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Full Length Article

Dynamic behavior of gas pressure and optimization of borehole length in stress relaxation zone during coalbed methane production

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ABSTRACT

Although coalbed methane (CBM) poses potential safety hazards in coal mines, it can also be used as a clean energy source. Optimization of the borehole length to maximize gas drainage and efficient use of human and material resources are key factors that determine the feasibility and cost of CBM production. In addition, three geo-stress zones are commonly formed in front of the working face due to underground mining activities, namely the stress relaxation zone (SRZ), stress concentration zone (SCZ), and original stress zone (OSZ). In this study, we conducted gas drainage experiments in a simulated SRZ to investigate gas pressure dynamic behavior and optimize the borehole length. The gas pressure gradient in the direction perpendicular to the borehole was greater than that in the direction parallel to the borehole, and the SCZ showed significant hindrance to gas seepage into the borehole. Longer boreholes resulted in higher gas production; however, the gas production increasing rate was not stable over time as the borehole length increased. The relationship between gas production and borehole length is a logarithmic function, which was used to further optimize the borehole length taking mine safety and economic factors into consideration. The following optimized borehole lengths were obtained under experimental conditions: 155.6–262.5 mm, 129.7–155.6 mm, and 24.5–129.7 mm for short-term, medium-term, and long-term gas drainage, respectively.

1. Introduction

Coalbed methane (CBM) is a methane-rich gas present in coal seams and is a source of clean energy that can be exploited either by drilling boreholes from the surface or from underground coal mines workings [1,2]. With the commercial development of CBM in the USA in the early 1980s, CBM extraction has received increasing interest from many countries, including Australia, Canada, India, and China [3,4]. Global CBM reserves have been estimated to be 84–262 trillion m^3, while China ranks third in the world after Russia and Canada [5–7]. In China, CBM development can be divided into two classes, surface extraction and underground gas drainage [8]. To accelerate the development of the CBM industry in China, a target production of 24 billion m^3 (10 billion m^3 for surface production and 14 billion m^3 for underground production) has been proposed by the National Energy Administration in the 13th Five Year Plan for National Energy Development [9,10].

CBM reservoirs in China are characterized by low gas saturation, low permeability, low reservoir pressure, and a relatively high metamorphic grade [11]. For example, the permeability of most coal seams in China ranges from 10^{-4} to 10^{-1} mD, which is three to four orders of magnitude lower than that of most countries in the world [12,13]. Meanwhile, as coal mining depths increase at an annual rate of 10–50 m in China, both the gas pressure and gas content increase along with much more complex geological coal structures and geo-stress states [14,15]. All these factors result in increasingly challenging CBM production in China.

Although CBM is a clean energy source, it poses potential risks and hazards in the coal mining process owing to the risk of fire and explosion [16–19]. Fig. 1 shows statistics of the causes of different coal mine accidents (i.e., gas, roof, flood, fire, electromechanical, transportation, blasting, and others) between 2011 and 2016 in China. It can be observed that gas-related accidents accounted for approximately 50% of the incidents, although the total number of accidents decreased every year this percentage increased slightly. To ensure the health and safety of coal miners, and improve CBM production, various methods have been employed to improve the efficiency of CBM extraction, including

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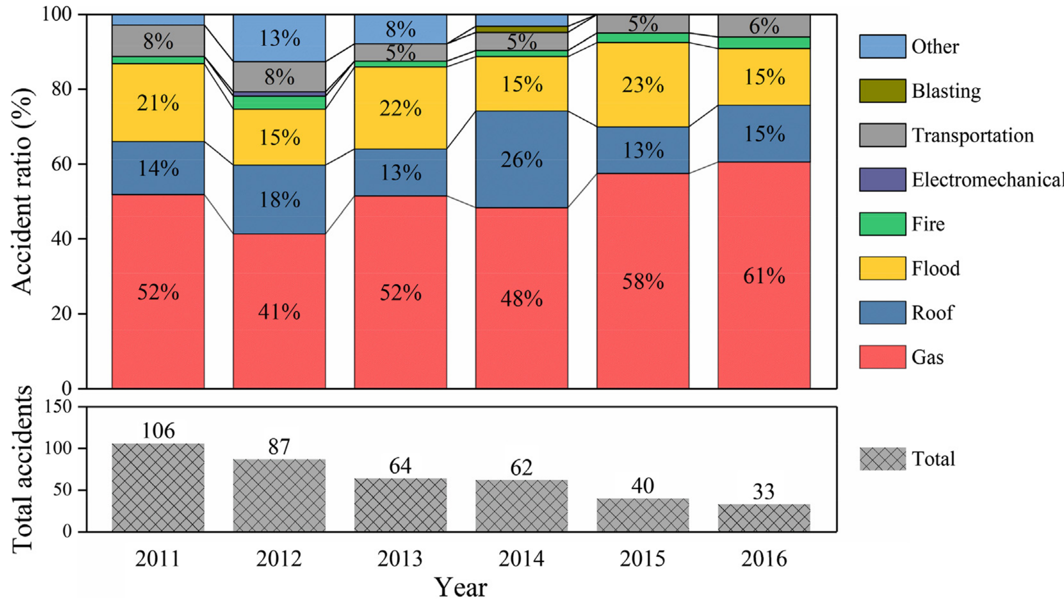

Fig. 1. Statistics of Chinese coal mine accidents (death of more than 3 people) between 2011 and 2016.

CO_2-enhanced CBM recovery (CO_2-ECBM) [20–22], hydraulic technology for seam permeability enhancement (HTSPE; including hydraulic fracturing [23], hydraulic slotting [24], hydraulic flushing [25], waterjet technique [26]), deep-hole pre-split blasting [27,28], high-voltage electrical pulse (HVEP) [29], and multi-branched horizontal wells (MBHWs) technology [17,30]. In addition, gas drainage borehole patterns were optimized by field tests and numerical simulations [31–33].

These past developments have shown an increase in CBM yields and decrease in coal mining accident frequency. Meanwhile, three geo-stress zones are commonly formed in front of the working face due to underground mining activities, namely, the stress relaxation zone (SRZ), stress concentration zone (SCZ), and original stress zone (OSZ) [34,35]. Gas drainage boreholes are usually positioned in the SRZ where the permeability is high [36]. However, few studies have focused on optimizing the borehole length, which is a key factor affecting CBM production and cost. Improper borehole length will lead to unsatisfactory gas drainage or inefficient use of human and material resources. Considering that field research is usually expensive and time-consuming, physical simulations are a suitable alternative [37,38]. This study conducted three gas drainage experiments with different borehole lengths. Three geo-stress zones were physically simulated and the gas pressure was measured. The dynamic behavior of the gas pressure was analyzed and the relationship between the borehole length and gas production was discussed. In addition, a method for optimizing the borehole length was proposed.

2. Material and methods

2.1. Experimental setup

Fig. 2 shows the photograph and schematic diagram of the experimental setup used in this study, which was developed in our laboratory; and it consists of the control and data acquisition system, coal specimen box, loading system, reaction frame, borehole, drainage pipe, flowmeter, gas cylinder, and vacuum pump. The effective dimensions of the coal specimen box were 1050 mm × 410 mm × 410 mm. The loading system consists of nine oil cylinders in three directions, which were used to simulate the three geo-stress zones (SRZ, SCZ, and OSZ). We used three boreholes with lengths of 45 mm, 90 mm, and 180 mm, each having a diameter of 6 mm. The bottom of the coal specimen box was made of metal foam, which allows fast gas adsorption.

2.2. Experimental scheme

Fig. 3(a) shows the SRZ, SCZ, and OSZ in front of the working face. In the OSZ the stress δ_H equals γ_H, where γ is the average unit weight of the overburden and H is the mining depth. In the SCZ, the stress is higher than δ_H, while in the SRZ, the stress is lower than δ_H. A schematic diagram of the stress loading experiments is shown in Fig. 3(b); σ_{11}, σ_{12}, σ_{13}, and σ_{14} were 0.9 MPa, 2.6 MPa, 2.6 MPa, and 1.8 MPa, respectively in the X direction, σ_2 was 2.2 MPa in the Z direction, and σ_{31}, σ_{32}, σ_{33}, and σ_{34} were 0.7 MPa in the Y direction. The gas pressure was 0.7 MPa at equilibrium. The values of the in-situ stress and gas pressure were in accordance with the previous study [39]. The in-situ stress was loaded throughout the duration of the experiment after vacuum pumping for 8 h, then the coal specimen was saturated by applying injection gas pressure of 0.7 MPa. The gas adsorption time required to saturate the coal specimen was approximately 48 h [40,41]. The gas inlet was closed after the adsorption equilibrium of the coal specimen, and the gas outlet was opened to initiate the gas production process.

2.3. Sensor arrangement

The raw coal samples were sourced from the Songzao coal mine, Chongqing Province, China. Proximate analysis of the coal sample was carried out according to the Chinese National Standard GB/T212-2008 guidelines [42], which is presented in Table 1. To facilitate the installation of gas pressure sensors within the coal, reconstituted coals were used to simulate a coal seam. It has been confirmed through laboratory experiments that raw coal and reconstituted coal have similar geomechanical properties and permeability [40,41,43–46]. Raw coal was first crushed and then shaped using a pressing machine. The reconstituted coal were divided into four layers, and each layer was pressed for 1 h under a shaping stress of 7.5 MPa. During the shaping stage, 32 gas pressure sensors (labeled P_1–P_{32}) and a borehole were placed in the simulated coal seam, as shown in Fig. 4. The gas pressure sensors were distributed in seven planes perpendicular to the borehole. For example, P_1–P_7 were in the z = 919 mm plane, while the x values of P_2–P_5 and y values of P_1, P_4, P_6, and P_7 were each 205 mm. The z values of the other six planes were 133, 264, 395, 526, 657, and 788 mm. The