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The impact of coal macrolithotype on hydraulic fracture initiation and propagation in coal seams

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ABSTRACT

Macrolithotypes control the pore-fracture distribution heterogeneity in coal impacting stimulation via hydro-fracturing and the coalbed methane (CBM) production. Given that it is affected by the discontinuities, hydraulic fracture geometry is complex in the vertical plane and is different from a simple fracture in a homogeneous reservoir. However, the initiation and propagation mechanism in the vertical plane is unclear. To clarify this, the cohesive zone finite element approach, with macrolithotype contributions included, was used to simulate and analyze the hydraulic fracture propagation. The experimental tests showed that, the bright and semi-bright coal usually have higher microfracture (cleat) density accompanied by the lower mechanical properties than that of the semi-dull and dull coals. The behavioral differences are likely to impact the geometry evolution of hydraulic fractures and which appears to vary when fracturing the different coal macrolithtypes. Thus, the cohesive zone finite element approach was used with two models to capture macrolithotype impacts. The result show that, when fracturing the dull coal (model 2), the overall propagation region rapidly displayed a simple plane in shape because of the less development of natural fractures. With the influence of the larger elastic modulus, the high-stress zone would be easy formed and suddenly release to generate pressure pulse when the hydraulic fracture penetrated the interface. As the hydraulic fracture initiates from the bright coal (model 1), the presence of the existing diverse cleat network contribute greatly to the increase of cracks number to form complex fractures. However, the opening of natural fractures will lead to the diversion of fracturing fluid, and the larger elastic modulus of the interlayer also plays a limiting role in the height of the hydraulic fracture. In addition, the monitoring of hydraulic fracture was carried out and shown that the height of the major fracture in model 1 was restricted and limited by the bright coal; and the height in model 2 is usually larger than the dull coal thickness, indicating that the hydraulic fracture has cut through the fracturing section (dull coal) and embedded into the upper and lower layers.

1. Introduction

China is rich in coalbed methane (CBM) resources, and is currently the third largest resource country after Russia and Australia. However, the low permeability and porosity of the coal seam lead to the low output of CBM wells (Chen et al., 2015a; Zou et al., 2013). Hydraulic fracturing is a commonly used method in the petroleum industry for substantially enhancing hydrocarbon production from reservoirs (Adachi et al., 2007). Compared with the conventional reservoirs, the coal seam has the characteristics of alternating output and intermittent distribution of different macrolithtypes (bright, semi-bright, semi-dull, and dull coal) (Mastalerz et al., 2008; Li et al., 2015a; Liu et al., 2017); the stratigraphic distribution of the coal seam is an important reason for the strong heterogeneity in the three-dimensional space and results in the fracturing of coal seam with its own characteristics (Chalmers and Bustin, 2007; Li et al., 2012, 2014a).

The tests in the laboratory have shown that from the bright to the dull coal, the density is gradually higher. Compared with the bright and the semi-bright coal, the semi-dull and dull coal have relatively less X-ray CT identifiable pores and fractures which have more mineral matter (Zhao et al., 2016). These differences in pore-fracture system between different macrolithtypes will not only cause the different physical properties of the two macrolithtype layers, but also affect the overall mechanical properties (Xu et al., 2016), and hence form the interlayer weak plane. Additionally, the coal seam is a laminated formation that composed of the layers of coal macrolithtypes (Fig. 1). Many studies have revealed that discontinuities had a significant effect on the hydraulic fracture (Meng et al., 2016; Cheng et al., 2013). When the

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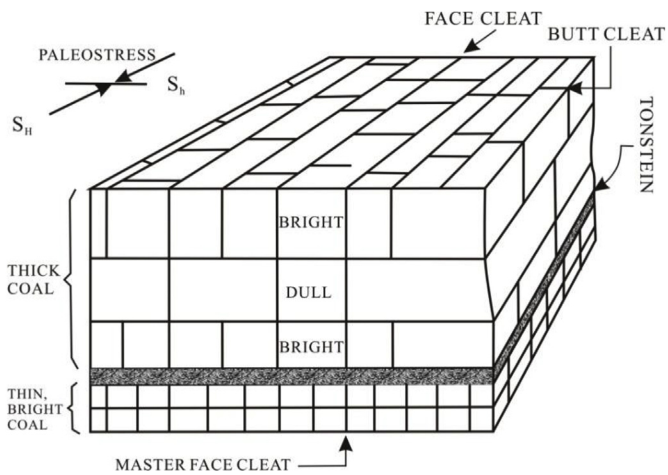

Fig. 1. Schematic showing cleat morphology and macrostructure model of coal.

hydraulic fractures encounter the interlayer interface, they could deflect, terminate, or cross the weak plane (Anderson, 1981). However, based on the concept of CBM development, the fracturing technology of composite reservoir not only requires fracturing of the intermediate fracturing layer, but also requires penetrating the interlayer interface, forming complex network in the coal seam and obtaining abundant CBM resources (Zhou et al., 2007; Zhang et al., 2007). Therefore, investigating the impact of coal macrolithtype on the mechanism of hydraulic fracture is important to maximize the stimulated reservoir volume.

The geometry evolution of fracture has been widely investigated; the results show that the growth of hydraulic fractures in reservoirs that presence of pre-existing natural fractures or discontinuities cause the fractures to become more complex, generating T-shaped, offset, branched, and multiple fractures (Tan et al., 2017; Fan et al., 2014; Warpinski and Teufel, 1984). Observations of a downhole television camera show that fractures in coal are complex. At the interface between macrolithtypes, shear slippage can occur and propping can be intermittent. Fractures affected by the pre-existing natural fractures (Jeffrey et al., 1998; Blanton, 1982; Eekelen, 1982). In the zones that the natural fractures are well developed, there are complex growth patterns of the hydraulic fractures in formations with natural fracture systems resulting from significant diversion of hydraulic fracture paths (Diamond and Oyler, 1987; Jeffrey et al., 2009; Li and Wong, 2002). In addition to reservoir physical properties, the influence of elastic modulus on the fracture propagation is also obvious. When fracture encounters the interface, the interlayer with high elastic modulus will hinder the height of fracture (Gu et al., 2011).

In order to solve the theoretical and technical problems in hydraulic fracturing, scholars have conducted a lot of researches on the initiation and propagation of hydraulic fracturing. In theory, based on plane strain principle, PKN and KGD models, quasi-three-dimensional model (P3D), and three-dimensional plane model (PL3D) are applied to fracturing problems (Valko and Economides, 1994; Dean and Schmidt, 2009). However, the theoretical models above assume that the rock layers are homogeneous, continuous and isotropic and that the fractures are limited to propagate in the plane and cannot analyze the deflection of the fracture (Zou et al., 2016; Salehi and Nygaard, 2015). Therefore, Boone and Ingraffea (1990) introduced the cohesive zone fracture model and used the method to simulate hydraulic fracture propagation. The cohesive zone model can provide a description of the initiation and propagation of stratification and overcome the difficulty that the fracture mechanics method cannot be used to predict the initiation of new cracks (Grasselli et al., 2014). In addition, when the scale parameter is equal to the geometric length of the material or structure (such as crack length), the linear elastic fracture mechanics theory is no longer valid, while the cohesive zone model is not limited by this (Chen, 2012; Carrier and Granet, 2012).

However, current researches of hydraulic fractures in coal mainly focus on the differences among coal beds, roof and floor (Abass et al., 1990; Zhu et al., 2009; Li et al., 2015b; Chen et al., 2015b), ignoring the fact that the coal is composed of small layers of macrolithtypes which have strong effects on the evolution of hydraulic fractures (Xu et al., 2016). In addition, no research has conducted the method of microseism to monitor the influence of coal macrolithotype on the geometry evolution of hydraulic fracture. In this paper, the fracture system and mechanical properties between coal macrolithotype were determined and the specimen that contains the bright-dull coal interface and the cohesion strength between the bright and dull coal was obtained by the laboratory in the first time. Additionally, the ABAQUS, a finite element simulation software, has been used to investigate geometry evolution of 3-D hydraulic fracture that controlled by coal macrolithtypes. With a focus on the injection pressure behavior and various factors on hydraulic fracture initiation and vertical propagation behavior, including the effect of bedding, natural weakness and elastic modulus were investigated. Furthermore, monitoring of hydraulic fracture by the microseism was carried out and the influence of coal macrolithotype on the hydraulic fracture was determined. Studying the fracture system heterogeneity of the macrolithotypes and the impact on hydraulic fracture propagation in coal is beneficial and of great significance to increase the refinement efficiency of the CBM exploration and development.

2. Method and experiment

2.1. Finite element simulations

2.1.1. The cohesive law

As illustrated in Fig. 2, the cohesive model can be divided into two parts, the broken cohesive and the unbroken cohesive zone. The unbroken cohesive zone is an incomplete fracture, and contains three parameters of numerical crack tip, cohesive crack tip and material crack tip. With the injection of fluid, the viscous traction increases with the viscous surface open. When the traction reaches the cohesive strength T_{max}, the cohesive crack tip begins to initiate and the separation reaches the critical value δ_0 (cohesive crack tip). As it greater than δ_0, the traction decreases as the material degrades until the separation reaches the critical value δ_f (material's crack tip), at which point the traction or cohesive strength T disappears and the crack tip completely cracks (Fig. 3) (Zou et al., 2016; Chen et al., 2015a,b).

Under single-type load, the interface has two characteristics of linear loading and linear degeneration in the process of stratification (Gong et al., 2016):

$$T = \begin{cases} k_0\delta,\ 0 < \delta \le \delta_0 \\ (1-D)k_0\delta,\ \delta_0 < \delta < \delta_f \\ 0,\ \delta \ge \delta_f \end{cases} \tag{1}$$

Where k_O is the initial stiffness of the interface, $k_O = T_O/\delta_O$; δ_O and δ_f are the relative displacements at initial and complete failure of the interface, respectively; D takes the value between 0 and 1, when D is 0, it means the material is intact at this moment, and when D is 1, the material has completely destroyed (Camanho and Davila, 2002).

$$D = \frac{\delta_m^f(\delta_m^{\max} - \delta_m^0)}{\delta_m^{\max}(\delta_m^f - \delta_m^0)} \tag{2}$$

${\delta_m}^O$ represents the displacement of the unit node at the beginning of the damage; ${\delta_m}^f$ is the displacement of the element node at $D = 1$; ${\delta_m}^{max}$ the maximum displacement of the element node during the loading history.

When the stress or strain of the dielectric material is equal to a