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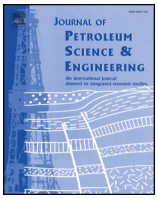

Experimental simulation of the hydraulic fracture propagation in an anthracite coal reservoir in the southern Qinshui basin, China

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ABSTRACT

As coalbed methane (CBM) reservoirs have extremely low permeability, hydraulic fracturing is a common stimulation process for enhancing the CBM production. An in-depth understanding about the propagation mechanism of hydraulic fractures in coal is important for designing a hydraulic fracturing process and thus for improving the CBM production. This study performed a set of true tri-axial fracturing experiments on six block samples (300 mm × 300 mm × 300 mm, including raw coal and artificial roof/floor) with consideration of in situ conditions, aiming at simulating the propagation of hydraulic fractures in the CBM reservoir in the Changzhi field, southern Qinshui basin. Four groups of experiments were organized to evaluate the influences from the pre-existing natural fracture, in situ stresses and injection flow rates on the hydraulic fracture propagation. Meanwhile, five series of numerical simulations were constructed to model the relationship between in situ horizontal stresses and hydraulic fracture propagation. The results show that the hydraulic fracture propagates only along the pre-existing natural fracture direction under a small approaching angle, while it propagates along both the directions of the pre-existing natural fracture and the maximum horizontal principal stress (σ < SUB > H < /SUB >) under a large approaching angle. Whether pre-existing natural fractures exist or not can result in a distinct influence on hydraulic fracture propagation. Hydraulic fractures straightly propagate along the σ < SUB > H < /SUB > direction under a high value of horizontal stresses difference coefficient (K_h), while they tend to deviate from the σ < SUB > H < /SUB > direction under a low K_h value. The influence of K_h is greater than that of the horizontal stresses difference ($\Delta\sigma$) in determining fracture propagation to extend along the σ < SUB > H < /SUB > direction in the coal seam. Large approaching angle, high in situ stresses and a high injection flow rate are three major factors to cause the roof/floor broken by hydraulic fluids.

1. Introduction

Hydraulic fracturing is usually defined as a process by which fractures are initiated and propagate resulted from hydraulic loading applied by fluid inside the fractures, which is a primary means in enhancing gas production from low-permeable rocks, such as tight sandstone, shale and coal (Ferrill et al., 2014; Yuan et al., 2015). Hydraulic fracturing can significantly increase the number of interconnected cracks and apertures and result in the improvement of gas permeability even though that some gas/oil is extruded by high-pressure fluid (Abass et al., 1992; Gan and Elsworth, 2016; Yuan et al., 2017). The hydraulic fracturing technology has hitherto been extensively employed in the petroleum industry to stimulate oil or gas productivity (Yuan et al., 2015). For example, almost all shale gas wells and more than 90% of coalbed methane (CBM) wells are improved by hydraulic fracturing in United States (Zhang and Bian, 2015).

Although gas extractions from coal and shale are both highly dependent on hydraulic fracturing, production requirement for the propagation of hydraulic fractures in coal seam is different from that in shale because coal and shale have large differences in petrological and mechanical characteristics (Penny et al., 1991; Liu et al., 2017; Wu et al., 2018). Hydraulic fracturing is expected to create extensive and complex fracture pathways in shale, which aims at minimizing the spacing between fractures and maximizing the total stimulated reservoir volume (Sobhaniaragh et al., 2016; Yuan et al., 2016). In contrast, in coal seam, hydraulic fracturing is supposed to stimulate long

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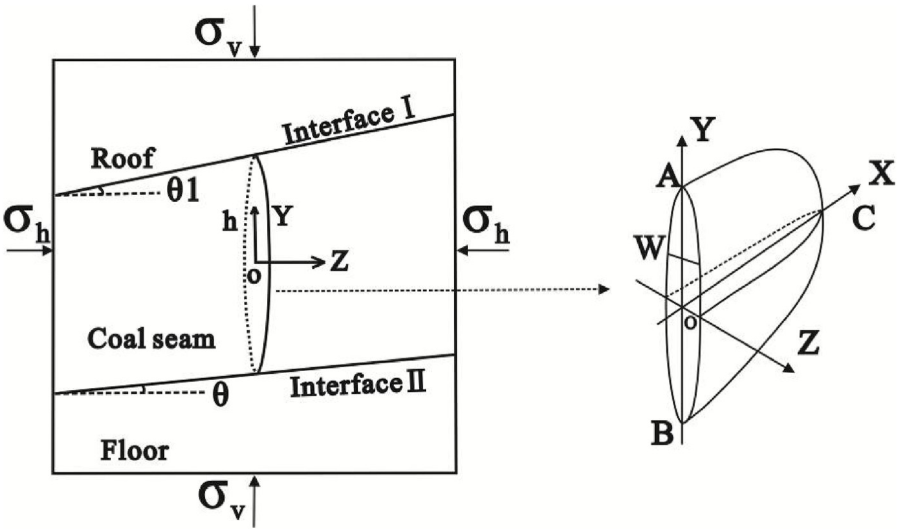

Fig. 1. Propagation mechanism of a hydraulic fracture in layered formations (Zhao and Chen, 2010).

and stable cracks that can be connected with the pre-existing natural fractures to improve drainage efficiency and gas extraction (Wu et al., 2018). Due to the special demand for hydraulic fracturing in coal seam, better understanding the propagation mechanism of hydraulic fractures in coal seam is of great significance for designing an optimal hydraulic fracturing process and thus for enhancing CBM production.

Existed achievements suggested the propagation of hydraulic fracture is influenced by various factors, among which the in situ stresses and the pre-existing natural fractures are two dominant factors (Renshaw, 1994; Yang et al., 2011; Zou et al., 2016). According an experimental study reported by Tan et al. (2017), larger horizontal stresses difference ($\Delta\sigma$) exerts more control on induced fracture morphology and makes the hydraulic fractures expand vertically in coal. Other experimental research (Beugelsdijk et al., 2000; Wu et al., 2018) also suggested that higher $\Delta\sigma$ tend to straighten the hydraulic fracture in coal and make the fracture surfaces more regular. The pre-existing natural fracture also acts important influence on the propagation of hydraulic fracture in coal. Based on a numerical study, Wang et al. (2017) stated that natural fracture contributes greatly to form a complex fracture network and increase coal porosity in the fractured region, which indirectly improving coal permeability. The third influence factor for the propagation of hydraulic fracture is the mechanical strength properties of coal seam and roof/floor. Wang et al. (2014) ever did a numerical simulation study and found that both the elasticity modulus and Poisson's ratio have a positive relationship with the scale of induced hydro-fracture in coal. Different from the view of Wang et al. (2014), Jiang et al. (2016) pointed out higher elasticity modulus impedes the development of induced hydro-fracture in coal. According to Jiang et al. (2016), the length, width and height of main hydraulic fracture respectively decreases about 21.3%, 13.8% and 14.2% when the elasticity modulus increases from 1.43 GPa–2.43 GPa. Previous researches also suggested that other mechanical parameters such as tensile strength and uniaxial compressive strength of coal have negligible influence on the development of hydraulic fractures (Wang et al., 2014). The mechanical strength of the roof/floor has certain influence on hydro-fracturing because the height of hydraulic fractures will be significantly controlled by the roof/floor and the fractures can only propagate in coal seam if the strength of roof/floor is stronger than that of coal (Wu et al., 2018). In addition, the propagation of hydraulic fracture is also related to the injected fracturing fluid: the injected fluid with high-viscosity commonly forms short and wide hydro-fractures in coal (Shimizu et al., 2011; Fan and Zhang, 2014); and different injection flow rate, time and pressure can induce different propagation rule of induced hydro-fractures in coal (Wang et al., 2014).

Although there are extensive investigations on the influences of the hydraulic fractures propagation in coal, most of these researches are based on mathematic modeling or simulation (e.g., Wang et al., 2014; Wang et al., 2017), other experimental researches only discussed some limited influence factors such as injection fluid (Fan and Zhang, 2014), natural fractures (Wang et al., 2017), or in situ stress (Tang et al., 2011). Moreover, there are also some other deficiencies for the existed simulation experiments on coals, for example ignoring the influences of the roof/floor (Jiang et al., 2016), or using artificial specimens (Lin and Du, 2011). As for as the anthracite coals of southern Qinshui basin in China, there is few report relating to direct predicting the hydraulic fracture propagation. In this study, a set of true tri-axial hydraulic fracturing simulation experiments are conducted on large natural anthracite coal samples from southern Qinshui basin. Different from existing researches, this study considered much more comprehensive influences on hydraulic fractures propagation, including the depth, triaxial stresses, pre-existing natural fracture, roof-floor, and injection flow rate. Thus, this study is helpful for forecasting the hydraulic fractures propagation in study coal seam, which would provide theoretical basis and technical support for the efficient CBM extraction in the southern Qinshui basin.

2. Mechanism of fracture propagation

Zhao and Chen (2010) established a model to explain the hydraulic fracture propagation in coal-bearing strata (Fig. 1), which is employed in this study. For the fracture propagation in coal and its roof and floor, in this model, the critical hydraulic pressures can be obtained by

$$P_1 = \frac{K_{1c}}{2}\sqrt{\frac{\pi}{h}} + \sigma_h \tag{1}$$

$$P_2 = \sigma_v \cos^2\theta + \sigma_h \sin^2\theta + \sigma_t \tag{2}$$

$$P_3 = \frac{K_{2c}}{2}\sqrt{\frac{\pi}{h}} + \sigma_h \tag{3}$$

where P_1 is the critical pressure (MPa) above which a hydraulic fracture stops extending at the interface, P_2 is the critical pressure (MPa) above which a hydraulic fracture extends along the interface I or II, P_3 is the critical pressure (MPa) above which a hydraulic fracture penetrates through the roof or floor, K_{1c} is the fracture toughness of coal (MPa·m$^{1/2}$), K_{2c} is the fracture toughness of the roof or floor (MPa·m$^{1/2}$), h is the fracture half-height (m), σ_t is the tensile strength of interface I or II (MPa), and θ is the stratigraphic dip of the interface (°).

The values of P_1, P_2 and P_3 are used to predict the patterns of