Journal of Natural Gas Science and Engineering 35 (2016) 455–467

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Experimental and numerical study on hydraulic fracture propagation in coalbed methane reservoir

Tingting Jiang, Jianhua Zhang*, Hao Wu**

School of Resource and Environmental Engineering, Wuhan University of Technology, Luoshi Road No.122, Wuhan, 430070, Hubei, China

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form
9 August 2016
Accepted 31 August 2016
Available online 1 September 2016

Keywords:
Coalbed methane reservoir
True triaxial test
Fracture propagation
Physical experiment
Numerical simulation

ABSTRACT

A true triaxial hydraulic fracturing system is built for carrying out fracturing stimulation experiments on cubic raw coal specimens to simulate the hydraulic fracturing by means of a vertical well in a coal seam. The effects of in-situ stress and injection rate on the hydraulic fracture propagation are analyzed. A three-dimensional hydraulic fracture numerical simulation model is developed to quantitatively study the effects of different geological and operational factors on the fracture propagation in coalbed methane (CBM) reservoirs. The results indicate that higher elasticity modulus and fracture toughness difference between coal and bedding show a strong inhibitory impact on the major fracture extension, but are good for forming more induced fractures. A smaller horizontal in-situ stress difference is beneficial in forming a crosscutting fracture network. A larger injection rate enhances the fracture size and the complexity of the fracture network. The experimental and numerical simulation study achievements can provide a case reference for optimization design of hydraulic fracturing and fracture network geometry control of CBM reservoirs.

1. Introduction

Hydraulic fracturing is an effective means to improve the output of producing wells and increase coalbed methane recovery (Islam et al., 2009; Lekontsev et al., 2012, 2014; Xu et al., 2013). The initiation and propagation of hydraulic fractures in a coal seam are complicated, which restricts the efficient implementation of hydraulic fracturing (Wessling et al., 2008; Ahn et al., 2014; Yang et al., 2016). Therefore, it is of great significance to fully understand the hydraulic fracture propagation in CBM reservoirs. Several theoretical and experimental studies have been carried out in the past to investigate the effect of formation mechanical properties and construction parameters on the fracture propagation of hydraulic fracturing in CBM reservoirs.

Based on the study of Yuan et al. (2012), injection pressure and elastic modulus of coal affected hydraulic fracturing propagation. They proposed fracturing fluid viscosity had limited effect on the fracture propagation. Wu et al. (2013) researched the influence of elastic modulus, Poisson's ratio, differential stress and pumping rate on fracture geometry. Ciezobka and Salehi (2013) illustrated how natural fractures were identified in real time through analysis of surface pumping parameters and confirmed their analysis with microseismic data and multiple production logs. Li et al. (2014) comprehensively studied the effect of formation mechanical property (in-situ stress, elastic modulus and permeability, etc.) differences between adjacent layers and fracturing fluid parameters (injection rate, viscosity, proppant size, etc.) on the hydraulic fractures propagation along the vertical direction of the formation. It turned out that the mechanical properties of strata have great influence on the fracture extension. Xu et al. (2014) indicated that the stress sensitivity, comprehensive filtration coefficient and pumping delivery capacity were the key factors affecting the fracture length. Klawitter et al. (2015) analyzed the fractures resulting in coal by using the Shore Scleroscope Rebound Hardness test, which can be scaled up to understand fracture propagation in CBM reservoirs. Li and Xing (2015) studied the effect of formation properties on the hydraulic fracture initiation. They argued that hydraulic fracture could initiate earlier if the values of permeability, porosity, Young's modulus and Poisson's ratio were larger, when the hydraulic pressure was constant. Kirk-Burnnand et al. (2015) achieved a conclusion similar to that of Li and Xing (2015). They further concluded that reservoir complexity was mainly impacted by the anisotropy of coal seams. Dehghan et al. (2016) confirmed

* Corresponding author.
** Corresponding author.
E-mail addresses: zjhwut@sina.com (J. Zhang), haowu1977@163.com (H. Wu).

http://dx.doi.org/10.1016/j.jngse.2016.08.077
1875-5100/

that the pre-existing fractures around the wellbore could reduce the effect of the original stress concentration, which led to a drastic decrease of the fracture initiation and propagation pressure. Moreover, they pointed out that the fracture propagation changed from a single fracturing mode to a multiple fracture mode with the increase of horizontal in-situ stress difference. Ma et al. (2016) studied the effect of the direction of the minimum principal stress and the difference between the maximum and minimum horizontal stresses on hydraulic fracture propagation. They confirmed that the two factors have notable effects on the fracturing pattern. Ciezobka et al. (2016) proposed an interesting method to use a pressure pulse to open previously unopened perforations and to increase fracture complexity through fluid diversion.

However, these achievements mentioned above were mainly based on the assumption that the coal seam was homogeneous or used for shale gas reservoirs. The effects of the bedding were not considered. This leads to the critical conditions for forming a fracture network and the effects of the bedding on the fracturing in CBM reservoirs not being well understood. The bedding has significant influence on hydraulic fracture geometry, which has been shown by Fan et al. (2014) and Grasselli et al. (2015). Moreover, studies about the effects of construction parameters on hydraulic fracture propagation in anisotropic coal seam are rare.

The motivation of this paper is to better understand the mechanism of how bedding affects the hydraulic fracture initiation and propagation and to find the main factors influencing the fracture geometry and morphology. The raw coal contains the natural fractures and bedding, which can reflect the actual situation of hydraulic fracturing in CBM reservoir more truly than prefabricated materials similar to coal (Cheng et al., 2013; Tian et al., 2014). Hydraulic fracturing experiments have been carried out on raw coal from Jiaozuo coal mine to obtain a fracture propagation rule. The threshold conditions for forming fracture networks are studied by carrying out true triaxial hydraulic fracturing experiments on large dimension natural coal specimens. The effects of in-situ stress difference and injection rate on the propagation of hydraulic fracture in the coal specimens are also investigated. 3D numerical simulation is conducted to quantitatively study fracture geometries in the coal seam. The research results can provide a reference for the optimization design of hydraulic fracturing and fracture network geometry control of Jiaozuo CBM reservoirs.

2. True triaxial hydraulic fracturing experiment

2.1. Experimental apparatus

Fig. 1 presents a true triaxial hydraulic fracturing physical simulation test system built to simulate the hydraulic fracture propagation in rock masses. This system consists mainly of three parts, (I) true triaxial servo loading system, (II) hydraulic fracturing pump pressure servo control system, and (III) acoustic emission monitoring system. Part I is used to simulate three-dimensional stresses acting on the in-situ coal seam, part II is used to precisely control the fracturing fluid injection rate and pressure, and part III is used to monitor the acoustic signal caused by the crack extension and propagation during hydraulic fracturing. A true triaxial testing machine can provide independent stress in three directions. Its maximum axial load is 3000 kN and the dimensions of the maximum allowable sample are 800 mm in the length, width and height directions. The pressure range of the pump pressure servo control system is 0–100 MPa, and its maximum control error is less than 1% of the maximum pressure; the available volume of supercharger is 800 mL and is measured by a displacement sensor with a maximum range of 210 mm. Information about fracture initiation and propagation is collected by the acoustic emission probe. Its operating frequency is 15 kHz–70 kHz, and the center frequency is 40 kHz.

2.2. Experiment design

The cases of the experiment scheme selected to simulate the possible conditions for the actual hydraulic fracturing are selected as shown in Table 1. Perforation completion is adopted to simulate the actual situation in CBM reservoirs. The borehole location is accurately measured before drilling a simulation wellbore in the specimen. The in-situ stress difference coefficient (k) is selected as a parameter measuring the horizontal principal stress difference, used to analyze the influence of the in-situ stress difference on the growth of hydraulic fractures. It is simulated as 0.54, 0.4 and 0.7 respectively. The pump rates are assigned as 30, 60 and 90 mL/min to study their effects on the hydraulic fracture propagation.σ_H is the maximum horizontal principal stress, σ_h is the minimum horizontal principal stress, and σ_v is the vertical stress; $k=(\sigma_H-\sigma_h)/\sigma_h$, k is the in-situ stress difference coefficient.

2.3. Specimen preparation

The standard coal sample is a cube with dimensions of 300 mm, prepared from the raw coal blocks taken from No. 2 coal seam in Jiaozuo mining area, Henan province, China. A borehole perpendicular to the bedding plane with a diameter of 24 mm and a depth of 170 mm was drilled in the samples to simulate the actual wellbore. Fig. 2 presents a high-strength steel pipe used in the tests to simulate the casing of an actual fracturing well. Its outer and inner diameters and length are 20 mm, 15 mm and 165 mm, respectively. It was then fixed to the hole. Two cuts in the lower end of the pipe, distributed symmetrically, with a width of 1.5 mm and a length of 30 mm, simulate the slotting. The end of the steel pipe was welded closed and on one head was placed a built-in thread to connect the pump pipeline of the fracturing pump pressure servo control system (Fig. 3). High strength epoxy sealant adhesive was used to cement the steel pipe in the hole. Components of the sealant epoxy were mixed at the rate of 5:1. They are stirred to a uniform consistency in order to avoid incomplete curing. The sample was maintained at least 24 h under room temperature to ensure the quality of curing. To prevent the adhesive plugging up the cuts, cotton swabs were fixed in the cuts in advance and we ensured their length outside the pipe was 2–5 mm. The directions of three dimensional stresses, bedding and wellbore are shown in Fig. 4.

2.4. Experimental procedure

To simulate the vertical well hydraulic fracturing, the wellbore is drilled parallel to the vertical principal stress. To assure a stable and accurately controlled hydraulic pressure and the safety of the laboratory technician, aviation hydraulic fluid was used as fracturing fluid. Its advantages include small compressibility and stability under high pressure. A red color agent was mixed with the fracturing fluid to conveniently visualize the hydraulic fractures.

After the sample was put into the true triaxial loading chamber, two acoustic emission probes were placed on each of the four surface planes parallel to the borehole. The acoustic emission detectors are arranged diagonally to effectively monitor the signals of crack initiation and propagation inside the specimen during the experiments (Fig. 5). The coordinates of the acoustic emission probes are listed in Table 2.

When applying the triaxial stress, a multistep loading mode is used to avoid sample mechanical shear failure caused by unbalanced loading of three-dimensional stresses. First, the stresses are