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Investigation of temperature effects from LCO_2 with different cycle parameters on the coal pore variation based on infrared thermal imagery and low-field nuclear magnetic resonance

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ABSTRACT

Enhanced coalbed methane (ECBM) achieved by injecting liquid carbon dioxide (LCO_2) has been proposed and applied in industrial production for decades and has been demonstrated to be an applicable method to boost CBM production. Most of the studies have concentrated on the gas bursting and flooding effect and have rarely focused on the accompanying "freeze–thaw" phenomenon, and the temperature effect of cyclic LCO_2 injection on the pore variation of different coals has been partly investigated. In this paper, the influence of cycle parameters, such as cycle number and cycle time, on the pore variation was studied. Infrared thermal imagery (ITI) and low-field nuclear magnetic resonance (NMR) were used to measure the temperature and pore size distribution (PSD) change, respectively. The results show the following: (1) The gas pressure displayed square cyclicity with different cycle time, the temperature of gasified CO_2 was almost 248.15 K, and the end and lateral surface temperatures of a core were in the range from 259.35 to 261.85 K, which could cause the water within the pores to freeze with a 9% volume increase, and the fracturing formula was deduced; (2) The relaxation time spectra obtained by different cycle parameters expressed changeable PSD of cores with increasing cycle parameters, and the magnified proportion of bulk water and capillary water, as well the diminished proportion of adsorbed water, all indicated that the increased number of macropores and mesopores formed a larger free volume; (3) The increased total porosity φ_t and the decreased $T_{2cutoff}$ of six cores with the increasing cycle parameters meant that the larger cycle number could enhance the porosity due to amount of damage accumulation, and the larger cycle time might make the water freeze completely with larger ice swelling stress; (4) There is a polynomial fitting between relative increase ratio $R\varphi$ and cycle time, and the fitting coefficients were all higher than 0.99, and the larger the cycle time was, the greater the $R\varphi_{(e/t)}$ increment and $R\varphi_{(r/t)}$ decrement were. The interval increase ratio $I\varphi_e$ was positively correlated to cycle time without obvious increase behavior; however, the $I\varphi_r$ variation expressed that the greater the cycle number was, the lesser the $I\varphi_r$ with the increasing cycle time was, which indicates that the increasing cycle parameters might help the proportion of connected pores to increase and provide more pathways for permeable fluid; (5) The NMR permeability k_{SDR} of a core increased as the cycle number increased, and the longer cycle time was superior in terms of permeability enhancement.

1. Introduction

According to Ministry of Land and Resources, PRC [1], the detectable coalbed methane (CBM) resource reaches 306.25 billion m^3, which provides abundant energy base for the energy structure improvement. However, the inherent characteristics, such as deep burial, low permeability, and high density, limit the efficiency of CBM extraction [2–4]. The CBM existence mainly has three states: free gas in porous matrix, free gas in natural fractures, and trapped gas adsorbed in matrix [5–8]. The flow capacity of reservoir is largely determined by internal natural-crack connectivity, by which approximately 20% of the absorbed CBM and 60% of the free CBM can be recovered [9,10]. However, external forcing is needed to additionally increase the CBM recovery. Enhanced CBM recovery (ECBM) by injecting carbon dioxide (CO_2), nitrogen (N_2) or a mixture of CO_2 and N_2 with various phase states (gas, liquid, or super-critical), belongs to the family of waterless

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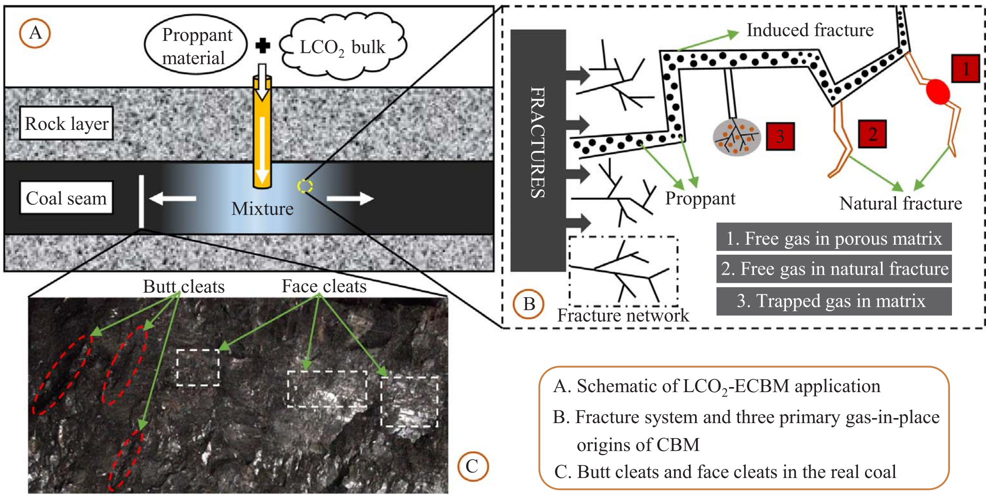

Fig. 1. Schematic of LCO_2-ECBM application and fracture system. Modified from Middleton et al. [21].

fracturing, is a means for increasing the extra CBM recovery [11,12].

CO_2-ECBM was first proposed by Bullen and Lillies [13], and its fracturing system and equipment [14–16] and technical design [17,18] were also further studied for decades. Compared to the same volume of CO_2 gas, liquid CO_2 (LCO_2) is superior for use in the CARDOX system device because its large liquid–gas ratio allows it produce higher gas pressures [19,20]. Field application of LCO_2-ECBM (seen in Fig. 1) has been carried out in many counties, e.g., the US and Canada, which all showed that LCO_2 injection could increase the CBM production and that CO_2 could be geologically sequestrated [22–24]. Amounts of CO_2-ECBM micro-pilot tests had been operated in some countries, such as Canada, China, Italy, Japan, and Netherlands, which all verified the feasibility of CO_2 in enhancing CBM recovery [12,25]. For example, some pilot tests of single-well/ multi-wells were successively carried out in Qinshui Basin by the collaboration of China United CBM Co. Ltd. and Alberta Research Council, Canada, and were reported a significant enhancement in CBM recovery [11,26]. Additionally, the application of LCO_2 with sand fracturing technology was successfully implemented in the Shenmu gas field in 2015, in which the extraction efficiency of industrial gas could reach $4.2 \times 10^4\,m^3$ per day [27].

The concentrations of the existed studies mainly focused on the effect of CO_2 gas bursting and flooding [12,20,21,28,29]; however, the occurrence of a “freeze–thaw” (F-T) cycle during a single LCO_2 injection process might make the coal matrix shrink and swell, which can have a significant influence on the core pore distribution [27]. Hale and Shakoor [30] investigated the effect of cyclic freezing and thawing on the compressive strength of six sandstones, and there was a significant deterioration during multiple F-T cycles. Yavuz et al. [31] studied the P-wave velocity, uniaxial compressive strength and Schmidt hardness of rocks under F-T and thermal shock conditions, and these index properties decreased to various extents. Qin et al. [32] explored how liquid nitrogen freezing affected the physical pore and fracture structure of coal, and the elastic moduli, uniaxial compressive strengths and P-wave velocities all decreased while the Poisson’s ratios increased. Xu et al. [33] has investigated the feasibility of using the cryogenic effect from LCO_2 multiple cycle fracturing technology on the pore change and porosity enhancement of five different coals. The pore variation of three cores with different ranks under the cyclic cryogenic LCO_2 injection indicated that the cyclic F-T process could increase the porosity and the increment was negatively correlated to the degree of metamorphism [27].

In this paper, the research focus is to study the influence of cycle parameters, such as cycle number and cycle time, from cryogenic LCO_2 multi cycle fracturing technology on the porosity variation. Cores drilled from the same coal block were prepared and put in an innovative cryogenic unconfined chamber. LCO_2 was injected into the chamber according designed cycle numbers and total cycle time (TCT). The gas temperature and coal temperature were monitored by thermocouple and infrared thermal imagery (ITI), respectively. Low-field nuclear magnetic resonance (NMR) was used to measure the pore size distribution (PSD) and core porosity changes. Finally, the relaxation time (T_2) spectra and their related parameters were analyzed, and relative increase ratio $R\varphi$ and interval increase ratio $I\varphi$ were proposed to characterize the relationship between the porosity and cycle parameters.

2. Materials and equipment

2.1. Core preparation

The experimental coal blocks from the Datong Coal Mine, Shanxi Province, China, were collected and covered with preservative film for transport to the laboratory. Cores with diameter of 25 *mm* and length of 50 *mm* were drilled using a rock coring machine from the same coal blocks, from which six cores with similar properties were selected to be the samples. The cores all satisfy the requirements of flat end faces and high integrity, and they were labeled *sx-i* (i = 1, 2, 3, 4, 5, 6). The maceral analysis and proximate analysis data of the six cores are shown in Table 1. Finally, all six cores were placed in the core curing room to preserve their original properties.

2.2. Experimental system and equipment

In this paper, the cryogenic monitoring system consists of three subsystems: the cryogenic chamber system, the LCO_2 injection system, and the data recording system, shown in Fig. 2. The chamber is sealed in a circular fashion using a seal ring at the contact face between the tectum and chamber body and fixed by several screw bolts. A pressure relief valve is set on the tectum to release the CO_2 gas when the pressure exceeds 800 *kPa*. The fixed disk is used to prevent the coal cores from being blown out. The LCO_2 injection system injects cryogenic LCO_2

Table 1
Maceral analysis and proximate analysis data of six cores.

Proximate analysis (wt.%)				$R_{o,max}$ (%)	Maceral analysis (vol%)			
M_{ad}	A_{ad}	V_{daf}	FC_{ad}		V	I	E	M
4.83	7.30	29.64	58.23	0.43	75.3	18.6	2.7	5.3

Note: M_{ad} – moisture; A_{ad} – ash yield; V_{daf} – volatile matter dry ash-free basis; FC_{ad} – fixed carbon content; V – vitrinite; I – inertinite; E – exinite; M – minerals.