\sigma_V + 2\upsilon(\sigma_H - \sigma_h)\cos 2\theta - \alpha P_p + \sigma_t\} \quad (1)$$

Where P_p is pore pressure, MPa; υ is poisson's ratio of the rock; σ_v is the vertical principal stress, MPa; σ_t is the tensile strength of rock, MPa; α is pore elasticity coefficient.

According to the formula, fracturing pressure largen with the increase of θ (perforation orientation), and the proportion of the increase on fracturing pressure affects by the in-situ stresses and the geomechanical properties of rock.

Samples were took out and observed the fractures. Fractures in four samples all initiated and extended along the direction of perforation and formed the shape of symmetrical wings on both sides of the perforated casing, as shown in Fig 4. Fractures did not deflect from the direction of perforation to the direction of maximum horizontal stress.

The experiment results shown that the geomechanical properties of rock can affected fractures propagation when the ratio of in-situ stresses and tensile strength was smaller than a certain value, which the fractures did not deflect to the direction of perpendicular to the minimum horizontal stress (along the direction of maximum horizontal stress) within a certain range.

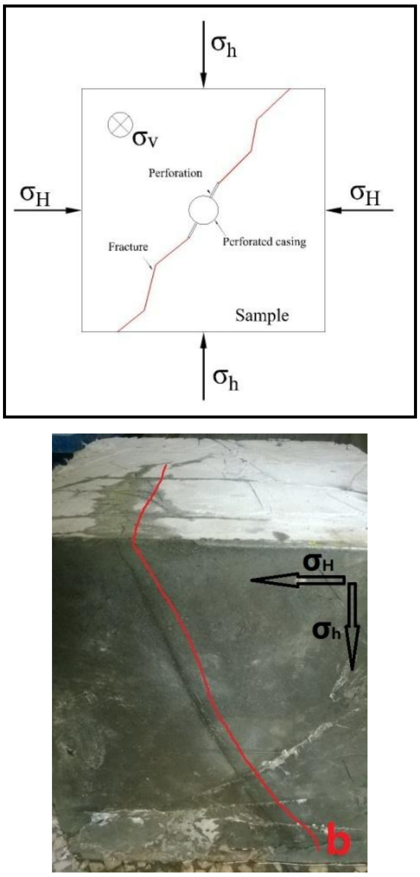

Fig.4 *Fracture propagation when perforation orientation is 60°*

2.3 Effects of perforation density on hydraulic fracturing

Table 5 showed the hydraulic fracturing experiment results when the perforation density were 1, 2, 3 pairs, respectively. The fracturing pressure decreased from 8.34 MPa to 6.47 MPa, 22.4% reduced, when perforation density increased from 1 pair to 3 pairs. These results showed that the fracturing pressure decreased with the increase of perforation density, which because more area of stress concentration around each perforation overlapped when perforation density increased.

Table 5: *Test results with different perforation density*

Sample number	Perforation density	Fracturing pressure/MPa
1	1	8.34
7	2	7.60
8	3	6.47

The direction of perforations was along the direction of maximum horizontal stress in sample 1, 7, 8(perforation orientation was 0°). The fractures in these samples all extended along the direction of maximum horizontal stress and perpendicular to the direction of minimum horizontal stress.

This paper conducted the preliminary study for oil shale hydraulic fracturing, and more researches need to be carried on in the future.

3. Conclusions

In this paper, we prepared 8 synthetic samples with different perforation parameters (perforation diameter, perforation orientation and perforation density) and conducted a series of oil shale hydraulic fracturing experiments. The following conclusions can be reached through analyzing the results of experiments.

(1) With the increase of perforation diameter, the fracturing pressure has a trend of decrease. The fracturing pressure should remain the same when the perforation diameter changes according to mathematical analysis. However, there are more nature micro cracks around the perforation, which create more possibilities to forming cracks.

(2) Perforation orientation has a evident influence on fracturing pressure and fracture propagation. Fracturing pressure increase obviously with the increase of angle of perforation orientation that because the stress distribution changes when the angle of perforation orientation increase. One main fracture forms easily while the angle of perforation orientation is 0°and more secondary cracks may appear with the increase of the angle of perforation orientation.

(3) Perforation density can effect fracturing pressure obviously and fracturing pressure decrease with perforation density increase. However, perforation density has a weak effect on fracture propagation.

(4) Fracture propagation has a little uncertainty in the same in-situ stresses in above experiments, which tensile strength of samples greater than three in-situ stresses. Considering the mechanical parameters and nature micro cracks of the sample, these two factors influent fracture propagation obviously in shallow oil shale hydraulic fracturing. Laminated structure of oil shale also can effect fracture propagation, and we will research on it in the following work.

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