Fuel 236 (2019) 709–716

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental investigation of CO_2 injection into coal seam reservoir at in-situ stress conditions for enhanced coalbed methane recovery

Zhengdong Liu[a,b,c], Yuanping Cheng[a,b,c,*], Yongkang Wang[a,b,c], Liang Wang[a,b,c], Wei Li[a,b,c]

[a] Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou 221116, China
[b] National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[c] School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

ARTICLE INFO

Keywords:
CO_2 injection
ECBM
Adsorption capacity
Coal permeability
Injection pressure

ABSTRACT

CO_2 geological sequestration is an effective method to reduce the concentration of CO_2 in the atmosphere. The injection of CO_2 into CH_4-containing coal seams also named CO_2-ECBM (CO_2 Enhanced Coalbed Methane Recovery), allows the storage of CO_2 and the enhancement of CH_4 recovery. Due to complex geological environment of the site, dynamic variation of CH_4 and CO_2 can hardly be monitored in real time during CO_2 injection into coal seams. Therefore, this paper conducted experimental studies were carried out on cuboid coal samples with a size of $300 * 70 * 70$ mm via a self-developed experimental device which can simulate in-situ stress and temperature conditions. In the experiment, different adsorbed gases (CH_4 and CO_2) were applied to determine the variation of permeability values under various load stresses and pore pressures. Results proved that the coal had greater adsorption capacity to CO_2 than to CH_4. The injected CO_2 occupied the original adsorption site of CH_4, thus leading to the rapid discharge of CH_4. Meanwhile, real-time dynamic monitoring was also performed on gas parameters in coal under different gas injection pressures to obtain variation laws of pore pressure, gas flow rate and concentration at the outlet with the increment of injected CO_2. The results reveal that with the increase of injected CO_2, pore pressure tended to equilibrium while CH_4 flow rate and concentration at the outlet gradually fall to zero. Therefore, CO_2 injection into the coal mass can effectively improve the recovery of CH_4. In addition, variations of gas flow rate and concentration at the outlet with the displacement ratio of gas volume under different gas injection pressures suggested that the enhancement of gas injection pressure boosted discharge efficiency of CH_4 from the coal mass and CO_2 consumption. Furthermore, inspired by the competition relationship between engineering efficiency and CO_2 consumption, we think a reasonable and effective economic cost model can be established as an effective method to guide the selection of gas injection pressure in the future. Hence, the experimental results have guiding significance for better understanding and application of CO_2-ECBM technology.

1. Introduction

Carbon dioxide is both an important raw material for plant photosynthesis that can elevate photosynthetic products, and a kind of greenhouse gas affecting heat balance of the earth [1,2]. With the heavy consumption of fossil energy after Industrial Revolution, the concentration of CO_2 in the atmosphere has increased year by year. At the current growth rate, the temperature of the earth is to witness an increase of 1.5–4.5 °C by 2030, which will exert a serious impact on global environment. Therefore, the reduction of CO_2 concentration in the atmosphere has become a hot research issue [3,4].

Geological sequestration and storage of CO_2, an effective measure of reducing greenhouse gases, has drawn the attention of scholars and organizations all around the world [5–7]. Based on the estimation of the world's underground storage capacity of CO_2 by Bruant et al., about 7.0×10^7 km^2 of sedimentary basin can be applied to storing 1.0×10^{14}–2.0×10^{14} t of CO_2 which is equivalent to the CO_2 emissions by mankind over thousands of years [8]. At present, CO_2 storage sites mainly cover unmineable coal seams, depleted hydrocarbon reservoirs, deep aquifers and marine strata [9]. However, in fact, storing CO_2 into a CH_4-containing coal seam can bring lots of benefits such as promoting the CH_4 recovery and reducing gas disasters [10–13]. It offsets the cost of capture, compression, transportation, and storage of CO_2 by producing natural gas. Besides, unmineable coal seams are also

* Corresponding author at: Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou 221116, China.
E-mail address: ypc901014@163.com (Y. Cheng).

https://doi.org/10.1016/j.fuel.2018.09.062
Received 2 May 2018; Received in revised form 16 August 2018; Accepted 12 September 2018

available for storage because of their wide distribution [14,15]. This technology is called CO_2 enhanced coalbed methane recovery (CO_2-ECBM) [16]. During the CO_2-ECBM process, CO_2 first enters the fracture system because the injection pressure is greater than coal reservoir pressure. When CO_2 is entering the coal matrix, it will sorb to the coal inner surface, replacing part of the CH_4 by a combined sorption/diffusion process, due to the adsorption capacity of CO_2 exceeding that of CH_4. Therefore, the understanding of dynamic variation of CH_4 and CO_2 in the coal is of great significance to improve this technology during the CO_2 injection into coal seams with CH_4.

Carbon dioxide-Enhanced Coalbed Methane Recovery was first proposed by Macdonald of Alberta Energy during discussions with Gunter and coworkers in 1991 [3]. To date, many scholars have proved the feasibility of injecting CO_2 into a CH_4-containing coal seam which has a promising future through various experimental methods. Clarkson et al. [17] reported during CH_4 recovery that the injected CO_2 could depressurize CH_4 in the free gas or occupied adsorption space to accelerate CH_4 desorption from the coal seam, thus boosting the production of CH_4. Stevens et al. [18], who specialized in the process of enhancing CH_4 recovery by injecting CO_2, considered that the CO_2 injected was conducive to maintaining the pore pressure and guaranteeing the cleat and pore channels unobstructed for smooth CH_4 emission. Zuber et al. [19] also verified that CO_2 injection into coal seams contributed to the improvement of CH_4 production.

To further verify that CO_2 injection into the coal mass can enhance the emission rate of CH_4, some scholars have conducted physical simulation experiments on cylindrical coal samples, making detailed record of the CH_4 recovery volume after CO_2 injection. Fulton et al. [20] injected CO_2 into dry and water-saturated CH_4-containing coal samples under low pressures. In these experiments, cylindrical coal samples used were 8.89 cm or 9.555 cm in diameter and 5.08 cm or 10.16 cm in length; the gas inlet and outlet were on the same side of the coal; and the CO_2 injection pressure was 45–200 psia. Experimental results revealed that the CH_4 recovery after CO_2 injection was 9%-57% higher than that of natural emission. Reznik et al. [21] conducted the CO_2 injection test on coal samples under high pressures following Fulton's experiment. The CH_4 emission rate was about 30%, but CH_4 in the coal was totally discharged under gas injection pressure of 200–800 psia. Besides, in their another experiment to inject CO_2 and N_2 mixture into samples, CH_4 recovery plunged. Jessen K et al. [22] carried out different experiments with 100% N_2, 100% CO_2, 85% CO_2/15% N_2, 46% CO_2/54% N_2, and 24% CO_2/76% N_2, respectively. The cylindrical coal sample with a size of 250 mm in length and 42.5 mm in diameter is made of 0.25 mm coal particles whose permeability reached $3.1 \times 10^{-14}\,m^2$. In addition, they also studied the effects of gases of different compositions on CH_4 recovery and breakthrough time, reporting that the injected gases could all achieve CH_4 recovery rate of over 94%, but the recovery rate would be lowered if the gas was mixed with N_2 (even with a trace of N_2). Furthermore, compared with pure CO_2, the gas mixed with N_2 injected into coal led to longer breakthrough time of CH_4 emission and less total injected volume. Dutka Barbara et al. [23,24] conducted CO_2-ECBM experiments on coal samples with a diameter of 96 mm and a length of 280 mm which consists of particles with a size of below 0.2 mm. They analyzed variation laws of pore pressure as well as CO_2 and CH_4 concentrations during CO_2 injection, concluding that CO_2 injection could improve CH_4 emission amount effectively.

Following physical simulation experiments that obtained favorable conclusions in the laboratory, field tests of CO_2-ECBM technology were also gradually carried out, and America took the lead. In 1996, the Allison Unit pilot, located in the Northern New Mexico part of the San Juan Basin, was selected as the first demonstration site for field test. After the implementation of CO_2-ECBM technology, CBM production was greatly improved and CH_4 recovery reached 77–95%, lasting for over 6 years [25]. To test and monitor the injectivity, capacity, heterogeneity, and performance of mature coalbed methane reservoirs, a CO_2-ECBM field injection project was performed in Black Warrior field in addition to other similar programs in North America [26–29]. Besides, other countries and regional organizations followed America in conducting field practices. In Canada, pure CO_2, pure N_2, flue gas, and CO_2-rich flue gas were injected into the experimental area in Fenn Big Vaney of the Alberta Basin. Results proved that CBM recovery was enhanced by injection of other gases. Besides, it was also observed that coal permeability was lowered and improved by injecting pure CO_2 and pure N_2 or N_2-containing flue gas, respectively [30]. To assess the technical and economic feasibility of CO_2 sequestration in coal seams, the Recopol project was implemented in the EU where a total of 760 tons of CO_2 was injected in Upper Silesian Basin of Poland [31]. In Japan, field test was conducted in the Ishikari Basin of Hokkai-do, where dynamic changes of the coal seams were monitored in real time via measures like field monitoring. Results suggested that there was an upsurge in CH_4 recovery after CO_2 injection [32]. A field research in Qinshui Basin, Shanxi Province, China, indicated an improved CBM recovery and the good effect of CO_2 sequestration after injecting CO_2 into coal seams [33].

Numerous experimental studies have been conducted on CO_2 injection into coal mass for enhancing CH_4 recovery, and fruitful results have been achieved. However, the aforementioned physical simulation experiments adopted cylindrical coal samples made of coal particles with the size below the millimeter level. Besides, experimental conditions in the laboratory, especially the stress and temperature, differed hugely from the real environment of coal seams. Hence, there are some defects in the aforementioned results [7,34–36]. Furthermore, in the field tests of CO_2-ECBM technology, the complex on-site geological environment constrained both the study on dynamic variation laws of gas during the CO_2 injection process and further understanding of CO_2-ECBM technology.

In view of the above research status, a new experimental apparatus was developed to simulate the process of enhancing CH_4 recovery by injecting CO_2. And the main innovation of this paper is the experimental design. Specifically speaking, it is reflected in three aspects: Firstly, a rectangular coal sample with a size of 300 * 70 * 70 mm as the research object, which is more close to the real coal seam in terms of scale. Therefore, the obtained migration laws of gases in this coal sample is more reliable compared with that of cylindrical coal samples with a size of 50 * 100 mm. Secondly, to better simulate the environment of coal seam, the condition of temperature and stress can be set according to the actual situation in our experimental system. Thirdly, some different types of sensors and monitoring devices are used on this experimental apparatus, which can better understand the effect of CO_2 injection.

In this paper, to analyze the CH_4 and CO_2 adsorption capacity of coal, the steady-state method was adopted to calculate permeability values under different conditions. In addition, the pore pressure, gaseous composition and flow rate at the outlet were tracked and tested in real time to dynamically monitor the effect and CO_2 consumption after CO_2 injection into CH_4-containing coal. Besides, the competition relationship between gas injection pressure and engineering efficiency and CO_2 consumption was discovered from our experimental results. Inspired by this relationship, we think a reasonable and effective economic cost model can be established as an effective method to guide the selection of gas injection pressure in the future [37]. Hence, the experimental study in this paper has positive significance for better understanding and application of CO_2-ECBM technology.

2. Materials and Methods

2.1. Coal sample preparation

Coal samples were obtained from No.2 coal seam, Haishiwan Coal Mine of Yaojie coal field, Gansu province, and they belong to gas-fat coal. To investigate the adsorption properties and the composition of