Journal of Petroleum Science and Engineering 168 (2018) 133–147

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Experiments and analysis on the influence of perforation mode on hydraulic fracture geometry in shale formation

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ARTICLE INFO

Keywords:
Shale gas
Hydraulic fracture
Perforation mode
Simulated reservoir volume

ABSTRACT

Hydraulic fracture (HF) geometry is significant when evaluating simulated reservoir volume for shale gas reservoirs. The HF geometry is affected mainly by geological and engineering factors. The physical simulation experiment of hydraulic fracturing is an effective way to obtain the geometry and propagation criterion of HFs in a shale formation. However, the HF geometries created by the different perforation modes are not been well understood. To clarify this mechanism, several groups of true tri-axial hydraulic fracturing experiments were conducted on Longmaxi shale specimens to investigate the influence of perforation modes on the HF geometry. Results show that the HF geometry displays five basic patterns when intersecting with structural planes (SPs), namely, penetration/non-dilation, penetration/dilation, branching, derivation, and deflection. The diversities of HF geometries are the precondition for the formation of complex fractures. The HF geometries induced from oriented, helical, planar and combinatorial perforations show great differences, in which the combinatorial perforation fracturing has a certain promoting effect on the formation of complex fractures. The fluctuation degree of the pressure-time curve and the complexity of fractures show a positive correlation. Similar to previous studies, the HFs show a tendency for propagation beyond the natural fractures when there are higher stress differences. Higher cementing strength and roughness of SPs with weak points is favorable for forming the complex fracture network. The results provide some theoretical support and experimental basis for the optimization of fracturing parameters in the field.

1. Introduction

Hydraulic fracturing has commonly been used in unconventional gas (shale gas, coalbed methane, tight sandstone gas, etc.) stimulations (Ju et al., 2016). Aiming at forming complex fracture networks, simulated reservoir volume (SRV) is a new reconstruction method developed for shale gas reservoirs to achieve commercial development (Mayerhofer et al., 2010). One important aspect of assessing the success of SRV is to evaluate the complexity of the hydraulic fracture (HF) (Zhou et al., 2016), which is mainly affected by both geological and engineering factors (Figueiredoa et al., 2017). Perforation holes are the channels connecting the wellbore and reservoir, which play a key role in pad fluid fracturing (Zhang et al., 2017a). The physical experiments of hydraulic fracturing on shale outcrops are a practical way to investigate the influence of multiple factors on HF geometry (Yuan et al., 2017).

An in-depth understanding of the influencing factors on HF geometry and behaviors has been widely reported. Warpinski and Teufel (1987) found that the permeability of rock, fracture frictional property, and fluid viscosity can influence HF geometry. Beugelsdijk et al. (2000) investigated the interaction of a propagating HF with natural discontinuities, and found that HF geometry was affected by flow rate, horizontal stress difference, and discontinuity pattern. Cipolla and Mayerhofer (2001) studied the complex fracture behaviors in exploratory wells by analyzing detailed case data. Savitski and Detournay (2002) analyzed the propagation of a penny-shaped HF in an impermeable elastic rock and found that the dimensionless toughness controlled the HF propagation path. Olson (2008) found that not only in situ stresses and the presence of natural fractures (NF), but net pressure magnitude and the HF height could influence the HF geometry. Weng et al. (2014) found that stress anisotropy and interfacial friction played critical roles in forming fracture networks by developing a new complex HF model. Morgan and Aral (2015) studied an algorithm for modeling hydraulic fracturing in complex HF geometries. Zhang et al. (2017c)

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https://doi.org/10.1016/j.petrol.2018.05.017
Received 27 November 2017; Received in revised form 26 April 2018; Accepted 4 May 2018
Available online 06 May 2018
0920-4105/

developed a new prediction composite model in shale reservoirs to analyze HF propagation path and geometry. Furthermore, experiments performed by many researchers made the HF geometry more intuitive. In laboratory hydraulic fracturing experiments, advanced techniques, such as computed tomography (CT) scanning (Hampton et al., 2014; Crandall et al., 2017) and nuclear magnetic resonance (NMR) (Gomaa et al., 2014; Grayson et al., 2015) were used to reveal the complex HF behaviors inside the rock. Nevertheless, limited by the scale of the specimen, the propagation of the HF was difficult to observe.

Numerical simulations conducted by Nagel et al. (2013), Farmahini-Farahani and Ghassemi (2016) showed considerable advantages in simulating HF geometry and propagation, however, the complexity of HF behaviors made it difficult to obtain the convincing results (Zhao et al., 2017). Therefore, large-size hydraulic fracturing experiment is a valid way to study the influencing factors on HF geometry and behaviors. Zhou et al. (2010) and Liu et al. (2017) performed experimental studies to investigate the influence of random NF systems and in situ stresses on the HF geometry. Three types of geometries were observed: (a) multiple HF branches; (b) radial HFs; and (c) vertical HF with random branches. Deng et al. (2016) investigated notch angle and length and injection rate on the directional hydraulic fracturing by experimental study. Fatahi et al. (2017) studied the interaction mechanism of HF and NF based on artificial specimen experiments. Huang and Liu, (2017) conducted hydraulic fracturing experiments with cement blocks containing artificial bedding planes. Three propagation forms of HF were summarized: (a) propagation along the beddings; (b) initial propagation along the bedding and along the principal direction; and (c) direct penetration of the bedding and along the principal direction.

These experiments were conducted mostly on artificial specimens, which is intrinsically different from shale specimens. Researchers have recently conducted experiments on shale outcrops. Notably, hydraulic fracturing experiments were carried out by Guo et al. (2014), in which the effects of horizontal stress difference coefficient, flow rate and viscosity of fracturing fluid on the HF propagation criterion was explored. Hou et al. (2014) proposed “stimulated rock area” to evaluate hydraulic fracturing operation by experimental investigation. Cheng et al. (2015a) performed a step-displacement fracturing experiment to explore the influence of fracturing fluid displacement on the HF geometry, and found that an increase in injection rate induced more HFs. Large size laboratory fracturing experiments were performed by Zou et al. (2016), and CT scanning was used to reveal the HF behaviors in shale specimen. Ma et al. (2017b) performed hydraulic fracturing experiments on shale outcrops, and studied the relationship between HF geometry and acoustic emission (AE) events distribution. Naoi et al. (2018) investigated the relationship between seismic events and HF propagation under uniaxial loading conditions by hydraulic fracturing experiments. Zhang et al. (2017b) performed super critical carbon dioxide fracturing on shale specimen to explore the influence of bedding planes, fracturing fluid property and horizontal stress differences on HF geometry. Tan et al. (2017a) performed a series of experiments to study multiple factors of HF vertical propagation, and five basic patterns of HF initiation and propagation were observed: propagation perpendicular to and along the bedding; interconnected bedding; initiation along bedding, then perpendicular to them; and multiple fractures between two bedding planes. Previous studies focused mainly on the general description of HF propagation and the relationship between HF and preexisting discontinuous. Perforation is one of the most important factors that affect HF geometry. Nevertheless, experimental investigations have rarely focused on the effects of the perforation mode.

In this article, shale specimens from the Longmaxi shale outcrops were used to study the influence of the perforation mode, and in part, the geological properties of shale on HF geometry. The geological properties include the structural planes (SPs), micro-fractures and stress difference coefficient. This research contributes to obtaining the HF geometry, as well as the initiation and propagation behaviors that occur in different perforation modes. The studies could provide some theoretical support and experimental basis for the optimization of parameters during actual development.

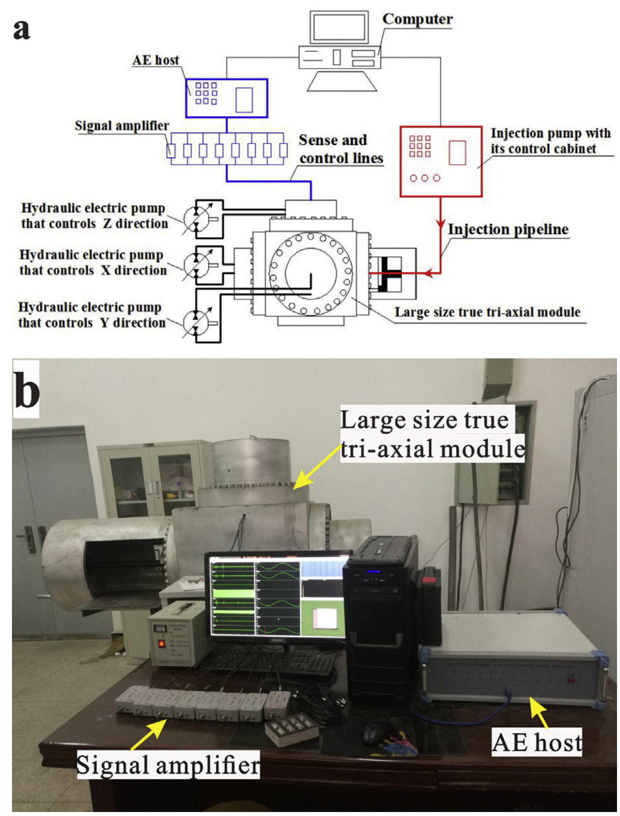

Fig. 1. The true tri-axial hydraulic fracturing system. (a) Technical route of the system. (b) True tri-axial module and AE monitor.

2. Hydraulic fracturing experiment procedures

2.1. Experimental apparatus

Hydraulic fracturing experiments were conducted using a true tri-axial hydraulic fracturing system (Fig. 1). The system comprises a true tri-axial module, a high-pressure injection pump, an AE monitor and a computer. A cubic specimen with dimensions of 300 mm × 300 mm × 300 mm could be positioned among the true tri-axial module. The external stresses in three orthogonal directions are supplied using three separated hydraulic voltage stabilizers, which can supply confining stresses of up to 35 MPa. The injection pressure is supplied using a high-pressure hydraulic pump, and the maximum injection pressure can reach up to 160 MPa. The injection pump is capable of pumping hydraulic fluid up to 18 mL/min. The AE event source mechanism locations were plotted in order to explore the HF geometry and propagation path. The experimental control and data acquisition are conducted using customized software running on a personal computer (Zhang and Fan, 2014). This apparatus provides good control of conditions, which has been used successfully to simulate hydraulic fracturing in various materials with different parameters.

2.2. Specimen processing

The specimens were collected from the Longmaxi shale outcrops in Pengshui County, Chongqing, south-eastern Sichuan Basin (Fig. 2). All the shale specimens used in the experiments were cut from the same shale outcrop, which guaranteed the consistency of the bedding direction in all the specimens and reduced the impact of individual differences (Wu et al., 2018). The shale specimens are composed of medium-