Fuel 215 (2018) 665–674

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental investigation of N_2 injection to enhance gas drainage in CO_2-rich low permeable seam

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ARTICLE INFO

Keywords:
Coal
Outburst
Coal seam gas
N_2-ECBM
Permeability

ABSTRACT

Seam gas pre-drainage, is widely used as an effective method to control gas and coal outburst in underground coal mines. However, in CO_2 abundant low permeable seams, this technology seems to be less efficient due to the CO_2 sorption characteristics and the lower safe mining threshold limit for CO_2 applied in many outburst risk management plans. This paper presents the experimental investigations of the applicability of nitrogen (N_2) injection to improve gas drainage in CO_2 rich seams. Core specimens were obtained from Bulli coal seam, Sydney Basin and N_2 flood tests were conducted under different permeability conditions (0.3 mD and 0.06 mD). A triaxial permeability test rig equipped with a back pressure regulator was used to conduct the test. The variation of gas composition, gas outlet flow rate, N_2 flushing efficiency, and permeability variation were analyzed. In addition, a comparative study between N_2 flushing coal seam CO_2 and N_2-ECBM was conducted and it was observed that CO_2 was much more difficult to drain out and with longer time compared with CH_4. Based on the test results, a two-stage flushing mechanism was obtained. In the first stage, the original free phase coal seam gas accounted for the large percentage and this stage last for a shorter time. In the second stage, desorption time governed the flushing efficiency and desorbed gas was the primary gas. It took much longer time than the first stage. The final recovery rate in 0.3 mD and 0.06 mD scenarios were 90.5% and 87.7%, and the N_2 consumption/CO_2 production ratios were 15 and 11.2, respectively. Through these laboratory experiments, we concluded that N_2 injection can significantly decrease coal seam CO_2 content level and increase gas drainage efficiency.

1. Introduction

Gas outburst is a sudden, violent emission of coal and gas from a mining working face in underground coal mines as a result of the rapid releases of gas pressure and this hazard has been reported in more than 16 countries [1]. Thousands of outburst activities have occurred around the world and most of the events are reported in Australia, Canada, China, Poland and Turkey [2]. The amount of coal that is thrown out may range from a few to hundreds of tons, while the released gas can be of significant volumes. Gas outburst can lead to serious damage to mining environment, including mining facilities and miner's fatality [3,4]. Two types of gases are associated with gas outburst, methane (CH_4) and carbon dioxide (CO_2) and CO_2 outburst is much more destructive than CH_4 outburst. From previous studies [4–6], most of the fatal outburst incidents in Australia were caused by CO_2 outburst. During the coalification process methane is generated and carbon dioxide is generated as a result of the presence of igneous intrusions, coal maturation and oxidation. From the previous research, two primary factors causing this hazard can be concluded as follows: 1. Higher gas content corresponding to high gas pressure, correlation for which can be obtained from the coal isotherm curve. 2. Lower coal seam permeability. Permeability is a key factor controlling the gas migration in coal seam. Low permeability can lead to a steep pressure gradient in the seam close to the working face. Many other factors are also related to gas outburst depending on different mining geology conditions such as geological structures, coal seam depth and so on [7–10].

Pressure relief techniques can be used to reduce the risk of outbursts [4,11,12]. One relief technique involves gas pre-drainage by drilling in-seam boreholes, across the long wall panels[13]. Fan-pattern boreholes are usually drilled from the roadways to minimize drilling rigs movement. This method can significantly reduce gas content in coal mines, while in some particular mines especially in low permeability coal seam, the efficiency is often unsatisfactory [14]. In some coal seams, the main gas composition is CO_2, which is much harder to drain than methane from coal seam [15]. Several coal mines experience this kind of drainage scenario when extracting the Bulli Coal Seam of the Sydney Basin in Australia [6]. In these particular conditions, the traditional drainage methods may take much longer time to reduce the gas content

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https://doi.org/10.1016/j.fuel.2017.11.129
Received 25 June 2017; Received in revised form 25 September 2017; Accepted 28 November 2017

Fig. 1. Coal lump and core sample.

below the threshold limit thus impact on the normal mining schedules.

In coalbed methane industry, the use of another gas injection into the gas reservoir can significantly improve the natural gas production and this process has been termed as Enhanced Coalbed Methane Recovery (ECBM) [16,17]. Usually the gases used in the ECBM process are CO_2, nitrogen or the mixture of the two [18–20]. Coal seam is preferentially to adsorb CO_2 than methane, as a result, the injected CO_2 can be more easily adsorbed onto the coal seam and replace the methane. N_2 injection displaces the methane in the pore spaces and reduce the methane partial pressure, which can improve the methane desorption from coal matrix [21]. Inspired by this technology in CBM industry, we are trying to use N_2 injection to enhance gas drainage efficiency. Because of the characteristics of nitrogen, several studies reported the feasibility of nitrogen enhanced coalbed methane. A field trial was conducted by Packham et al. [22], in an Australia coal mine by using nitrogen as an enhanced recovery agent, and the results showed that nitrogen injection could increase the gas production rate. Nitrogen enhanced coalbed methane production trials were also performed in San Juan basin, America [23] and the results showed an earlier breakthrough compared to CO_2-ECBM. However, not all the trials were successful and recently Bustin et al. [24] reported a failed nitrogen enhanced coalbed methane trial in Piceance Basin, Colorado. In this trial, after a period of 15 days nitrogen injection, no nitrogen was observed from the production well and one possible reason was the low permeability. Laboratory studies of core flooding using nitrogen gas were conducted to investigate the enhanced coal bed methane production process. Connell et al. [25] used coal core samples obtained from Bowen Basin to do the flooding tests at different CH_4 saturated pressures, and the efficiency of N_2, CO_2 and the binary gas mixture were analyzed. Zhou et al. [26] also conducted enhanced coalbed methane laboratory experiments using pure N_2 and CO_2, and found that CO_2 injection had a higher recovery rate but the breakthrough time of N_2 injection was much shorter than CO_2 injection.

To understand gas migration mechanism in coal seam during gas drainage and ECBM process, several mathematical models for gas transport were developed by previous researchers [10,27–30]. A general porosity and permeability model was developed by Zhang et al. [31], and this model demonstrated the evolution of porosity and permeability during gas production process. The model results revealed the characteristics of the gas desorption process from coal matrix. Wu et al. [32] built a dual poroelastic model to describe CO_2-ECBM process and binary gas flow in coal seam was analyzed. A finite element model coupling gas flow and coal deformation was proposed by Liu et al. [27], whilst considering the Klinkenberg effect. Ren et al. [33] studied N_2 injection into coal seam to enhance gas drainage efficiency by developing a new finite element model with the consideration of the viscosity of gas mixture. These theoretical models can explain the coal seam gas migration under some assumptions and describe the gas transport process in particular condition. It can be found that most of the previous studies are focused on theoretical analyses of CO_2 or nitrogen enhancing methane recovery, whilst laboratory investigation of nitrogen injection to enhance CO_2 gas recovery is limited. This paper describes the laboratory studies of nitrogen gas flushing of CO_2 saturated coal samples collected from Bulli seam of Sydney Basin. The flushing efficiency and N_2 consumption/CO_2 production ratio at different testing conditions were analyzed.

2. Experimental methodology

2.1. Sample collection and preparation

Coal samples were obtained from a longwall development heading of an underground coal mine currently extracting the Bulli seam, Sydney basin of Australia. This coal mine is experiencing high CO_2 composition greater than 80 percent in some areas and gas drainage results are extremely unsatisfactory. Due to the preference of CO_2 in coal seam, it usually takes much longer time to reduce the gas content below the threshold limit value (TLV) of 5 m^3/t for pure CO_2 based on