Journal of Natural Gas Science and Engineering 38 (2017) 402–411

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Response characteristics of coal subjected to hydraulic fracturing: An evaluation based on real-time monitoring of borehole strain and acoustic emission

Yunpei Liang [a], Yunhai Cheng [b, *], Quanle Zou [a], Weide Wang [b], Yankun Ma [b], Quangui Li [a]

[a] State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
[b] The Key Laboratory of Safe and High-efficiency, Mining of Ministry of Education of Anhui, University of Science and Technology, Huainan Anhui Province, 232001, China

ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form
26 December 2016
Accepted 1 January 2017
Available online 2 January 2017

Keywords:
Hydraulic fracturing
Fracture behaviors
Borehole wall strain
Acoustic emission
Fracture morphology

ABSTRACT

With the increasing consumption of conventional oil and gas reservoirs for gas recovery/production, unconventional reservoirs, such as coalbed methane, shale gas, and gas hydrate, have become very popular in recent times. In this regard, hydraulic fracturing is an effective technique commonly used for enhanced coalbed methane recovery. In previous studies, the fracture morphology was described by comparing the fracture morphology before and after hydraulic fracturing from a macroscopic perspective. Because fracture initiation and subsequent networks of fractures are formed instantly when coal mass is subjected to hydraulic fracturing, it is almost impossible to acquire complete information about fracture initiation by only analyzing the change in hydraulic pressure and fracture morphology. In this paper, a triaxial experimental system was developed to simulate hydraulic fracturing using raw coal and briquette coal samples, respectively. The borehole wall strain observed during hydraulic fracturing was plotted (borehole wall strain curves) and the acoustic emission response was also obtained. In addition, the fracture behaviors during hydraulic fracturing were analyzed. Our results show that the response of coal subjected to hydraulic fracturing can be divided into the following four stages: microcrack formation, fracture initiation, unstable crack propagation, and fracture closure. The borehole wall strain curves effectively reflected the deformation and failure of borehole wall. Acoustic emission response can thus be utilized to identify the orientation of fractures during hydraulic fracturing. The combination of the two methods offers an effective option for clarifying the fracture initiation and instability mechanism near the borehole subjected to hydraulic fracturing.

1. Introduction

Coalbed methane (CBM) is a natural resource formed during coal generation. CBM is an environmentally friendly clean energy with a high calorific value. Its main component is methane (CH_4). The net calorific value of 1 m^3 CH_4 is 35.88 MJ under the standard condition, which is equivalent to 1.13 kg gasoline or 1.21 kg standard coal (Liu et al., 2016a; Sarhosis et al., 2016; Zou et al., 2014, 2015). Chinese CBM reserve at depths below 2000 m is estimated to be about 36.81 trillion m^3. This reserve is slightly lesser than that of conventional natural gas (38 trillion m^3). Therefore, CBM exploitation contributes to Chinese energy structure improvement and energy supply enhancement. Distributions of Chinese CBM reserve are depicted in Fig. 1 (Yuan, 2016). It can be seen from Fig. 1 that the majority of CBM reserves are stored in deep coal seams. However, the deep coal seams in China are characterized by low permeability and high gas adsorption capacity, which are unfavorable for CBM extraction (Wei et al., 2016). Therefore, stimulation measures are urgently needed to overcome the limitations of extracting CBM from deep coal seams (Aminto and Olson, 2012; Liu et al., 2016b; Dahi Taleghani et al., 2016; Zhang and Bian, 2015; Grimm et al., 2012; Park and Liang, 2016; Zhou et al., 2016). Hydraulic fracturing is a process in which initiation, propagation, and coalescence of microcracks inside coal masses are induced by continuous hydraulic loading, which results in enhancement of permeability in coal seams (Li et al., 2013, 2014; Hossain and Rahman, 2008; Towler et al., 2016). This technique has been

---

* Corresponding author.
E-mail address: 18701670510@163.com (Y. Cheng).

http://dx.doi.org/10.1016/j.jngse.2017.01.001
1875-5100/

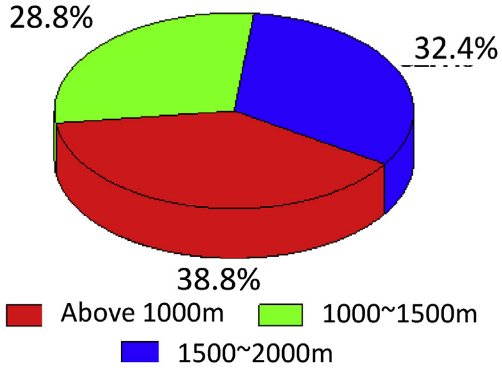

Fig. 1. CBM reserve distribution in China.

extensively adopted in enhanced CBM exploitation due to the advantage of large disturbance range and desirable permeability enhancement effect (Li et al., 2015a).

Several studies on hydraulic fracturing have been carried out, including theoretical analyses, laboratory experiments, numerical simulations, and field tests. With regard to theoretical analysis, Bunger (2013) adopted the energy balance theory to predict the conditions under which multiple hydraulic fractures will grow simultaneously. It was indicated in that study that both geometry and fluid flow are crucial when it comes to understanding the importance of input power dependence on the number of hydraulic fractures in the array and that these fractures evolve by interaction of stress of one fracture with neighboring hydraulic fractures, a process termed “fracture transition.” Besides, considering the spatial relation of natural fractures and perforations under intersection, Zhao et al. (2013) established the calculation model of tensile hydraulic fracture initiation pressure based on the elastic mechanics, rock mechanics, and tensile initiation criterion. Similarly, according to the maximum tension stress theory, the initiation pressure calculation model and corresponding judgment criterion were derived by Cheng et al. (2015) to analyze the stress state around the hydraulic fracturing borehole in the inclined coal seam. Laboratory experiments are aimed at obtaining relatively real conclusions by small-scale physical simulation. A laboratory borehole simulator was developed by Bohloli and de Pater (2006) to investigate the effect of fluid rheology and confining stress on fracture initiation and propagation. A high-stress triaxial cell with pore pressure was developed by Zhang and Fan (2014) to simulate hydraulic fracturing. Stanchits et al. (2011) elaborated the fracturing mechanism of porous rock induced by fluid injection. A large number of laboratory experiments concerning hydraulic fracturing after water pressure control blasting were performed by Huang et al. (2011, 2014, 2016) to overcome the limitations of traditional hydraulic fracturing such as lesser number of main fractures and poor fracture morphology. Similarly, pulse hydraulic fracturing is proposed to lower the initiation stress level and improve the fracture network (Zhai et al., 2015a). Recently, the CT technology was introduced to quantitatively describe the hydraulic fracture morphology including induced fracture length, width, and tip inclination angle (Shi et al., 2016; Jia et al., 2013). Numerical simulation was another crucial method used to understand the potential laws of hydraulic fracturing. A non-Darcy flow MsFHW numerical simulator was developed by Guo et al. (2015) based on black-oil simulator to evaluate the gas production performance of tight sandstone reservoirs. A two-phase, three-dimensional model of fracturing coalbed methane was developed and coded by Zhang (2014) to analyze the impact of permeability, original volume density, and Langmuir constants on the gas production. Besides, the particle flow code, RFPA, and ABAQUS were used to successfully simulate the hydraulic fracturing (Lian et al., 2009; Shimizu et al., 2011; Lin et al., 2012; Deng et al., 2014; Wang et al., 2014; Zhang, 2014; Guo et al., 2015). The field test can provide a verification for the conclusion/findings of the aforementioned methods, that is, theoretical analyses, laboratory experiments, numerical simulations. Li et al. (2015b) chose pulse hydraulic fracturing to improve the gas drainage effect in Yuwu Coal Mine in China and field test results indicated that the gas drainage volume of fracturing borehole increased by 3.32-fold compared with the traditional borehole. In addition, the impact of the geological structure on hydraulic fracturing effect was investigated by Ni et al. (2015) and the phenomenon of methane flow driven by hydraulic fracturing was proposed by Huang et al. (2016). As has been detailed in the previous section, significant achievements have been made in this subject. However, previous studies only focused on the description of the fracture morphology by comparing the fracture morphology before and after hydraulic fracturing from a macroscopic perspective. Because fracture initiation and subsequent networks of fractures are formed instantly when coal mass is subjected to hydraulic fracturing, it is almost impossible to acquire complete information about fracture initiation by only analyzing the change in hydraulic pressure and fracture morphology. Borehole wall strain is a manifestation of borehole wall deformation under hydraulic pressure, which can reflect the rate of borehole deformation and the intensity of energy accumulation and release (Zhai et al., 2015b). Acoustic emission technology can measure the intensity of borehole wall fracture and the number of fracture events, providing information in real-time about fracture initiation and propagation (Agioutantis et al., 2016). The combination of strain measurement and acoustic emission monitoring can systematically and comprehensively analyze the initiation, propagation, and interconnection of hydraulic fractures under hydraulic pressure. In this paper, a triaxial experimental system for simulating hydraulic fracturing was developed. In this work, we combined monitoring of both borehole wall strain and acoustic emission to investigate the fracture initiation and propagation behaviors near the borehole. Besides, hydraulic fracturing experiments were performed using briquette coal and raw coal samples under various confining pressures. Based on the experimental results, the characteristics of borehole wall strain and acoustic emission response were discussed and the possible underlying mechanism was proposed.

2. Experimental system and procedures

2.1. Experimental system and sample preparation

The triaxial experimental system was developed to simulate hydraulic fracturing. As shown in Fig. 2, this system is composed of two subsystems: hydraulic fracturing generation subsystem and monitoring subsystem. The hydraulic fracturing generation subsystem includes the following: high-pressure water pump, water pressure recorder, sealed tank, high-pressure nitrogen cylinder, and vertical stress generation equipment. High-pressure water pump (Model: CYJ2-1.2/20) is used to inject water into specimens with a preset flux. The water pressure is recorded in real time by a water pressure sensor (MD-8088) and a water pressure recorder (RX200A). The confining stress is imposed by a combination of sealed tank and high-pressure nitrogen cylinder. The axial stress is imposed by the vertical stress generation equipment. The monitoring subsystem includes strain gauge, strain indicator, acoustic emission indicator, and data-acquisition indicator. The CM-1A-10 static strain indictor is used to monitor the borehole wall strain in real time. The DS2 full-information acoustic emission indicator is used to quantitatively describe the fracture behaviors. Eight