Rapid co-extraction of coal and coalbed methane techniques: a case study in Zhangji coal mine, China

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Abstract. Coalbed methane (CBM) is one of elements of coal mine hazards, the high CBM content and low permeability coefficients of coal seams in Huainan coal filed result in high difficulty of coal exploitation and CBM drainage, and the potential risk of gas explosion and combustion. The CBM drainage works are time-consuming and they typically delay the coal mining operations. A set of novel techniques of rapid co-extraction of coal and CBM are proposed in this paper. In the practice of 1413A longwall panel of Zhangji coal mine, a set of overlying and underlying drainage galleries were replaced by two overlain drainage galleries which were excavated by TBM, thereby the stress of excavation works was reduced. The pre-drainage and roadway excavation are conducted simultaneously and the overlying drainage gallery can also be used for post-drainage purposes. The bolter miners and automatic or remote control of longwall mining have also been used in the practice. The 1413A longwall extracted 2.31 million tons of coal and 15.02 m\textsuperscript{3} of CBM with the extraction rates of 93.5\% and 63.8\% respectively in 448 days. The speed and efficiency of co-extraction operations were improved significantly.

1. Introduction

Highly gassy coal mines are concentrated in Huainan coal field, Anhui province, China. More than 90\% of the coal seams within this area have low permeability coefficients which are less than 0.1 m\textsuperscript{2}/(MPa\textsuperscript{2}/d). That leads to high difficulty of coal exploitation and coalbed methane (CBM) drainage, and the potential risk of gas explosion and combustion[1]. In recently years, CBM is considered as a type of green resource to extract and utilize, therefore the co-extraction is playing an increasing important role in coal industry[2]. Many researchers proposed the co-extraction of coal and CBM techniques by excavating overlying or underlying drainage gallery[3]. However, excavating overlying or underlying CBM drainage galleries in stiff rock layers of coal roof or floor leads to unacceptable long construction period because penetration rate of conventional excavation techniques in rock layers is much lower than that in coal seams[4]. This paper proposed a rapid co-extraction technique of coal and CBM by excavation overlying CBM drainage galleries above longwell panel using tunnel boring machine (TBM).
which significantly shorten the construction period[5]. Moreover, the overlying CBM drainage galleries were used for pre-drainage and post-drainage operations, which simplified the CBM drainage system and saved the construction costs[6]. The rapid co-extraction technique had been successfully applied in 1413A longwall which is located at West-II mining area, Zhangji coal mine, China. This result proves that the approach is safe, efficient, low cost and green for co-extraction of coal and CBM.

2. Project overview

2.1. Engineering background
Zhangji coal mine is located in Huainan city, Anhui province, Eastern China with the annual output capacity is 12.4 million tons of coal. The main products are high volatile bituminous coal and coking coal. There are five minable coal seams and the total thickness is 21.08 m. The shaft mining is adopted due to the mining operations are conducted from 480 m to 1000 m beneath the sea level.

2.2. Geological setting
The bed rock layers are covered by a thick alluvium which consists of clay, sand, sandy clay and gravel, and the thickness of alluvium is 384.65-460.70 m, average thickness is 426.73 m. Coal measure strata lie in Shanxi formation of Permian and Taiyuan formation of Carboniferous, Consist of coal, medium sandstone, fine sandstone, siltstone and argillaceous sandstone. The No.1 coal seam is the only minable coal seam within West-II mining area of Zhangji coal mine, with a sandstone roof and a sandstone-mudstone floor. The No.1 coal seam has an average thickness of 6.5 m and a dip angle of 3°-8°. The coal is classified as high volatile bituminous coal and coking coal and the thickness of overburden is about 500 m. the coal and CBM resource in 1413A longwall panel are 2.47 million tons and 23.55 million m$^3$ respectively[7].

The measurement results suggested that the ground stress is controlled by tectonic stress. The magnitude of vertical stress, the minimum horizontal stress and the maximum horizontal stress are 14.5 MPa, 13.4 MPa and 37.4 MPa respectively. The high ground stress also increases the potential risk of CBM outburst.

2.3. Layout of longwall panel and CBM drainage system
In previous CBM drainage operations in Zhangji coal mine, two underlying CBM drainage galleries and one overlying CBM drainage gallery were excavated for the purposes of pre-drainage and post-drainage respectively. Due to the high CBM content and high pressure, the drainage boreholes are drilled from underlying drainage galleries for ensuring the safety of excavation works of main gate and tail gate. An overlying drainage gallery is excavated for collecting CBM released from longwall face and gob. The conventional co-extraction technique is named ‘one panel, six roadways’, which include main gate, tail gate, longwall face, two underlying drainage galleries and an overlying drainage gallery. The conventional technique leads to excessive excavation works and a low efficiency of co-extraction, and the significant increasing in total cost. The layout of conventional layout of longwall panel is shown in Figure 1a and Figure 1b.
In this paper, a novel layout of longwall panel is proposed (shown in Figure 1c and Figure 1d). The longwall panel is 1500 m in length and 230 m in width. The No.1 coal seam has an average thickness of 6.5 m, and a dip angle of 8°. Two overlying CBM drainage galleries were excavated 25 m above the No.1 coal seam, and the horizontal distance from No.1 and No.2 overlying drainage gallery to main gate and tail gate are 30 m. Before the excavation of main gate and tail gate, the overlying drainage galleries were constructed, and downcast boreholes were drilled from overlying drainage galleries to the coal seam in order to conduct pre-drainage and eliminate outburst risks in roadway excavation works. After coal extraction works started, the longwall face advanced forward, the coal roof collapsed and fractures generated between coal seam and No.1 overlying drainage gallery, therefore the CBM could be extracted from No.1 overlying drainage gallery.

Due to the high stiffness of rocks and excessive wear of drilling bits, the penetration rate of roadway driving was 50 to 60 m per month by using drilling and blasting excavation. Considering the unacceptable low penetration rate, a tunnel boring machine (TBM) was introduced in the project. The TBM penetrated about 500 m per month and it finished the excavation works within three months before the construction of 1413A panel.

The main gate, tail gate and longwall face of 1413A longwall were excavated by two bolter miners. The excavation and rock bolt supporting works were conducted simultaneously, which increased the penetration rate from 150 m/month to over 300 m/month.

2.4. Excavation of CBM drainage galleries

The overlying drainage galleries were excavated by hard rock TBM that manufactured by Northern Heavy Industry, China. The TBM with a diameter of 4.5 m equipped with a hard rock cutterhead and two rock bolters could be operated in hard rock strata in underground coal mines[8].

3. CBM pre-drainage

In this paper, the downcast boreholes and in-seam borehole were drilled from overlying drainage galleries for eliminating the outburst risks during roadway excavation and longwall mining respectively. The downcast boreholes were specialized designed to increase the drainage efficiency and resolve the problem of waterlogging and jamming. One overlying drainage gallery was used to extract CBM from gob during longwall mining works.

3.1. Downcast cross measure boreholes

In the practice of 1413A longwall, the overlying drainage galleries were excavated for using of both pre-drainage and post-drainage. Downcast boreholes arranged into a fan shape were drilled to excavation sections of main gate and tail gate for preventing CBM outburst in the excavation works.

In No.1 and No.2 overlying drainage gallery, each group of boreholes contains 7 and 8 boreholes respectively. Boreholes were drilled to the main gate, tail gate and the main gate of the next longwall. Each borehole penetrated coal seam and drilled down 15 m to the bottom rock layer. The space between each group is 50 m and there were 30 groups of boreholes were drilled in each overlying drainage gallery. The layout of downcast boreholes is shown in Figure 2.
Downcast drainage boreholes were special designed for avoiding the problem of borehole jamming or clogging [9]. First of all, the boreholes extend to bottom rock layer so that the section in rock layer of boreholes provided enough space for deposition of coal grain and ashes. Considering the water ingress could causes jamming or clogging of boreholes, each borehole is equipped with a steel water drainage pipe. In addition, a compress air pipe and a CBM drainage pipe were also set in each borehole, and the top of boreholes were sealed. Normally the water drainage pipe and compress air pipe are shut down and the CBM drainage tube is switched on for CBM drainage. When water drainage is demanded, the CBM drainage pipe is turned off and water drainage pipe and compress air pipe are turned on, the water logged in borehole is drained out of borehole through the water drainage pipe under the pressure of compress air. All tubes are controlled by electromagnetic valves and water drainage time can be set based on the quantity of water inflow.

3.2. CBM post-drainage
The TBM excavated overlying CBM drainage galleries was also been used for post-drainage which is also known as gob-drainage. The coal roof collapse after coal mass is extracted, the fractures formed in overlying rock strata lead to the creation of spaces for methane accumulation and channels for CBM migration. Many researchers studied the mining-induced fractures distribution behaviors of the overlying strata. Their results indicated that the permeability of the rocks in the center of gob decreased due to compression, while there is an annular fracture zone in the border of gob named the ‘O shape’ zone [10], as shown in Figure 3. The ‘O shape’ zone provides main pathways for CBM migration because the permeability in the sides of gob is greater than that in the middle part.

In coal extraction operations, CBM migrates toward fracture zone of overlying strata above the gob and accumulates there due to the stress relief and lighter-than-air density of CBM. The fracture zone reaches up to overlying drainage gallery and therefore the CBM suction can be conducted through the No.1 overlying drainage gallery. The No.1 overlying drainage gallery was sealed from the entry with a set of drainage pipes installed in it. Drainage pipes were connected with a pump, due to the negative pressure generated by the pump station, the gob gas and depressurized gas from adjacent coal seams flow through the mining-induced fractures finally to the drainage pipes [11], as shown in Figure 3.
4. Field application and analysis
The co-extraction works of 1413A longwall panel started in 1st Dec 2014 and finished in 22nd Feb 2016, the total duration is 448 days. The pure CBM volumetric flow and daily coal output are shown in Figure 4. The overlying CBM drainage galleries was excavated firstly for protecting excavation of main gate and tail gate, the drainage galleries excavation started in 1st Dec 2014 and finished in 9th Mar 2015, followed by the downcast boreholes drilling works. The main gate and tail gate were excavated under the protection of pre-drainage and destressing which conducted by downcast boreholes, and the excavation works persisted for 146 d, from 9th Dec 2014 to 4th May 2015. The in-seam boreholes were drilled behind the excavation faces and unequal spacing layout of in-seam boreholes were adopted for gaining balance between CBM drainage performance and economics. The coal extraction operations started 20th Jul 2015 after finishing longwall installation, and the longwall mining were finished in 22nd Feb 2016. The whole co-extraction of coal and CBM lasted for 448 d, from 1st Dec 2014 to 22nd Feb 2016.

The CBM drained from downcast boreholes increased from 7.68 m$^3$/min in 8th Dec 2014 to 36.16 m$^3$/min in 9th Mar 2015 due to the increasing number of downcast boreholes. Then the CBM flow decreased to approximate 0 m$^3$/min because the roadway excavation works damaged the downcast boreholes. The CBM extracted by in-seam boreholes increased from 1.65 m$^3$/min to 38.13 m$^3$/min during the time from 5th Jan 2015 to 1st Jun 2015. After the longwall mining started, the CBM flow of in-seam boreholes declined sharply due to the longwall mining works destroyed the in-seam boreholes. The CBM exploited from No.1 overlying drainage gallery stabilized at around 3 m$^3$/min in first 7 days due to the coal roof hadn’t collapse. Along with the cutting of coal face and the collapse of coal roof, the CBM drained from No.1 overlying drainage gallery shot up to above 10 m$^3$/min and peaked at 16 m$^3$/min in 23rd Nov 2015, then the CBM flow dropped slowly. The daily coal output fluctuated from 5000 to 7000 t/d at the beginning of longwall mining, after 10th Aug 2015, the daily coal output increased to 10000 t/d because of the improvement of longwall operations. The longwall mining works stopped in 22nd Feb 2016. The proposed co-extraction techniques exploited 2.31 million tons of coal and 15.02 m$^3$ of CBM. The extraction rates of coal and CBM are 93.5% and 63.8% respectively.

5. Conclusions
The practice of 1413A longwall panel in Zhangji coal mine achieved a rapid and efficient approach for co-extraction of coal and CBM. Most researches focus on the CBM drainage efficiency but the coal extraction works are usually influenced or delayed by complicated and time-consuming CBM drainage works. The integration of advanced drainage, excavation and mining techniques such as TBM, water jet permeability enhancement, water drainage of downcast boreholes, bolter miner and longwall automation significantly increased the efficiency of CBM drainage and coal mining. Using overlying CBM drainage galleries for both pre-drainage and post-drainage also reduced the workloads and costs of CBM drainage.

For coal seams with low permeability and risk of outbursts, the appropriate drainage, excavation and mining techniques should be chosen to meet the requirements of co-extraction of coal and CBM, and these techniques should be conducted in parallel as far as possible. The integration of CBM drainage and coal extraction works is crucial and it needs to be seriously considered so that different subprojects of co-extraction cannot be interfered with each other.

Because the proposed co-extraction techniques were applied in 1413A longwall panel for the first time, two overlying CBM drainage galleries were constructed for pre-drainage works of main gate and tail gate of 1413A longwall and the main gate of adjacent 1415A longwall. For 1415A longwall and further longwall panels, only one overlying drainage galleries is required. Compare with conventional layout of longwall panels, at least one drainage gallery is saved, and therefore the exploitation efficiency is enhanced significantly.
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