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Experimental investigation of proppant settling in complex hydraulic-natural fracture system in shale reservoirs

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ABSTRACT

The general development mode of shale gas reservoirs, as an unconventional resource, cannot yield good results. Hydraulic fracturing is a widely used method in the development of unconventional reservoirs. This method's nature is to create hydraulic fractures in the reservoir, providing a flow path for oil and gas. To achieve a satisfying output, fracture dimensions matter greatly, as well as the fracture effective period. Maintaining these parameters requires that proppant can be distributed in fracture systems abundantly and evenly such that reservoirs can have durable fractures with good conductivity.

Shale gas reservoirs have small porosity and permeability. Gas contained in them is difficult to exploit; thus, massive stimulation methods are needed. Conventional fracturing usually aims to create a long single planar fracture in a reservoir, while in shale gas reservoirs, complicated fracture networks are needed. Thus, the fracturing method in shale gas reservoirs should take natural fractures into consideration, link original micro-fractures in the reservoir, and increase the drainage area as much as possible. This type of fracturing method is called volume fracturing. Volume fracturing can also create multiple artificial fractures perpendicular to the main fracture, improving the stimulation effect and extending the stimulation effective period.

Proppant distribution is critical to maintaining fracture network conductivity and enhancing a shale gas reservoir's output. Moreover, proppant migration and settling during fracturing can affect the activation of natural fractures and the formation of fracture networks greatly, as well as the final effective fracture geometry. The body of research concerning proppant's distribution law in conventional single fractures is quite mature, but the distribution law in complicated fracture networks has not been thoroughly elucidated. Obviously, the current understanding cannot satisfy the demand of practical stimulation. This paper considers the difference of the proppant distribution law between complicated fracture networks and conventional fractures and uses a self-designed complex fracture network simulation device to study proppant migration and the settling law in a complicated fracture network. The research results provide theoretical support for fracturing design in shale gas reservoirs.

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1. Introduction

1.1. Creation of complicated fracture system

Recent studies demonstrate that hydraulic fractures created by volume fracturing have high levels of complexity compared with single planar conventional fractures, which are created by viscous fracturing fluid and packed with fracturing proppant. It is quite challenging to match well the performance using conventional fracturing theories. The development of fracturing monitoring approaches has enabled the industry to understand the complexity of fractures generated by fracturing in shale formations. Warpinski and Mayerhofer (2008) made the observation from the field and believed that a stimulated volume is created while the main fracture and secondary fractures are grown simultaneously.

Further studies determined that natural fractures widely exist in shale formations. Complicated fracture networks are created in shale formations due to the weak planes in natural fractures in addition to the rock brittleness. There are three modes of natural fracture creation in reservoirs: extension, shear with displacement perpendicular to the fracture edge, and shear with displacement

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parallel to the fracture edge. Natural fractures enhance the flow capability of the reservoir. The effective width, length and fracture density, as well as their interconnectivity, dictate the output of stimulation. Interactions between hydraulic fractures and natural fractures were studied by Renshaw and Pollard (1995), who presented the criteria for a vertical fracture intersection. Gu et al. (2012) extended Renshaw and Pollard's study to a non-orthogonal case. Fig. 1 shows 6 different interaction patterns between hydraulic fractures and natural fractures.

As shown in Fig. 1, the hydraulic fracture penetrates a natural fracture and continues propagating (Mode C). In this mode, the hydraulic forces in the artificial fracture can either open up natural fracture or neglect it. In the previous case, hydraulic fractures can stop growing while the natural fractures continue to extend, or both hydraulic fractures and natural fractures propagate in the reservoir. Either way elevates the complexity of the fracture system. Zhao et al. (2013) noted that fracture network creation is strongly influenced by the brittle minerals in the matrix. Variables such as high brittle mineral content, high horizontal elastic modulus, and low horizontal stress contrast are favorable conditions for fracture network creation. They also suggested pumping lower viscosity fluid during stimulation so that the stimulated reservoir volume could be increased.

1.2. Fracture conductivity in complicated fracture system

Lu et al. (2010) developed orthogonal fracture network models using granite and stainless steel plates. They found the non-linearity in the flow pattern with increasing flow capabilities and that fractures parallel to the created main fracture greatly increase the conductivity of the system. Briggs et al. (2014) and Zhang et al. (2014, 2015a, 2015b) systematically investigated shale fracture conductivity via numerical studies using the Barnett Shale, the Eagle Ford Shale and the Fayetteville Shale. They measured the shale fracture conductivity when it was unpropped and propped, being either hydraulically created or naturally occurring. Their work also included the effect of water damage on shale fracture conductivity. Wen et al. (2012) studied the complex fracture conductivity using different patterns of fracture distribution. These researchers recommended optimizing fracturing design by balancing fracture width (fluid viscosity) and the number of fractures (perforation cluster spacing). The researchers found that a system with vertical fractures parallel to the main fracture has the largest fracture conductivity followed by a system with parallel horizontal fractures. The system with a vertical fracture perpendicular to the fluid flow direction has the smallest conductivity.

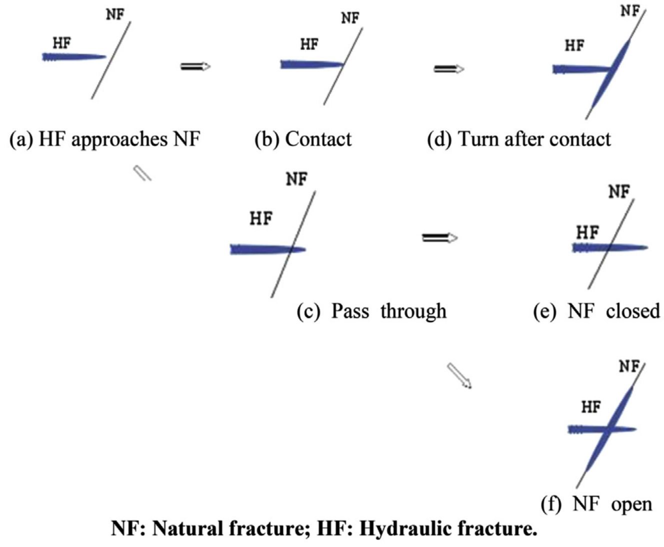

Fig. 1. Interaction modes between hydraulic fractures and natural fractures.

2. Experimental preparation

2.1. Sample preparation

The fracture and matrix system is simulated using acryl glass, which can withstand certain deformation under evenly distributed stress due to its weak elasticity. The transparent glass also allows us to closely observe the proppant migration and settling. The workload of equipment maintenance is also reduced. A disadvantage of the glass material is that it can only be used under low pressure and temperature. The temperature limit of the experimental acrylic material is 80 °C and the pressure limit is 1 MPa. All experiments are conducted under room temperature, with no confining pressure, meeting the requirements of acrylic material.

In the discrete fracture network model, a fracture system consists of single or multiple main fractures that intersect with secondary fractures at certain angles. The tertiary fractures intersect with the secondary fractures at an angle. A "node" is defined as the intersecting point between fractures. During proppant transport, the process in which proppant shunt enters the next level of a fracture is called diversion. In this paper, we define the main fracture as the primary fracture. Fractures directly feeding into the primary fractures are secondary fractures. Likewise, tertiary fractures only feed into the secondary fractures. The experimental apparatus is shown in Fig. 2.

Acryl glass is used to simulate symmetric fractures with fixed width. Multiple fractures with varying angles form the fracture network system. Inside the network, a primary fracture connects the inlet and outlet. Tertiary fractures are parallel to the primary fracture, with a constant spacing. Six symmetric fractures perpendicular to the primary fracture are considered as secondary fractures, as shown in Fig. 3. The 3 × 3 network pattern contains 9 nodes for investigating the proppant distribution law in fracture networks.

In this experimental apparatus, the primary and tertiary fractures are 60 cm; the secondary fractures are 30 cm. All fractures have the same height of 40 cm. In hydraulic fracturing, the fracture width is usually 1–10 mm. However, considering the experimental challenge, in which narrow fractures can be filled up with proppant in a short experiment time scale and impair the accuracy of the testing, we set the primary fracture width as 10 mm. The width of

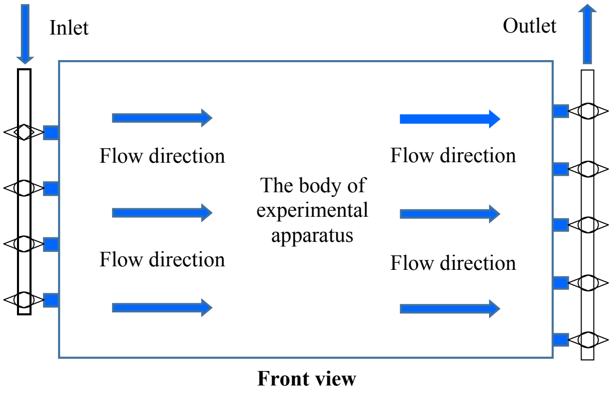

Fig. 2. The principle diagram of the experimental apparatus.

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