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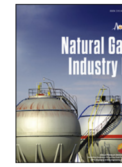

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Research article

Impacts of bedding directions of shale gas reservoirs on hydraulically induced crack propagation☆

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Abstract

Shale gas reservoirs are different from conventional ones in terms of their bedding architectures, so their hydraulic fracturing rules are somewhat different. In this paper, shale hydraulic fracturing tests were carried out by using the triaxial hydraulic fracturing test system to identify the effects of natural bedding directions on the crack propagation in the process of hydraulic fracturing. Then, the fracture initiation criterion of hydraulic fracturing was prepared using the extended finite element method. On this basis, a 3D hydraulic fracturing computation model was established for shale gas reservoirs. And finally, a series of studies were performed about the effects of bedding directions on the crack propagation created by hydraulic fracturing in shale reservoirs. It is shown that the propagation rules of hydraulically induced fractures in shale gas reservoirs are jointly controlled by the in-situ stress and the bedding plane architecture and strength, with the bedding direction as the main factor controlling the crack propagation directions. If the normal tensile stress of bedding surface reaches its tensile strength after the fracturing, cracks will propagate along the bedding direction, and otherwise vertical to the minimum in-situ stress direction. With the propagating of cracks along bedding surfaces, the included angle between the bedding normal direction and the minimum in-situ stress direction increases, the fracture initiation and propagation pressures increase and the crack areas decrease. Generally, cracks propagate in the form of non-plane ellipsoids. With the injection of fracturing fluids, crack areas and total formation filtration increase and crack propagation velocity decreases. The test results agree well with the calculated crack propagation rules, which demonstrate the validity of the above-mentioned model.

Keywords: Shale gas; Hydraulic fracturing; Laboratory test; Bedding direction; Damage; Fracture initiation; Crack; Filtration; Extended finite element method

According to an IEA bulletin in August 2014, China had the largest recoverable shale gas reserves around the world, with technically recoverable resources up to 25.08×10^{12} m^3 [1]; however, the exploitation of shale gas in China remained in its initial stage, and its overall development was hindered by some technical and geological challenges [2]. Studies on fracturing rules of conventional reservoirs have made certain progress [3−6], but shale reservoirs [7−9] have complex bedding architectures, making their hydraulically induced cracks no longer plane ones [10]. Therefore, the hydraulic fracturing rules of shale gas reservoirs are different from those of conventional reservoirs, and the bedding direction of shale reservoirs has direct impacts on the propagation of hydraulically induced cracks. Available research results indicate that shale can be hypothesized to be a transverse isotropic medium [11,12]. Conventional hydraulic fracturing model assumes that cracks propagate in a predesigned plane. Alfano et al. [13] employed a cohesion model developed to study how cracks open along the joint plane. Based on the energy equation, Almia et al. [14] assumed that cracks propagated in the predesigned weak plane, and proposed the hydraulically induced quasi-static crack propagation variation model. In fact, however, cracks are generally three-

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dimensional, with complex shapes and random propagation paths. Common algorithms are generally limited in dealing with the propagation of complex cracks along random paths. Finite element method allows the cracks to cross the unit boundary and through the unit, and the complex-shaped cracks can be calculated in the regular grid without a given propagation path or redivision of the grid for the crack tips, which economizes calculation cost. Thus, it is the most effective method to deal with complex cracks. By rearranging extended finite element and virtual node freedom, Song et al. [15] used the superposition of unit and virtual node to describe the discontinuity. Du Xiuli et al. [16] and Zhang Qing et al. [17] discussed the application of extended finite element method and general extended finite element in dealing with cracks.

The authors selected several shale samples with different bedding directions for hydraulic fracturing test with the triaxial hydraulic fracturing test system. Based on the extended finite element method, the hydraulically induced fracture initiation criterion and the three-dimensional hydraulic fracturing model of shale gas reservoir were established to identify how the bedding direction affects the propagation of hydraulically induced cracks.

1. Hydraulic fracturing tests

1.1. Test schemes

Samples were taken in vertical and parallel bedding planes, with a size of 5 m × 5 m × 5 m. Before the test, an independently developed triaxial loading device was used to apply hydrostatic pressure on the sealed test-piece to simulate the formation stress. When the external load stabilized, the ISCO non-pulse high pressure pump was used to inject high-pressure liquid to the prepared borehole at a rate of 5 mL/min Table 1 shows the test scheme. Fig. 1 gives the schematic diagram of the hydraulic fracturing test scheme, and Fig. 2 shows the shale samples in vertical and parallel bedding planes.

1.2. Test results

Fig. 3 shows the variation of injection pressure along with time, and Fig. 4 shows the morphology of samples after fracturing. Accordingly, the following conclusions were drawn.

1) In Test 1, shale bedding is vertical to the minimum in-situ stress direction, and the induced cracks propagate along the bedding plane. As is shown on the fracturing curve, cracks are initiated at the eighth second and 9.87 MPa. The instantaneous initiation pressure declines and then rebounds. With the propagation of cracks, the injection pressure stabilizes at 6.5–7.0 MPa. At the thirty-second second, factures penetrate the entire sample, the injection pressure sharply declines, and liquid outflows from exit end of the sample.

Table 1
Test schemes.

No.	Axial pressure/MPa	Confining pressure	Bedding direction
1	10	6	Parallel
2	10	6	Vertical

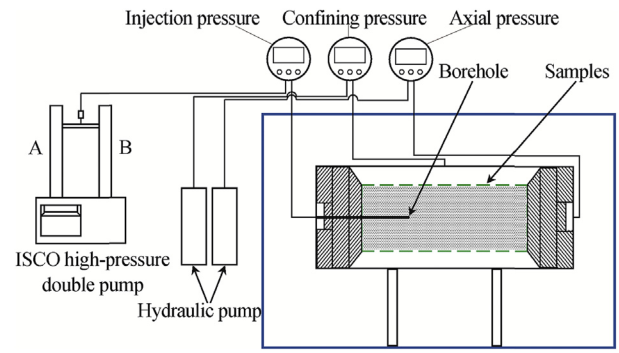

Fig. 1. Schematic diagram of the hydraulic fracturing test system.

a. Bedding parallel to borehole

b. Bedding vertical to borehole

Fig. 2. Shale samples before hydraulic fracturing.

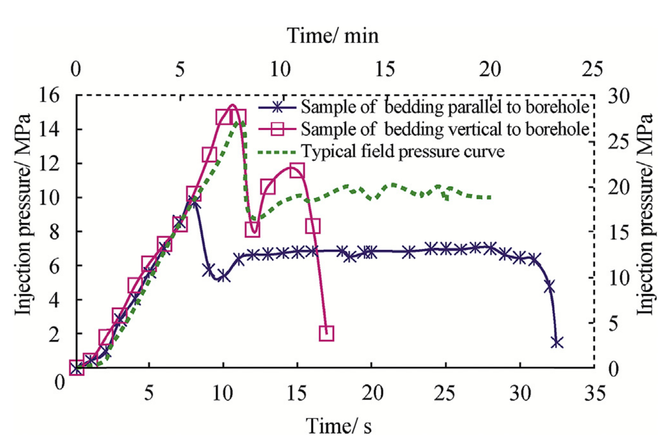

Fig. 3. Injection pressure vs. time in hydraulic fracturing.