Fuel 206 (2017) 371–380

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Feasibility investigation of cryogenic effect from liquid carbon dioxide multi cycle fracturing technology in coalbed methane recovery

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ARTICLE INFO

Article history:
Received 14 March 2017
Received in revised form 10 May 2017
Accepted 31 May 2017

Keywords:
Coalbed methane
LCO_2 multi cycle fracturing technology
Nuclear magnetic resonance
Cryogenic effect
Effective porosity
Permeability

ABSTRACT

Liquid carbon dioxide (LCO_2) fracturing technology has been applied in the enhanced coalbed methane recovery (ECBM), and it has made some progress in the physical experiments and field applications. However, the freeze phenomenon during the injection process might induce coal matrix shrinkage, hindering the fracturing efficiency. A multiple cycle LCO_2 fracturing technology is proposed, and the feasibility of the cryogenic effect from LCO_2 on the crack evolution of five different coal cores under the loading state was investigated by using an innovative cryogenic loading experimental system. Nuclear magnetic resonance (NMR) and infrared thermal imaging (ITI) were used to measure the pore changes and temperature distribution, respectively. After 25 injection cycles, some cracks on the side and lateral surfaces of five cores were generated, and a low temperature distribution was formed. The temperature values were almost less than −18 °C, which could cause the saturated water to freeze into ice with a 9% volume increase; thus, the stress analysis diagram during one cycle injection was analyzed, and the initiation criterion was deduced. The T_2 spectra variation showed that the various pore sizes changed with the increased number of cycles. The peaks increased in amplitude and shifted to the right under saturated conditions, while they decreased and shifted to the left under centrifuged conditions, causing the amplitude increment ΔA in the post-test stage to be greater than that in the pre-test stage, which indicated that the cryogenic effect of LCO_2 could significantly improve the connectivity of pores. The total porosity φ_t and effective porosity φ_e of all five cores increased with the number of cycles. A quadratic function described the relationship between incremental ratio of φ_e (D_c) and cycle number, the fitting coefficients for which all exceeded 0.99, which indicated that the cryogenic effect of LCO_2 could improve the permeability observably.

1. Introduction

Coalbed methane (CBM), as an accessory product of the coalification process, is stored in the pores, flaws, and beddings of the coal matrix in both free and adsorbed states [1–3]. More than 70% of the coal deposits in China have relatively high contents of CBM [4,5]. As a green and unconventional resource, CBM should arouse more attention from governments, scholars, and entrepreneurs. However, the common characteristics of deeper burial depth, lower permeability, and higher dense of the matrix greatly hinder the efficiency of CBM recovery [4–6]. Generally, the number of fissures could improve the coal permeability and enhance gas desorption and flow by providing flow channels. Currently, hydraulic fracturing (HF), which could produce some fractures with a mass of pressure water, is commonly used for CBM extraction [7,8]. Nevertheless, some drawbacks, such as huge water consumption, water block and sensitivity effect, and fracturing fluid contaminant pollution, have become apparent in many field applications [9,10]. Thus, some waterless fracturing technologies rely on carbon dioxide (CO_2) or nitrogen (N_2) with various phase states (gas, liquid, or flue gases) are being developed alternative methods for the prospective fracturing targets.

Enhanced CBM recovery (ECBM) by injecting liquid CO_2 (LCO_2) is a means of fracturing the reservoirs to extract CBM. The first proposal of CO_2 fracturing on record occurred in the 1980s, and its first patent was registered by Bullen and Lillies [11]. In more recent

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http://dx.doi.org/10.1016/j.fuel.2017.05.096
0016-2361/

years, LCO_2 fracturing technology with different additives (proppants, bubbles, *etc.*) has been widely used to stimulate the unconventional resource reservoirs. In 1981, the USA first adopted the fracturing fluid of 100% LCO_2 to stimulate the low-permeability gas reservoir, which attained a good production-increase effect [12]. Thereafter, LCO_2 fracturing technology with/without different additives was used in the shale gas and CBM reservoirs in America and Canada [13,14], and some micro-pilot tests of CO_2-ECBM were conducted in Canada, the Netherlands, Italy, and Japan [15,16]. In China, the micro-pilot tests all proved the feasibility of CO_2-ECBM for high rank coal in the Qinshui Basin [17], which verified that the CBM extraction ratio was enhanced by sequestering CO_2 coupled with flooding CBM effectively.

Compared with HF, LCO_2 fracturing technology has some advantages: i) LCO_2 has a lower temperature (−37 °C) than the coal rock, which could produce a temperature gradient in the rock and induce temperature stress [18]. ii) LCO_2 could produce a huge gas pressure with a liquid-gas expansion ratio of 1:557 at 0 °C, and it is compatible with rock without water-block and water sensitivity. Moreover, the water-soluble CO_2 forms an acidic environment facilitating the removal of plugs in the fissures [19]. iii) CO_2 can easily flood the adsorbed CBM and be sequestered in the reservoirs [20], the application of CO_2-ECBM in the southern areas of the Qinshui Basin, carried out by the governments of China and Canada, helped the gas production to increase by 1.04×10^{12} m^3 and the CO_2 sequestration to reach 47.7×10^8 t [21].

The effect of CO_2 injection on heterogeneously permeable coalbed reservoirs with a finite element model was investigated [22] based on an evaluation of dimensionless pressure, permeability and fracture spaces. Zhou et al. [23] studied the principle of the LCO_2 blasting mechanism by monitoring the pressure-time curve in the main pipe blasting and determined the optimal borehole parameters of LCO_2 by establishing a $FLAC^{3D}$ numerical model. LCO_2 was injected into the low permeability coal seams in Jiulishan Mine and Pingdingshan thirteen mine, inducing the generation of many cracks by the phase transition of LCO2, which greatly improved the permeability [24,25]. Moreover, the performance evaluations of LCO_2 fracturing systems [26–28], technology process and equipment [29], technical design [30,31], fracture evolution [32], and analysis about LCO_2 fracturing prospects and development trends [33] have also been studied.

The previous studies were mostly focused on the single injection method with large volumes of LCO_2, and they ignored the cryogenic effect of LCO_2 on the pore evolution in coal rock. However, a freezing/shrinking phenomenon would occur near the bore wall during the single injection process due to the heat transfer between cryogenic LCO_2 and the coal matrix, which might reduce the fracturing efficiency.

As a result of the temperature gradient formed in the coal, the matrix goes through a 'shrinking-swelling' process during a single cycle of LCO_2 injection, which might generate fatigue damage. Additionally, the exiting water in the cleats or pores would be frozen into ice with a 9% volume expansion. Thus, in this paper, the multiple LCO_2 injection cycle fracturing technology, similar to the pulse hydraulic fracturing [34,35], was proposed for application in ECBM, focusing on the cryogenic effect. Five coal cores from different coal mines were used to investigate the feasibility of the cryogenic effect from multiple LCO_2 injection cycles on the crack evolution under the loading states. Notice that the multiple cycles of LCO_2 injection means that the coal cores were placed in the LCO_2 environment and then in the normal temperature environment alternately many times. Nuclear magnetic resonance (NMR) and infrared thermal imaging (ITI) were used to measure the changes in their internal pores and the temperature distributions, respectively. Finally, the improvement in potential applications of LCO_2 multi-cycle fracturing technology for CBM recovery is discussed.

2. Materials and experimental introduction

2.1. Specimen preparation

The experimental coal blocks (from Datong coal mine Shanxi, Hancheng coal mine Shaanxi, Shengli coal mine Inner Mongolia, Yuanzhuang coal mine Huaibei, and Yangzhuang coal mine Huaibei, China) were drilled from the reservoirs, wrapped in airproof packages and transported to the laboratory. Fig. 1 shows the raw coal block from Datong coal mine. There are some cracks on the block surfaces, and the *y* direction and *z* direction are oriented parallel to and perpendicular to the tape measure direction, respectively. The cores were drilled from the coal block along all three axes, avoiding the crack zones. The cores were cylinders with diameter of 50 mm and length of 60 mm and were wrapped with preservative film and set into the core curing room to preserve their original properties. The main properties and proximate analysis data of different cores are shown in Table 1.

2.2. Experimental system and equipment

In the experiment, an innovative cryogenic loading experimental system was established, as shown in Fig. 2. The system mainly consisted of three parts: hydraulic loading system, monitoring system, and LCO_2 injection/recovery system. The hydraulic loading system could provide uniaxial compression with 0–18 MPa on the cores that were placed in a sealed core chamber. A decompression valve was used to relieve the CO_2 gas pressure at a threshold value (0.5 MPa) for test safety. The monitoring system contained an air thermocouple (HY101) and a pressure sensor, which were used to monitor the temperature and gas pressure, respectively. The LCO_2 injection/recovery system used a liquid charge pump to inject LCO_2 into the chamber or used a CO_2 gas collector to convey CO_2 gas into the alkaline solution sink. In addition, a vacuum drying oven (DHG-9023A), a vacuum water saturation device (NEL-VJH), and a rock centrifuge (TG16-WS) were used for sample processing (drying, saturating, and centrifugation). Finally, all the core samples were tested by NMR (Mini MR60, Niumag) and ITI (Fluke Ti450) to analyze the pore changes and temperature distribution after one and after multiple cycles of the LCO_2 injection process, respectively.

2.3. Experimental procedures

The experimental system was connected in sequence as shown in Fig. 2. Notice that five cores were selected; these cores had similar characteristics as pre-tested by uniaxial compression, and the threshold values of the linear plastic deformation stage from stress-strain curves were in the range of 0.6–5.4 MPa (seen in

Fig. 1. Picture of raw coal block Datong coal mine.