

Research article

# Analysis of multi-factor coupling effect on hydraulic fracture network in shale reservoirs<sup>☆</sup>

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## Abstract

Based on the research results of lab triaxial hydraulic fracturing simulation experiments, field fracturing practice, and theory analysis, the factors affecting the growth of hydraulic fracture network in shale reservoirs, including brittleness, difference of horizontal stress, distribution and mechanical characteristics of natural fractures, fluid viscosity and fracturing parameters, etc are analyzed in this study. The results show that the growth of fracture network in shale reservoirs is affected by geological factors and engineering factors jointly. From the perspective of reservoir geological factors, the higher the rock brittleness, the more developed the natural fractures, and the poorer the natural fracture consolidation, the more likely hydraulic fracture network will be formed. From the perspective of fracturing engineering factors, lower fluid viscosity and larger fracturing scale will be more helpful to the formation of extensive fracture network. On the basis of the analysis of single factors, a multi-factor coupling index has been established to characterize the growth degree of hydraulic fracture network and evaluate the complexity of hydraulic fractures after the fracturing of shale reservoirs.

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**Keywords:** Shale; Fracture network; Brittleness; Stress difference; Viscosity; Natural fracture; Fracturing (rock); Evaluation

According to the estimation of U.S. Energy Information Administration (EIA), shale gas in China is huge in recoverable reserves, and broad in development prospect [1,2]. Due to low porosity and super-low permeability, shale gas reservoirs must be stimulated by hydraulic fracturing to gain economic production [3]. Study on the factors affecting fracture network extension in shale gas reservoirs and the proper characterization of network fracture extension, are of great significance to fracturing design optimization and stimulation effect improvement. At present, foreign researchers use brittleness

index [4] to characterize fracture network forming capacity of shale reservoirs by hydraulic fracturing. However, the brittleness index alone cannot reflect the actual difficulty of reservoir fracturing. Yuan Junliang [2] proposed the fracturing index ( $F_{rac}$ ) to describe the complexity of reservoir fracturing based on the brittleness index and fracture toughness of shale gas reservoirs, taking no consideration of the influence of engineering factors on hydraulic fracture extension. Zhao Jinzhou et al. [5,6] analyzed geological and engineering factors affecting the growth of fracture network in shale reservoirs, but didn't consider the coupling effect of these factors.

In 2008, Cipolla et al. [7] initiated to use fracture complex index which equals the ratio of width to length of the fracture network to characterize the complexity of hydraulic fracture network in shale reservoirs. The width and length of fracture network are commonly calculated from the width and length of event point “cloud” obtained from micro-seismic monitoring.

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Since the accuracy of micro-seismic monitoring is not clear and the relationship between seismic events and fracture extension is quite uncertain, the fracture complex index itself has a high uncertainty. Moreover, this parameter, which can only be used to evaluate fracture network complexity after hydraulic fracturing operation with micro seismic monitoring, lacks the predicting significance for fracturing design improvement and optimization. In actual fracturing treatment, the complexity of fracture network extension is quite different due to different reservoir properties and fracturing technical processes. Therefore, study on the factors affecting hydraulic fracture network extension in reservoirs and the proper methods for characterizing network fracture extension complexity are of great significance to fracturing design optimization and reservoir stimulation effect improvement. The effects of geological and engineering factors on shale reservoir hydraulic fracture network extension were explored, and a fracture network extension index based on multi-factor coupling effect was proposed to characterize and evaluate the complexity of shale reservoir hydraulic fracture network in this study, which has major guiding significance to the optimization of hydraulic fracturing technologies for shale reservoirs.

## 1. Analysis of factors affecting hydraulic fracture network growth in shale gas reservoirs

### 1.1. Geological factors

Geological factors affecting hydraulic fracture network growth in shale gas reservoirs include reservoir rock properties, horizontal stress field and the direction, the development degree and the consolidation of natural fractures, etc [8].

#### 1.1.1. Effect of rock brittleness

Extensive theoretical and experimental work was conducted on the evaluation of mechanical properties of shale reservoirs [9–11]. According to the experience of shale reservoir stimulation evaluation abroad, the complexity of fracture network induced by hydraulic-fracturing treatment is in positive correlation with rock brittleness. Therefore, the dimensionless brittleness index  $B$  has become an important parameter used to select high-quality shale gas reservoirs. Rickman et al. [11] presented a mathematical equation to calculate  $B$  with Young's modulus and Poisson's ratio, based on the practical hydraulic-fracturing experience in North America, and advanced the relationship between rock brittleness and fracture pattern. A number of studies show that the higher the rock brittleness index, the more complex the fracture network pattern in shale reservoirs will be. The rock brittleness index  $B$  is calculated by the equation below:

$$B = 0.5 \left( \frac{E - E_{\min}}{E_{\max} - E_{\min}} - \frac{\mu - \mu_{\max}}{\mu_{\max} - \mu_{\min}} \right) \quad (1)$$

where,  $E$ ,  $E_{\max}$  and  $E_{\min}$  are the Young's modulus, the maximum value of Young's modulus and the minimum value of Young's modulus of shale reservoirs respectively (MPa).  $\mu$ ,

$\mu_{\max}$  and  $\mu_{\min}$  are the Poisson's ratio, the maximum value of Poisson's ratio and the minimum value of Poisson's ratio of shale reservoir respectively.

#### 1.1.2. Effect of horizontal stress and natural fractures

Assuming that the overburden stress is the maximum principal stress, according to the classic hydraulic fracturing theory, hydraulic fractures propagate along the direction of the maximum horizontal principal stress in the far-field. When a hydraulic fracture encounters a natural fracture, the hydraulic fracture may cross the natural fracture and propagate on, or cause shear or opening of the natural fracture, forming fracture network, which will increase the contact area between fractures and reservoir, and improve the effect of reservoir stimulation.

Whether a hydraulic fracture diverts or not when intersecting a natural fracture depends on the horizontal principal stress, intersection angle and mechanical properties of the natural fracture. As is shown in Fig. 1, suppose that the natural fractures are vertical, and natural fractures with a consistent dip angle are referred to as a natural fracture group. There are  $m$  (dimensionless) natural fracture groups, and the intersection angle of  $i$ th group is  $\theta_i$  ( $^\circ$ ).  $\sigma_H$  and  $\sigma_h$  are the maximum and minimum horizontal principal stress respectively.

The fluid pressure at the intersection point of the hydraulic fracture and  $i$ th natural-fracture group is  $p_{fi}$ . The normal stress  $\sigma_{ni}$  and shear stress  $\tau_i$  acting on the plane of the natural fracture are:

$$\sigma_{ni} = \frac{\sigma_H + \sigma_h}{2} - \frac{\sigma_H - \sigma_h}{2} \cos(2\theta_i) \quad (2)$$

$$\tau_i = \frac{\sigma_H - \sigma_h}{2} \sin(2\theta_i) \quad (3)$$

Therefore, shear happens to the natural fracture plane of the  $i$ th natural fracture group, when the condition in the following equation is satisfied [12]:

$$|\tau_i| = c_i + f_i (\sigma_{ni} - p_{fi}^c), \quad (4)$$

where,  $c_i$  is the cohesion of the  $i$ th natural fracture group, MPa;  $f_i$  is the frictional coefficient of the  $i$ th natural fracture group;

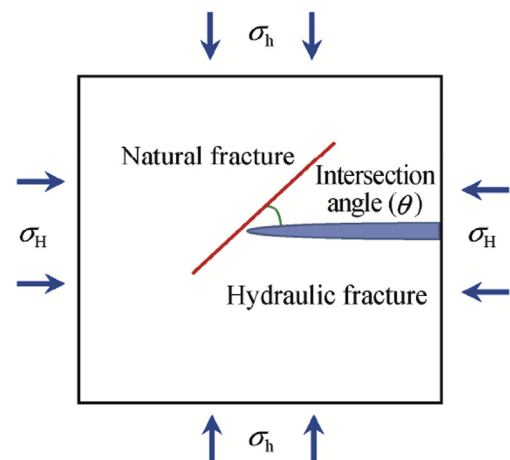


Fig. 1. Schematic of a hydraulic fracture approaching a natural fracture.

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