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Experimental and numerical simulation study on fracturing through interlayer to coal seam

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Taking the technology of horizontal well fracturing through interlayer to coal seam as the simulation object, the true triaxial test system was employed for the first time in a fracturing stimulation experiment of layered combination specimens comprised of natural rock. The effects of in-situ stress, natural fracture and elastic modulus on hydraulic fracture propagation were studied. On this basis, the effects of different geological and engineering factors on fracture propagation in coal seams were studied quantitatively using the three-dimensional hydraulic fracturing numerical simulation model based on the fluid–solid coupling finite element method. The results indicate that the roof and floor in coal-bearing stratum with larger differences (5 MPa) between vertical stress and the maximum horizontal stress is preferential in the implementation of horizontal fracturing through interlayer to coal seam. The influence of a natural fracture on the propagation of a hydraulic fracture is mainly related to the width of the natural fracture, the injection pressure in the hydraulic fracture and the angle of approach. Under high injection pressure, the impact of natural fractures on hydraulic fracture propagation was significantly lessened. Depending on the developmental degree of a natural fracture, the effect of the approaching angle between the natural fracture and the hydraulic fracture will be smaller. The lower stress difference, elastic modulus difference and permeability difference between layers and higher pumping rates are beneficial in forming longer fractures in a coal seam. Permeability anisotropy characteristics of a coal seam and its roof and floor make the fracture geometry higher, wider and shorter. The experimental and numerical simulation study achievements provide a theoretical basis for effective implementation of this new technology in coalbed methane development.

1. Introduction

The permeability of coalbed methane reservoirs in China is so low that it must be stimulated before the gas can be produced (Wright et al., 1995; Li et al., 2004, 2010; Shan et al., 2005; Meng et al., 2011). The application of horizontal well technology is limited in coal seams with depths below 1000 m due to substantial formation pressure, in-situ stress and poor borehole stability. In such instances, the initiation and propagation mechanism of hydraulic fractures near a wellbore is more complex. Over-pressure and fracture failure occur frequently in stimulation treatments (Zhao and Qin, 2010; Zhang, 2011; Lu, 2011). Therefore, it is crucial to develop new technologies to overcome the instability problems of deep coal seam wellbores in order to exploit deep coal seam gas efficiently.

In this article, we propose a novel stimulation technology: drill horizontal wells in the roof or floor of a coal seam and communicate with the coal seam through hydraulic fracturing. This new technology will not only effectively overcome the adverse effects of the instability of a deep coal seam, but can also eliminate the influence of downhole string on coal mining afterward. The key to this technology is whether hydraulic fracture can penetrate into coal seam from the roof or floor and propagate efficiently in coal seam or not. Several theoretical and experimental studies have been carried out in the past to investigate the effect of formation mechanics characteristics and interfacial properties between layers on the vertical propagation of hydraulic fracturing in layered formation.

Simonson et al. (1976) concluded that a formation with higher Young's modulus can halt a fracture from a lower modulus layer based on a linear elastic fracture mechanism. Conversely, a

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hydraulic fracture in a higher modulus formation can penetrate the interface to a lower modulus layer. Hanson et al. (1978, 1980) found in a similar way that the vertical propagation of a fracture may be halted whether the fracture is extended from a lower modulus layer to a higher modulus layer or in the opposite direction. Fung et al. (1987) argued that Young's modulus ratio between the layers (even increases up to 5) have no noticeable effect on the vertical propagation of a fracture using semi-analytical methods. They found that contrasts in elastic modulus between layers are not the main factor influencing the height containment of a fracture. Smith et al. (2001) came up with a similar conclusion. However, he further concluded that Young's modulus could affect the net pressure in a fracture. The net pressure in a layer with higher Young's modulus was larger, which would encourage fracture propagation in a vertical direction.

Daneshy (1978) first studied the effect of interfacial property on the vertical propagation of fractures by experimenting on layered rock samples. He argued that fractures could easily penetrate the interface and propagate into other layers if the cementing strength between layers was high enough. With a weak cementing strength, fracture containment is possible within the layer and is associated with slippage at the interface. The conclusion was later confirmed by the experimental work of Anderson (1981), Defuel and Clark (1981) and Abass (1990).

According to the study of Defuel and Clark (1981), in-situ stress had control effects on the vertical propagation of hydraulic fractures. With the increase of minimum horizontal principal stress in an adjacent layer, hydraulic fracture was difficult in penetrating into the adjacent layer. Warpinski et al. (1982) and Settari (1988) also agreed that stress contrast between layers was the most important factor affecting the height containment. Meanwhile, modulus contrast and interface cementing strength were not sufficient enough to stop the growth of a fracture. Thiercelin et al. (1989) researched the effect of fracture toughness on the vertical propagation of fractures. His study revealed that the layer with low fracture toughness could promote the propagation of fracture and the fracture might be limited in the layer with higher fracture toughness. However, Hsiao et al. (1987) proposed fracture toughness had a limited effect on the propagation of fracture based on experiments because variation ranges of fracture toughness is rather small. Rahim and Holditch (1995) studied the effect of formation mechanics characteristics (in-situ stress, Young modulus and fracture toughness) and fracturing fluid properties (apparent viscosity and volume of fracturing fluid) comprehensively on the vertical extension of fracture. It turned out that formation mechanics properties had a significant impact on fracture vertical propagation. An adjacent layer with high in-situ stress could limit the fracture in pay formation. For specific reservoirs, vertical propagation of a fracture was mainly affected by apparent viscosity and the volume of the fracturing fluid.

However, the research achievements mentioned above were based on the assumption that hydraulic fractures can penetrate into an interlayer interface and an adjacent layer. It was not clear under what conditions such hydraulic fractures can be formed, nor was the effect of natural fracture on the propagation of hydraulic fracture in layered formation considered. What's more, changes of fracture parameters in adjacent layers were not investigated.

Therefore, this article will clarify these mechanisms and their rules. The conditions for forming a vertical fracture in the roof or floor of a coal seam is studied through a true triaxial hydraulic fracturing experiment with layered samples made of natural rocks. The effects of natural fracture and elastic modulus between layers on the propagation rules of hydraulic fracture in layered medium were also investigated. In addition, three-dimensional numerical simulation of horizontal well fracturing in the roof and floor of a coal seam was also conducted in order to study the changes of fracture parameters in the coal seam quantitatively. The research results will provide a theoretical basis for the application of this technology in the effective development of coalbed methane.

2. True triaxial experiment of hydraulic fracturing

2.1. Experiment apparatus

Experiment apparatus used to conduct hydraulic fracturing simulation is a true triaxial simulation system (Zhou et al., 2008; Guo et al., 2014). This simulation system, as shown in Fig. 1, is composed of a large-sized pressure bearing system, a hydraulic intensifier system, a fluid injection system, a data acquisition system and other auxiliary devices.

2.2. Experiment design

The stress parameters and experiment program are designed as shown in Table 1. To study the effects of natural fractures on the propagation of hydraulic fractures, simulated wellbore should be avoided so as not to intersect with natural fractures. Therefore, natural fractures strike are analyzed, parameters of natural fractures are accurately measured, and the location of the borehole section are also measured accurately before drilling a simulated wellbore. Large natural fractures exist in the roof and floor blocks of sandstone 2, limestone 1 and sandstone 4. Natural fracture lengths are 9.60 cm, 21.30 cm and 20.80 cm, respectively with corresponding widths 0.05 mm, 0.01 mm and 0.05 mm, respectively. The angles of approach between natural fractures and vertical hydraulic fractures are 75°, 30° and 15°, respectively.

The natural fractures are relatively wide in coal samples M1, M5, M10 and M11. The natural fracture in sample M5 is parallel to the bedding plane with a width and length of 0.07 mm and 19.90 cm, respectively. Two crossed natural fractures exist in sample M1 with widths of 0.09 cm and 0.07 mm, respectively. And the corresponding lengths of natural fractures are 9.41 cm and 16.92 cm, respectively. In sample M10, the width and length of the natural fracture are 0.10 mm and 2.49 cm, respectively. In sample M11, the width and length of the natural fracture are 0.28 mm and 1.28 cm, respectively.

In order to study the influence of the difference in modulus between layers on the growth of a hydraulic fracture, a limestone block was designed as a contrast sample. Young's modulus of

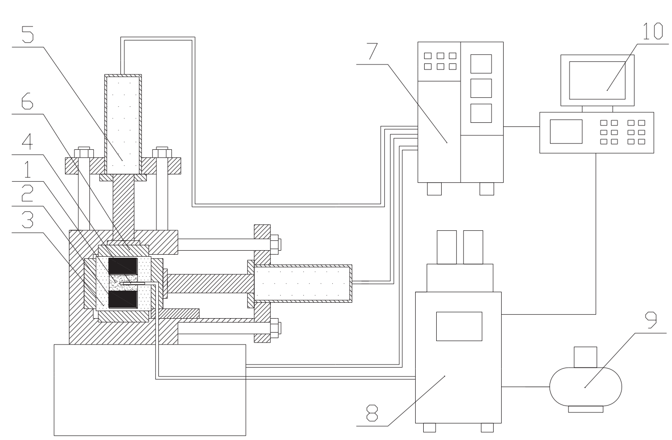

Fig. 1. Schematic plot of a true triaxial hydraulic fracturing simulation system. In the figure: 1-roof and floor rock; 2-coal; 3-cement; 4-sealed injection tube; 5-hydraulic cylinder; 6-pressure plate; 7-hydraulic cylinder system; 8-fluid injection pump; 9-air compressor; 10-data acquisition processor.