Journal of Natural Gas Science and Engineering 26 (2015) 960–973

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Novel integrated techniques of drilling–slotting–separation-sealing for enhanced coal bed methane recovery in underground coal mines

Quanle Zou [a, b], Baiquan Lin [a, b, *], Chunshan Zheng [c], Zhiyong Hao [a, b], Cheng Zhai [a, b], Ting Liu [a, b], Jinyan Liang [d], Fazhi Yan [a, b], Wei Yang [a, b], Chuanjie Zhu [a, b]

[a] School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, PR China
[b] State Key Laboratory of Coal Resources and Safe Mining, Xuzhou 221116, PR China
[c] School of Mechanical and Mining Engineering, the University of Queensland, QLD 4072, Australia
[d] Department of Safety Engineering, Xuzhou Higher Occupation School of Mechanical and Electrical Engineering in Jiangsu Province, Xuzhou 320305, PR China

A R T I C L E I N F O

Article history:
Received 26 May 2015
Received in revised form
19 July 2015
Accepted 20 July 2015
Available online 26 July 2015

Keywords:
Enhanced coal bed methane recovery
Permeability enhancement
Dual-power drilling
Sealing material
Coal-water-gas separation

A B S T R A C T

Coal bed Methane (CBM), a primary component of natural gas, is a relatively clean source of energy. Nevertheless, the impact of considerable coal mine methane emission on climate change in China has gained an increasing attention as coal production has powered the country's economic development. It is well-known that coal bed methane is a typical greenhouse gas, the greenhouse effect index of which is 30 times larger than that of carbon dioxide. Besides, gas disasters such as gas explosive and outburst, *etc*. pose a great threat to the safety of miners. Therefore, measures must be taken to capture coal mine methane before mining. This helps to enhance safety during mining and extract an environmentally friendly gas as well. However, as a majority of coal seams in China have low-permeability, it is difficult to achieve efficient methane drainage. Enhancing coal permeability is a good choice for high-efficiency drainage of coal mine methane. In this paper, a modified coal-methane co-exploitation model was established and a combination of drilling–slotting-separation–sealing was proposed to enhance coal permeability and CBM recovery. Firstly, rapid drilling assisted by water-jet and significant permeability enhancement via pressure relief were investigated, guiding the fracture network formation around borehole for high efficient gas flow. Secondly, based on the principle of swirl separation, the coal–water–gas separation instrument was developed to eliminate the risk of gas accumulation during slotting and reduce the gas emission from the ventilation air. Thirdly, to improve the performance of sealing material, we developed a novel cement-based composite sealing material based on the microcapsule technique. Additionally, a novel sealing–isolation combination technique was also proposed. Results of field test indicate that gas concentration in slotted boreholes is 1.05–1.91 times higher than that in conventional boreholes. Thus, the proposed novel integrated techniques achieve the goal of high-efficiency coal bed methane recovery.

1. Introduction

It has been widely accepted that emissions of greenhouse gases (GHGs) are the primary contributor to anthropogenic climate change (Lashof and Ahuja, 1990; Hook and Tang, 2013). The atmospheric concentration of methane (CH_4) has increased to 1803 ppb by 2012, which is 2.5 times larger than the pre-industrial level (Bamberger et al., 2014; Li et al., 2015b). In general, atmospheric methane originates from both anthropogenic and natural activities (Al-Amin and Kari, 2013; Warmuzinski, 2008; Su et al., 2005, 2011). Among the various anthropogenic sources, methane emission from coal mining accounts for 8.9–12.8% (Cheng et al., 2011; Yusuf et al., 2012). It is estimated that coal mine methane (CMM) emission would increase to 793 $MtCO_2e$ by 2020 (IPCC, 2007). Approximately 85–90% of the total CMM emission comes from underground coal mines, a majority of which is from drainage systems and ventilation air (Karakurt et al., 2011; Baris, 2013). Therefore, it is of crucial significance to develop corresponding techniques to reduce such

* Corresponding author. School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, PR China.
E-mail address: 15262143114@139.com (B. Lin).

http://dx.doi.org/10.1016/j.jngse.2015.07.033
1875-5100/

high amounts of coal bed methane emission.

Since adopting the Policy of Reform and Opening-Up to the outside world in 1978, China has not only achieved exceptionally rapid economic growth but also became the ‘workshop of the world’ (Li et al., 2015b). The primary, secondary and tertiary industries account for 9.2%, 42.6% and 48.2% of China's GDP in 2014, respectively. This industrial structure relies on an adequate supply of affordable energy consequentially. China's total proved coal, oil and natural gas reserves are 114.5 billion tons, 2.5 billion tons and 33 trillion cubic metres, respectively, indicating that its energy structure is characterised by rich coal reserve, and meagre oil and gas reserves (BP, 2014). Coal accounts for approximately 70% of Chinese primary energy consumption in a long term. Chinese coal production and consumption constituted 47.5% and 52% of total worldwide coal production and consumption in 2013, respectively (Nejat et al., 2015). At present, China is the world's largest coal producer and consumer (Shealy and Dorian, 2010; Zhao and Chen, 2014).

As shallow coal reserves in China have been exhausted by a rapid coal-production rate, coal mining level is deepening at an annual rate of 10–20 m (He and Li, 2012). As a result, the high gas pressure and gas content in coal seams are becoming a key constraint on the deep high-efficiency coal mining in China (Li et al., 2015a; Ni et al., 2014; Wang et al., 2014; Liu et al., 2014c). Gas drainage is an effective measure to solve the aforementioned problem. The main benefits of gas drainage in gas-rich coal seams are as follows: decreased environmental impact, an improvement in the health and safety of underground workforce and the production of a relatively clean source of energy (Wang et al., 2012; Yan et al., 2015). However, the permeability of coal seams in China is universally low. As shown in Fig. 1, the permeability coefficients of Chinese raw coal seams are four orders of magnitude lower than that of American coal seams. From a geological viewpoint, a majority of coal seams in China took shape over the Carboniferous–Permian period, during which the coal suffered from strong tectonic movements and its original cracks were destroyed. Consequently, the coal structure became soft and complicated, which is not conducive to gas flow (Pan et al., 2015). CMM in China is characterised by poor drainage performance (Lin et al., 2014; Hao et al., 2014). Therefore, measures should be taken to enhance the permeability of the high gassy and low-permeability coal seams.

Carbon dioxide capture and storage (CCS) technologies involve capturing CO_2 from anthropogenic sources, depositing it in suitable deep geological formations and isolating the gas from the

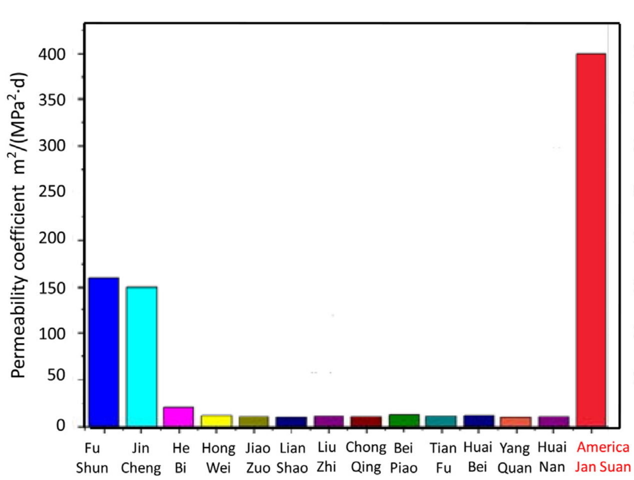

Fig. 1. Comparisons of permeability coefficients of raw coal seam in typical coal mines in China with those in America.

atmosphere (Mazzotti et al., 2009; Budzianowski, 2012, 2013). This is an effective and vital option for atmospheric CO_2 concentration control and climate change mitigation, which attributes to the continued utilisation of fossil fuels. Recently, the techniques for enhanced coal bed methane (ECBM) recovery have attracted wide attention. The enhanced gas recovery (EGR) technology using CO_2 injection was considered as a promising measure for realising the design of efficient null-greenhouse-gas-emission power plants fuelled by CBM extracted from deep coal seams (Gunter et al., 1997; Rodrigues et al., 2013). Once injected into coal seams with sealing cap rock, CO_2 is adsorbed and retained permanently. Meanwhile, the injected CO_2 will displace coal bed methane owing to its higher affinity for coal, thereby enhancing the primary recovery of methane. Substantial research has been conducted to evaluate the storage capacity of coal seams (Saghafi, 2010; Pan and Connell, 2011), understand adsorption/desorption dynamics during injection (Li et al., 2014a; Yu et al., 2014; Liu et al., 2014d) and characterise coal swelling and permeability (Mazumder and Wolf, 2008; Kiyama et al., 2011; Qu et al., 2012). These investigations provide the experimental and theoretical basis for field tests and future commercial deployment of CO_2-related enhanced coal bed methane (CO_2-ECBM) recovery (Qin, 2008; White et al., 2005). Obviously, this technique is not suitable for exploitation of deep high gassy and low-permeability coal seams due to the fact that the risk of coal and gas outbursts still exists after adopting this method (Lama and Bodziony, 1998; Sobczyk, 2014). Several hydraulic techniques have been proposed to solve the aforementioned problem (Liu et al., 2014, 2015; Li et al., 2015; Yan et al., 2015; Wang et al., 2014, 2015). In this paper, novel integrated techniques of drilling–slotting–separation–sealing were elaborated. Initially, a modified coal-methane co-exploitation model was proposed. Based on the model, the proposed techniques were introduced via the following three methods: drilling–slotting integrated technique, coal–water–gas separation technique and sealing–isolation combination technique. Finally, field tests were conducted. The proposed techniques could significantly enhance coal bed methane recovery and substantially reduce the coal mine methane emission from drainage system and ventilation air, which makes them viable and highly efficient methods for the exploitation of deep coal seam with low permeability and high gas content.

2. A modified coal–methane co-exploitation model

Coal and methane are two kinds of resources in a gas-rich coal seam (Karacan et al., 2011). If methane resource only is exploited, it is difficult to drain coal bed methane. Likewise, if coal resource only is exploited, there is a risk of gas explosion and outburst due to the high gas concentration in coal seams. Moreover, the emission of methane into the atmosphere could have a serious impact on climate change (Sander and Connell, 2012, 2014). Therefore, a coal–methane co-exploitation model was established by Wang and Cheng (2012) to solve the aforementioned dilemma. In this model, a coal seam with relatively lower gas risks is selected as an initial mining coal seam (Fig. 2). Upon mining this coal seam, the gas pressure in the adjacent coal seams (top and below) are relieved, thereby increasing coal permeability, which facilitates high-efficiency methane drainage. Adjacent coal seams could become less gas-rich with the help of effective methane drainage, and thus, both coal and methane could be exploited simultaneously in a safe environment (Liu et al., 2013; Zhou et al., 2015). The proposed coal-methane co-exploitation model could solve the gas problems in multiple coal seam mining and recover coal bed methane, thereby reducing the GHGs emissions. However, the high efficiency and safe mining in the initial coal seam under the gas-rich and low permeability condition is not taken into consideration in this