WASM: Minerals, Energy and Chemical Engineering

RESEARCH OF INSEAM HORIZONTAL DRAINAGE FOR COALBED METHANE PRODUCTION

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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research does not include any human and animal ethics issue

Signature: Zidong Zhao

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Abstract

Coalbed methane is a kind of natural gas generated during coalification. It is considered as the primary factor which gives rise to gas exploitation and outburst in the underground during coal production. For reducing the risk of these mine accidents, it is usual to drill boreholes into coalbed to eliminate methane before and during coal extraction. However, as a result of the development of technology, the minable coal seam becomes more depth. Besides, gas content typically increases with the burial depth of the coal seam. The traditional method of drilling single boreholes is insufficient to reduce the gas content and keep the safety in the underground. Thus, other options are of necessity to eliminate gas from coal seams.

In-seam horizontal borehole pattern for gas drainage is one of the most effective methods to eliminate methane from coal seams before or during coal extraction. Boreholes are drilled into pre-developed coal panels or coal seams then drain the methane out in order to reduce the gas content. There are several parameters of this pattern such as borehole length, borehole configuration, boreholes orientation, lateral space of boreholes, leading time and others, that need to be determined by engineers to accommodate special conditions of the underground. Any change of one parameter may result in a significant influence of the effectiveness of methane drainage.

The application of in-seam horizontal borehole pattern differs from case to case, because normally the pattern is applied with the experience of engineers and every company have different methods. Sometimes the gas elimination may not adequate as expected. It is critical to solving this problem as it may delay the coal extraction and danger the safety of underground. Sometimes the gas content is higher than usual, and the permeability is lower, which also result in the inadequate methane drainage. Companies usually only drill more boreholes in coal seams to increase the volume of gas drainage, and this will not achieve a performance as expected. Hence, to find out how the parameters of the in-seam horizontal boreholes pattern impact the performance of methane drainage and optimizing the pattern are of significance.

According to the studies, the parameters of the in-seam horizontal boreholes pattern are researched on how to impact the performance of methane drainage. In addition, a real methane drainage pattern applied in the coal mine located in China is investigated, and an optimized pattern will achieve a better performance of gas drainage, which not only avoids the production delay but also increases the safety in the underground.

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1. Chapter 1

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1.1.Background

Coalbed methane is well known as the major factor which can trigger mine catastrophes such as gas outburst and gas explosion in the underground. A mass of methane is reserved in the coal seams in the USA, Russia, China, Australia, and Canada (Al-Jubori et al., 2009). In China, around 70% of coal mines have prone to gas outburst due to the high gas content and low permeability (Fu, 2005; Li, 2001). More than 82% of mine accidents are caused by gas explosions. In the US, more than 600 times of mining explosions have been recorded and took thousands of peoples life since the 1830s (Thakur, Schatzel, & Aminian, 2014). Thus, it is important to solve the problems caused by methane.

Generally, methane releases into the underground during the mining process and can be diluted by the ventilation system (Flores, 1998). If the methane-in-air proportion accounts for between 5% and 15%, the mixture would have an explosive risk. During coal extraction, the methane-in-air proportion usually is controlled within 1% worldwide. However, the traditional ventilation cannot sufficiently dilute the methane at those mines with high gas content. The air intake of ventilation cannot be increased without limitation due to the underground structure. Additionally, the air from underground usually is released into the atmosphere. The methane is a kind of greenhouse gas and has 25 times greater potential of global warming than carbon dioxide. Releasing a mass of methane into the atmosphere would cause a significant impact on global warming. Hence, many companies prefer to eliminate the gas from coal seams prior to and during coal extraction by drilling boreholes into coal seams.

In-seam horizontal boreholes pattern is one of the most effective methods for methane drainage before or during coal extraction. Boreholes are drilled into coal seams to eliminate and collect the methane then transport to underground for further usage. Although this method is more effective than others, sometimes it also will result in unexpected consequences. For achieving a better performance of the in-seam horizontal boreholes pattern, it is vital to understand how the parameters of the pattern impact the drainage performance. Instead of drilling more boreholes to achieve a better result which is usually undertaken by most companies, understanding these parameters and optimizing the pattern is more critical.

1.2.Research Problems and Objectives

In order to solve the problems shown above, this thesis aims to research:

The first paper aims to research the necessary conditions of gas outburst by the numerical simulation. The prediction of gas outbursts during uncovering coal in crosscut is improved.

The second paper aims to improve the performance of the drainage pattern as the current pattern is inadequate to eliminate the methane to a safety level. By optimizing the boreholes length, boreholes configuration and the lateral space of boreholes, a better result is achieved, and the safety of the underground environment is increased.

The third paper is a literature review of the in-seam horizontal boreholes pattern for methane drainage. This paper investigated how parameters impact the effectiveness of methane drainage. Additionally, different parameters are researched for the best adaptive conditions.

Overall, this research will investigate controllable factors including boreholes configuration, leading time, boreholes orientation, lateral space of boreholes, borehole length, pressure, and borehole direction, which impact the horizontal methane drainage performance for underground. In addition, the results would be applied to improve a methane drainage system in a specific coal mine.

2. Chapter 2

A Review for Underground In-seam Methane Drainage

Brief Introduction

Coalbed methane is the primary factor which causes numerous underground mining catastrophes. In-seam horizontal methane drainage pattern is one of the most effective strategies to eliminate methane from underground whenever before or during coal extraction. An integrated drainage pattern of in-seam horizontal borehole involves several parameters including borehole configuration, borehole orientation, borehole length, lead time and others. Every small change may increase the effectiveness of methane production or result in borehole failure. This paper reviewed the most usually approaches of in-seam horizontal methane drainage pattern and figure out how these parameters impact the methane production rate during different conditions.

2.1.Introduction

Coalbed methane (CBM) is a form of natural gas adsorbed into the solid matrix of the coal. Since coal mine industry became prevalent in the 19th century, CBM has been well known and considered as the primary factor which give rise to gas outburst and exploitation in underground, where it emerges a serious risk (Anderson, 1995; Flores, 1998; Lama, 1995; Okten, Biron, Saltoglu, & Ozturk, 1995). Substantial CBM reserves are found in the USA, Russia, China, Canada, Australia, the UK, and India (Al-Jubori et al., 2009). Based on the Chinese occupational standards for mines (Campoli, Trevits, & Molinda, 1985), about 70% of mines in China are coal and gas outburst-prone due to the low permeability and high methane content in coal seams (H. Li, 2001). In addition, as shallow coal seams are exploited, the target mining seams become increasingly deeper, and usually, the methane content increases with the burial depth of the coal seam. In Australia, the maximum depth of underground coal mining exceeds 600m (Lunarzewski, 2001a), and the in-situ methane contents of coal in deeper seams are between 5-20m^3/t. In China, at least 50% of underground coal mines are defined as gassy or outburst-prone mines (Fu, 2005). Moreover, the development of mining equipment and technique in the last 20 years results in the increase of coal production, which leads to more gas emissions in the underground during the coal extraction periods (Black & Aziz, 2008b). In Australia, an outburst occurred at Westcliff Colliery in 1994, and then as a requirement, every gassy mine must have an Outburst Management Plan after this outburst (Frank, Ting, & Naj, 2013). Under these situations, the conventional ventilation system and gob-gas drainage usually cannot sufficiently dilute the methane concentration below the prescribed Threshold Limit Value and eliminate methane from the underground. For solving this problem, normally, increasing the air intake and drilling more vertical drainage wells are the traditional methods (Flores, 1998; Karacan, Diamond, & Schatzel, 2007; P. C. Thakur, Little, & Karis, 1996). However, geology, mining structure and other relative reasons would restrict the air intake volume, so that traditional method cannot solve this problem in gassy coal matrix or explosive-prone coal seams. Hence, other solutions are of necessity such as in seam horizontal boreholes for CBM drainage.

Contemporarily, there are several methods that can eliminate methane from underground, which are divided into two types including pre-drainage and post-drainage. Pre-drainage is to drain the methane prior to coal extraction, such as vertical wells drilled from the surface into coal seams, long length of horizontal methane drainage boreholes drilled from the surface of the longwall development, and inseam drainage. These methods usually are applied months or years before coal extraction. On the other hand, post-drainage is to drain the methane during or after mining, such as cross-measure boreholes drilled into overlying and underlying strata, old active goaf drainage (Lunarzewski, 2001a; Su et al., 2006). Table 1 shows some CBM drainage methods and their application conditions.

Globally, underground in-seam methane drainage is the most common and effective method to reduce gas emissions before and during mining to decline the catastrophe rate (Black & Aziz, 2008b). For instance, in Australia, the underground in-seam methane drainage has extended through the Australia coal mine industries and has becomes the most effective method, especially for underground gas drainage in mining regions such as Illawarra which mines between 450 to 500 metres depth and have many limitations to access surface which can hardly apply surface relative methane drainage methods (D. J. Black & N. Aziz, 2009). Although traditional vertical wells can also eliminate gas from underground, the methane production performance of inseam methane drainage is 2 to 10 times greater than that of traditional vertical wells while the cost of in horizontal seam boreholes is only higher 1 to 4 times as much (Diamond, Oyler, & Fields, 1977; Gentzis, 2009; Palmer, 2010). The first in-seam horizontal borehole for methane drainage borehole practised in the late 1950s by Consolidation Coal Company in the Pittsburgh coal seam (Spindler & Poundstone, 1960), and the first directional in-seam long hole was drilled in Australia at Appin Colliery in 1987 to drain gas from adjacent coal seam located 18m below the working seam (Lunarzewski, 2001b).

This in-seam horizontal boreholes pattern is to drill boreholes into the coal seams and underlying and overlying strata and drain gas prior to or during mining to control gas content and gas emission. These boreholes would form an integrated drainage pattern. Patterns may differ due to different geological conditions, mining face arrangement, or even available equipment. Drainage performance would be impacted by CBM drainage pattern parameters, and reservoir factors such as gas content, coal seam thickness, and maceral. An integrated in-seam methane drainage pattern would involve several parameters including borehole length, interval space of boreholes, the diameter of boreholes, drainage direction, and shapes which also named borehole configuration. Nevertheless, there are no systematic studies of methane drainage pattern; sometimes a methane drainage program would not obtain an expected production outcome. Some previous studies show that 50% of the total gas drainage only have little or no effectiveness for a gas content reduction in coal seams. In

China, in-seam horizontal CBM drainage began after the 1980s. However, there is only a little effort (Yanbin et al., 2008). Despite that the CBM drainage efficiency has been grown from 15% to 26% between 1998 and 2004, most of the drained methane are poor of quality. It is estimated that the concentration of more than 70%-80% of drained methane is under 30% (Su et al., 2006). Some previous studies find that there are many factors which can impact the CBM drainage performance including geological and operational factors. It is however found that, on the operational level, the CBM drainage system was not well understood which resulted in the ineffective methane drainage for reducing the gas content. Moreover, it was common that many coal mine industries chose to drill more additional boreholes in the same coal seam or panel to improve drainage performance, rather than improve the controllable factors such as drilling orientation, borehole length. Unfortunately, these additional boreholes had very little ability for methane drainage to improve the drainage system performance. Also, because of the different geologic conditions and mining plan, the CBM drainage system has to be designed site-by-site for successful methane elimination from coal seams (Karacan et al., 2007). Thus, it is significant to deeply investigate in seam methane drainage pattern.

Table 1 Gas drainage technologies and their application conditions

Drainage without de-stressing			Drainage with de-stressing		
Heading face	Coal face	Surrounding rock	Heading face	Coal face	Goaf
Pre-drainage in advance	In-seam drainage	Overlying and underlying borehole drainage	Co-operation of drainage and extraction	Co-operation of drainage and extraction	Goaf borehole drainage

In-seam drainage	Crossover borehole drainage		Water injected fracture	Crossover borehole drainage	Roadway drainage
Multi-lateral borehole drainage	Cross-measure borehole drainage		explosion	High position borehole drainage	High position borehole drainage
Forward-direction drainage	Multi-lateral borehole drainage			De-stressed borehole drainage	
	Surface borehole drainage			Surface borehole drainage	

2.2.In-seam methane drainage Patterns

The cleat system is significant to the methane drainage in the underground. During coalification, fractures, usually also name cleats system are generated. Face cleats are continuous within the coal matrix, while butt cleats are terminated at the face cleats (Al-Jubori et al., 2009). Generally, water would fill into the fractures in the coal reservoirs. In addition, coal has inherent porosity, which can store up to six times the volume of methane compare to sandstone under the same pressure (Al-Jubori et al., 2009). The coal acts as both sources and reservoirs of methane rather than the conventional reservoirs, and typically substantial volumes of methane are adsorbed in coal matrix at micropores level (Clarkson, Bustin, & Seidle, 2006). Generally, methane is stored in coal reservoirs in three different types: 1) as free state stored in pore spaces and fractures, 2) as a dissolved gas in water, 3) as adsorbed gas stored in the coal surfaces (Twombly, Stepanek, & Moore, 2004). Methane adsorbed in the coal surfaces is existed at the molecular level and only can be eliminated by the reservoir pressure gradient. This adsorption process is described by Langmuir isotherm (McLennan, Schafer, & Pratt, 1995). During methane production, water is eliminated at first to drop the formation pressure, then methane desorbs from the matrix and migrates into fractures which are controlled by the concentration differential and obeys the Fick's Law(Meng, Wang, Li, & Zhang, 2018). Moreover, methane flows from fractures into boreholes by the diffusion process which is controlled by the Darcy's Law. The Fick's Law and Darcy's Law are impacted by each other (Ren et al., 2014). Sometimes boreholes produce methane instantly without water production. This is because mature fields may partially or fully dewater the coal reservoirs during previous works.

In-seam horizontal methane drainage boreholes have been applied for methane drainage to decline the outburst risk and reduce the methane concentration in the underground ventilation in the past three decades (Frank et al., 2013). The purpose of the in-seam horizontal gas drainage is to eliminate gas content from coal seams to dilute to the level where the gas concentration can be sufficiently diluted by the mining ventilation system during mining. In-seam methane drainage is the most common method to drain methane in which coal matrix is with high gas content and low permeability (Chi & Yang, 2000). In China, coal permeability in more than 90% of coal seams in lower than 0.001mD, which is four times lower than the coal permeability in coal seams in the USA and three orders lower than that of Australia (Cheng, Wang, & Zhang, 2011; Lu, Liu, Li, & Kang, 2010). Also, most of the coal seams in China are identified as soft and low permeability, with gas content between 8m^3/ton and 10m^3/ton in the most minings (Lu et al., 2010; X. Su, Lin, Liu, Zhao, & Song, 2005; Yanbin et al., 2008). If the cleat system in coal matrix is not developed enough, gas elimination could be inadequate, because of the low porosity and permeability in the matrix which makes the gas hardly to move from the matrix into the fracture (Maricic, Mohaghegh, & Artun, 2008).

In-seam methane drainage has two basic safety advantages: decreasing the gas content of the target panel prior to panel extraction, and protecting active workings including development sections (Karacan et al., 2007). This method is to drill boreholes into the target coal seam or long wall panel, then drain methane from boreholes and eliminate from the underground. Usually, boreholes are drilled usually from tailgate into the panel prior to panel extraction to reduce the gas content of the coal matrix (Diamond & Garcia, 1999; Karacan et al., 2007). Borehole configuration and arrangement will form a network system. In addition, the leading time is one of the most significant factors of this drainage method. The life of the drainage of one panel is dependent on the mining plan. When the panel extraction is approaching, these boreholes would be blocked the flow by grouting, or injecting water or gel due to mining safety reasons. Hence, there are two stages of in-seam methane drainage, methane production prior to mining, and methane production termination during panel extraction. In the beginning, the coal seam is in dynamic equilibrium. Basically, water in coal seam must be drained at first and continuously to reduce the reservoir pressure and then release the methane. Methane from the coal matrix can only be eliminated after initial dewatering and upon reaching the critical reservoir pressure. After the reservoir pressure decreases under the critical desorption pressure, methane desorbs from the coal matrix (Guo, Du, & Li, 2003). The dewatering process can take from several days to several months, that depends on borehole configurations (Maricic et al., 2008).

Usually, the curves of gas production differ from vertical wells to horizontal wells. In a short time, the horizontal wells need to dewater the coal seam, produce a significant volume of water. The gas flow rate will peak soon after the wells dewatering. The most significant part of the gas flow rate curve is after the gas flow rate peak. The slope of the curve is the most vital part of the curve because the horizontal wells will produce methane as the same as a conventional methane reservoir. The flatter the curve, the better result of methane production for the production life of the wells. It is more capable of gas drainage for the horizontal wells due to much longer borehole contact with the coal seams. Consequently, the adsorption process occurs more quickly, the production of wells would decline relatively faster. After the methane production rate reaching the peak, the rate will start to decline, due to the large contact between the horizontal wells and the coal seam. Figure 1 and Figure 2 illustrate the comparison of production rates and production accumulation respectively, of vertical and horizontal wells as a typical CBM production (Maricic et al., 2008).

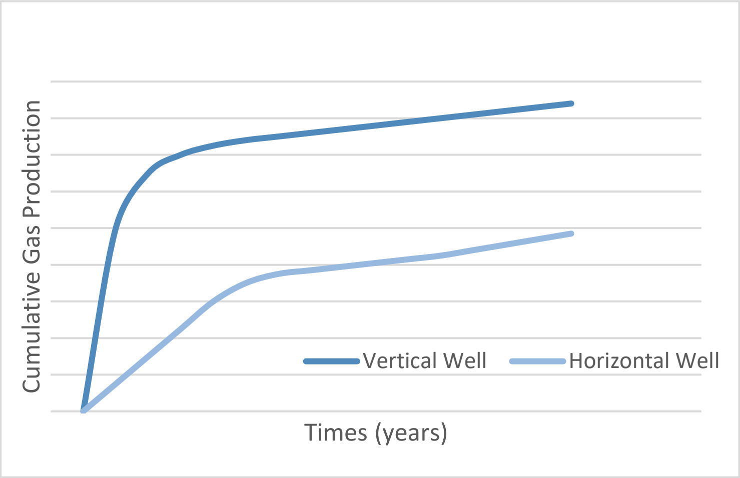

Figure 1 Accumulative gas production with time

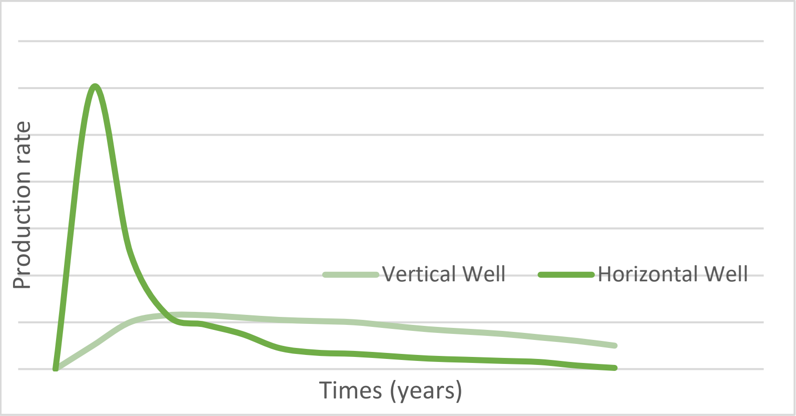

Figure 2 Production rate with time

2.3. Factors impacting the performance of CBM exploitation

Although methane drainage is not only associated with drainage time, borehole diameter, borehole length, suction pressure, borehole configuration, borehole orientation, and lateral space of boreholes, but also related to coal seam permeability, gas content, and other factors, which play important roles in methane drainage (Meng et al., 2018). However, based on an operational level, this study will only research "controllable factors" which coal mine industries can control and adjust. Based on a specific coal seam condition, these "controllable factors", or named parameters, of an integrated in-seam methane drainage must be determined including boreholes configuration, length of a single borehole, the lateral spacing between boreholes, the diameter of a single borehole, position of boreholes drilling, the direction of boreholes drilling, and leading time. Any changing of these parameters may impact the performance of the whole methane drainage system. In this study, these parameters will be researched separately.

2.3.1. Boreholes configuration

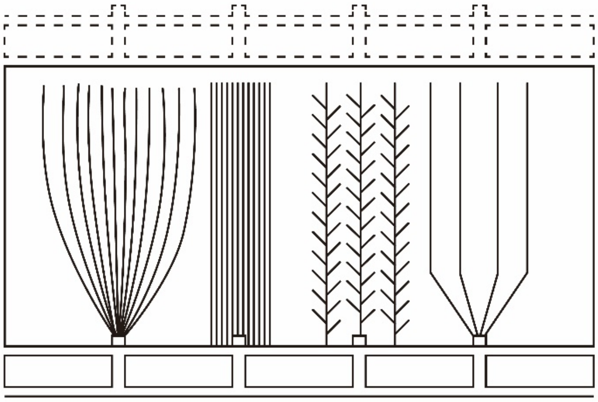

Figure 3 Boreholes configuration

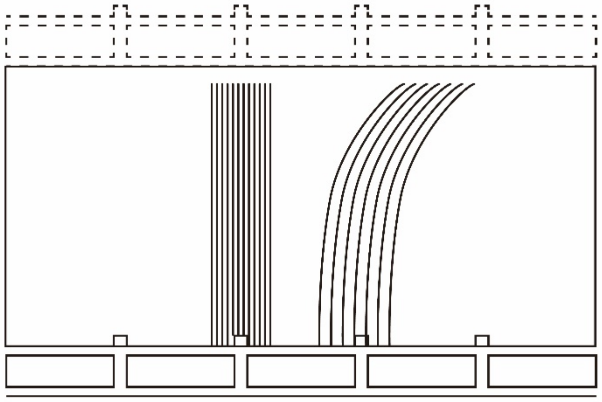

Figure 4 Boreholes with initial curvature and straight boreholes

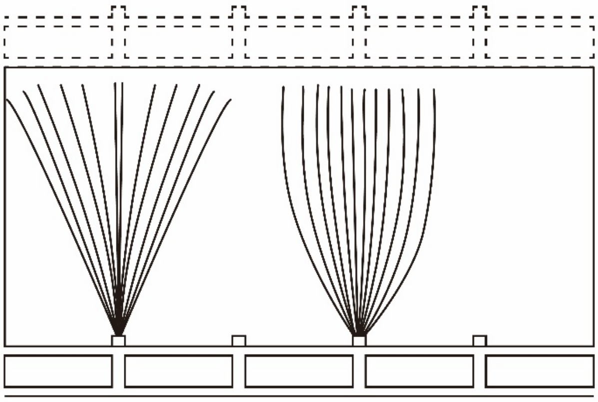

Figure 5 Fan patterns with straight or curved boreholes

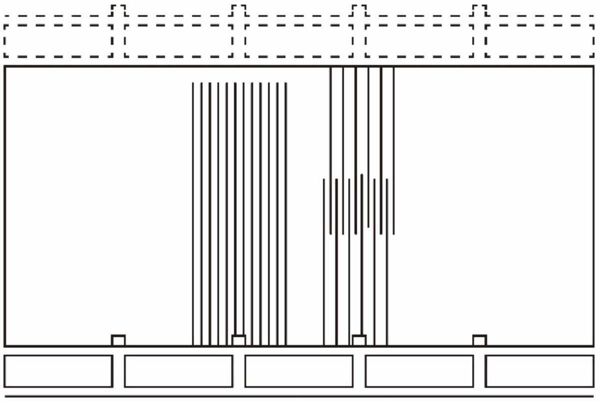

Figure 6 Parallel patterns

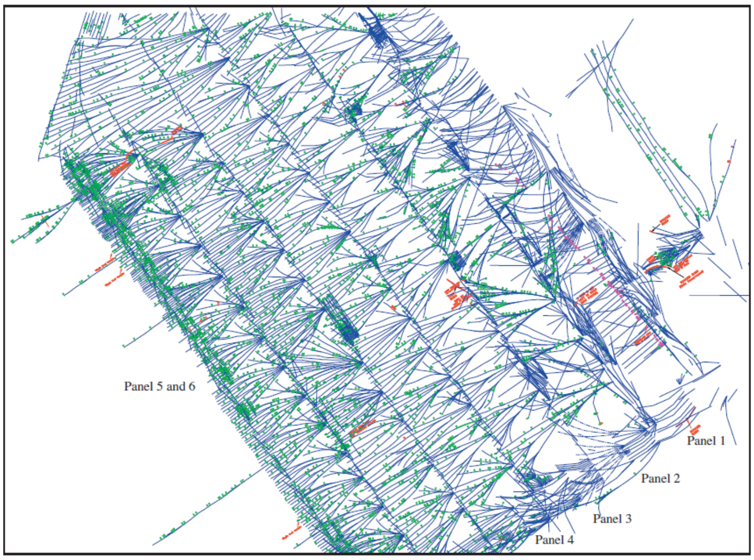

Figure 7 Progressively improved drilling patterns (Frank et al., 2013)

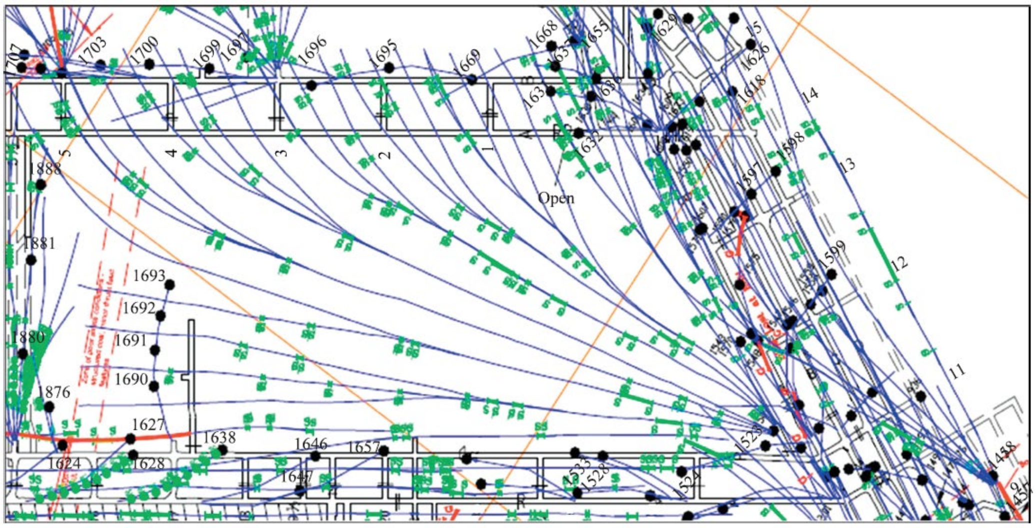

Figure 8 Drilling pattern for special requirements (Frank et al., 2013)

Generally, there are several tyres of boreholes configuration, including parallel pattern, fan pattern, and pinnate pattern. Figure 3 shows some common boreholes configuration, and the first two patterns are the most popular pattern, named fan pattern and parallel pattern. The boreholes configuration varies from site to site and usually is determined by the corporations. Usually, at the beginning of the design of methane drainage, if the coal permeability exceeds 3mD, the single lateral borehole is adequately for CBM drainage. If the permeability is less than 3mD, the single lateral borehole may not adequate to eliminate methane from the coal seam, which requires multi-lateral wells (Palmer, 2010). Currently, a lot of mine companies drill boreholes with fan patterns across each coal panel along with the development. Some companies apply the parallel pattern at the same lateral space with the initial curvature, while some mines also prefer basically the same pattern but drill straight trajectory of boreholes, shown in Figure 4. Hence, as described above, several boreholes configurations are defined, each pattern is revised and modified to adapt specific conditions as a requirement (Frank et al., 2013; McInerney & Brown, 2016). There are usually three stages of in-seam boreholes drilling (Frank et al., 2013):

a) Drilling parallel boreholes with regular lateral space across a coal panel and assuming these boreholes are all straight and stable.
b) Drilling boreholes with a fan pattern based on the curvature of previous boreholes.
c) Drilling boreholes with a fan pattern and sealed after drilling. Each borehole is drilled follow the optimum trajectory which investigated already.

Fan pattern is to drill boreholes at a single point then develop several boreholes, usually five laterals as a maximum. These boreholes usually are straight, sometimes could be curved which is shown in Figure 5. In Australia, due to the relative longer length of the adjacent gateroad covered, the fan pattern is the most common pattern for a single drilling site (D. J. Black & N. Aziz, 2009). However, there are three negative aspects of drilling fan pattern for methane drainage, include (D. J. Black & N. Aziz, 2009; Keim, Luxbacher, & Karmis, 2011):

a) Incapableness to orient boreholes to the optimum drilling path direction.

b) Incapableness to maintain boreholes on a positive level to contain coal fines, methane and water within the boreholes, and
c) Methane and water may flow between holes due to the extremely close spacing of boreholes while close to the collar, which is the vital problem during drilling and production.

The parallel pattern also is the most common pattern for methane drainage. Figure 6 Shows two popular parallel patterns. The first pattern is normal, which straight drills boreholes from tailgate to headgate, sometimes also with initial curvature. However, when the length of coalface is much longer than the length of the drilling rigs, usually the second pattern is adapted. Boreholes are drilled from both tailgate and headgate to the opposite direction then alternately to each other. This is one of the easiest drilling patterns for CBM drainage.

There is another drilling pattern called a pinnate pattern, which is barely used in CBM drainage, shown as the third pattern in Figure 3. Pinnate pattern sometimes is also called fishbone pattern, or herringbone branching from the primary lateral, has a more complex configuration than others. The pinnate pattern has two sets of lateral boreholes that perpendicular to each other, and all lateral boreholes are connected to the single main boreholes (Keim et al., 2011). Pinnate may have collapsed since the region is chopped up by faults (Palmer, 2010). This pattern is usually used to drain the methane from a whole coal section prior to coal extraction for years.

Although every mine has its specific characteristics and every company has the unique design of boreholes configuration, drillers usually modify and improve the design progressively based on the previous drilling experience advanced drilling skills. There are some boreholes configuration shows Figure 7 (Frank et al., 2013). The boreholes in panel 1-3 show the regular rotary drilling with a parallel pattern. This is the most common drilling method that boreholes are drilled parallelly from tailgate to headgate. As the drilling skills improved and based on previous experience, the drilling pattern are revised into fan pattern and becomes more consistent as shown in other panels. Additionally, sometimes the regular drilling method is unavailable due to some structure reasons or other special requirements. In some cases, for example, the gateroad is inaccessible for boreholes drilling; the remote drilling is modified to suit such this condition, such as drilling boreholes from the head of the panel and across to the opposite site (Frank et al., 2013), which is shown in Figure 8.

2.3.2. Leading time

During a CBM drainage process, leading time refers to the period starting at gas production and ending with boreholes blockage and determination. Within all the controllable factors during methane drainage, lead time is the most correlated factor to the total methane production as recorded (Black & Aziz, 2008b). Some previous studies show that whatever in high CH_4 zones or high CO_2 zones or any forms of in seam boreholes direction, the lead time has the most correlation with the total methane production. Lead time is the most significant factor which could impact the methane production result.

Generally, the length of this period is based on mining plan or panel extraction plan, although in-situ gas content, desorption characteristics, natural fracture and cleat permeability determine the leading time required for in-seam gas drainage and borehole spacing. For most mines, a coal panel would be extracted within 12 months, for example, so the next coal panel would be drained within 12 months because the second panel should be ready for methane drainage while the first panel is ready for coal extraction. Moreover, when the methane production rate reaches a peak, it would be continuous to decrease. With the reservoir pressure and permeability fluctuate, this period is not as good as longer. Usually, it will be ended before the last panel extraction finished. Even though the leading time intensively relates to the gas production, the maximum period begins at the second-panel preparation and ends at the first-panel extraction finish.

2.3.3. Borehole orientation

Generally, there are three factors of borehole orientation that impact the gas drainage performance including the boreholes orientation relative to the horizontal stress, the orientation relative to the face cleats, and the orientation relative to the dip of the coal seam, which must be considered when arranging the gas drainage boreholes. Boreholes drilled parallelly to the major horizontal stress and orthogonal to the face cleats would gain a better methane production rate. However, it should be tested that which is more dominant to impact the methane production rate between the significant horizontal stress and borehole orientation to the face cleat. For instance, in the Bulli coal seam, borehole orientation to the primary horizontal stress is more dominant than the borehole orientation to the face cleat (Black & Aziz, 2008b). Generally, a horizontal borehole drilled to the axis with larger permeability will result in better methane production than other horizontal wells (Deimbacher, Economides, Heinemann, & Brown, 1992; Logan, 1988).

Some studies considered that borehole orientation is a significant factor which will impact the total methane production. During methane drainage, methane is transferred from coal surface to boreholes through cleats. Cleats are normal into the coal seams usually shows in pairs. There are two sets of near perpendicular fractures that intersect the whole coal seam and form an interconnected network. The two fractures are named face cleats and butt cleats. The face cleats are continuous through-going the coal seam, and the butt cleats, usually shorter than face cleats, intersects with face cleats and terminates at face cleats. The permeability value of the face cleat direction usually could be 1.8 to 17 times greater than the value of butt cleat direction, with an approximate average four times greater (Massarotto, Rudolph, & Golding, 2003). This is because the gas flows more easily within the face cleats than the butt cleats. The face cleats are developed more mature than butt cleats so that it can achieve better drainage performance while drilling across the face cleats than butt cleats (Logan, 1988; Palmer, 2010). Generally, it would rich more merits of the permeability while in-seam horizontal boreholes intersect with the face cleats as more as possible (Karacan et al., 2007). Some studies support that there is better gas drainage results for in-seam horizontal boreholes which drilled perpendicular to the face cleats (Diamond et al., 1977), due to the permeability is of anisotropy and forced in the face cleats rather than butt cleats (Deimbacher et al., 1992; Pashin, 1998). More studies support that for the best performance of methane drainage, the borehole drilling orientation for single lateral boreholes is drilling the main lateral within the face cleat. For the multi-lateral pattern, all laterals should be drilled parallelly to each other, and intersect to the face cleat. However, drilling boreholes into face cleats may decrease the stability of borehole networks. Some in-seam horizontal boreholes usually fail during or after drilling. This issue occurs while the drill bits trail the arranged borehole direction. The boreholes also failed while laterals are drilled with the same direction on the cleat (McInerney & Brown, 2016). Some other studies also claim that boreholes should be drilled a little bit slope in an up-dip orientation to promote the water flow in boreholes by gravity (Keim et al., 2011). It is better that do not drill boreholes down-dip unless it is a dry gas reservoir (Palmer, 2010).

The drilling orientation is significant, for instance, despite that, the multi-lateral pattern offers the better drainage performance for high methane production compared to the single lateral pattern, it will take vital methane production decrease due to inaccurate orientation. There are some merits of directional borehole drilling (F. Wang, Ren, Hungerford, Tu, & Aziz, 2011):

1) improve methane drainage efficiency and longer drainage time.

2) make sure boreholes are drilled into the target area.

3) build a more simplified and more focused methane drainage system.

4) provide geological information.

5) efficiently prevent the gas and coal outburst for underground coal seams. 5) reduce the borehole collapse during and after borehole drilling.

2.3.4. Lateral space of boreholes

While CBM drainage, the lateral space of boreholes, drilling density, must be considered. As shown in Figure 9, if the lateral space of boreholes is inadequate, the methane content may not be reduced under prescribed Threshold Limit within the available period. On contrast, if the lateral space of boreholes is over-low, the cost of the methane drainage program would be higher than usual (Black & Aziz, 2008b). However, coal mine companies always to choose to drill more boreholes in coal seams to increase methane production for avoiding production delays. Unfortunately, additional boreholes only have little increase in methane production, which are ineffective to increase the methane drainage rate (D. J. Black & N. Aziz, 2009). Drilling boreholes with high density would not gain the expected results. Drilling twice boreholes would not make the accumulative production as twice. The additional boreholes would only accelerate the methane production rate with some limits (Hower, Jones, Goldstein, & Harbridge, 2003). Before designing the borehole configuration, the methane volume and concentration of the coal seam must be estimated to ensure that the lateral space of boreholes is adequate to drain the methane (Black & Aziz, 2008b).

The lateral space of boreholes also impacts the effectiveness of the borehole drainage radius. Some previous studies indicate that the effectiveness of borehole increases with the drainage time and reach the extreme drainage radius while the drainage time reaches the threshold. If the lateral space between two boreholes exceeds the twice length of the effectiveness of borehole drainage radius, there are always some volumes of methane that cannot be drained from the reservoir whatever how long the boreholes are operated. If the lateral space of boreholes is over-low, this will result in the methane flows between boreholes, or borehole drilling failure. It is ineffective to increase the methane production rate through increasing the drainage pressure in the coal seams with low permeabilities. This is because the methane pressure in coal seams are several times of barometric pressure, it would not have more effectiveness even drain the methane onto vacuum pressure

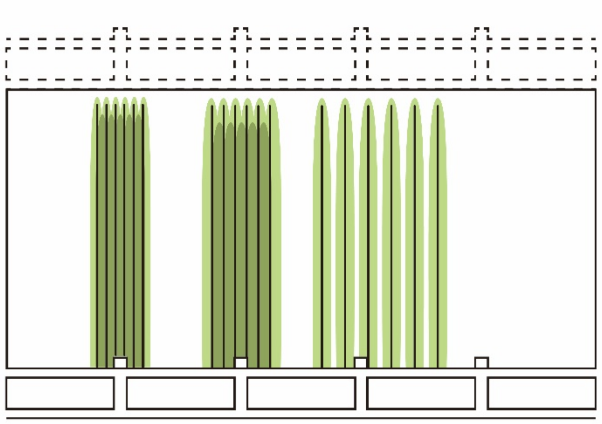

Figure 9 Lateral space of boreholes

2.3.5. Borehole length

Borehole length usually is determined by the width of the panel and the available drilling rigs. When methane drainage for a coal panel, the borehole length usually is a little shorter than the width of the panel. Some studies show that the length of a borehole usually is 150m to 1500m, and 300m is acceptable until higher demand (Palmer, 2010; Zuber, 1998). If the drilling rigs cannot drill a borehole as the length as the coal panel, boreholes can be drilled both from tailgate and headgate perpendicularly to the opposite direction, which is shown in Figure 6. If the methane drainage requires special drilling condition, then the boreholes can be drilled from the end of the coal panel, and the length of boreholes can vary from case to case.

Some previous studies claim that the length of in-seam horizontal boreholes is restricted by frictional drag forces along with the drilling holes which must be overcome. Factors that affect the frictional force include accumulative cutting force, rock and coal roughness, surrounding pressure and the total weight of the drill rigs. When the frictional force develops along the borehole drilling and over the axial force triggered by the drilling rigs, a restriction condition will occur which usually called “lockup”, and finally result in the helical buckling within the boreholes. The direction of borehole drilling and the length of boreholes significantly impact the frictional force while drilling in and pull-out of rigs (Black & Aziz, 2008b).

2.3.6. Pressure and borehole diameter

Vacuum is commonly applied to the underground methane drainage boreholes. The purpose of the vacuum is to contain the pressure in boreholes below barometric pressure hence to accelerate the methane production rate and to prevent methane leakage from boreholes into the airways. 10-15Kpa of suction pressure usually applies to the drainage boreholes. Vacuum is applied to keep a slight pressure differential in boreholes to increase the flow rate hence to promote the methane production (Zuber, 1998). Increasing the suction pressure will not increase the production rate as expected, as contrast, it will increase the air leakage into the boreholes which reduce the methane quality and effective drainage area.

Methane production rate with large diameter (150mm to 300mm) boreholes of the parallel pattern was more than 25 times that of 65mm to 75mm diameter boreholes (K. Wang & Xue, 2008). Small diameter boreholes would perform better unless it is a dry methane reservoir (Palmer, 2010). However, if the diameter of boreholes is too small, the internal pressure will lose substantially high, which results in boreholes reticulation capacity being trapped (Black & Aziz, 2008b). Although, enlarge the diameter of boreholes can obtain better performance shortly but will have little effect with long period drainage while methane drainage of in-seam horizontal borehole pattern.

2.4. Discussions and conclusion

There are some advantages of the in-seam horizontal borehole pattern, which include:

1) In-seam horizontal boreholes have more exposure to the matrix and fracture systems than vertical wells, significantly increase the flowability and conductivity and promote the boreholes production (Ren et al., 2014).
2) The methane produced from in-seam horizontal boreholes typically is pure with little contamination from air flows in working place (Zuber, 1998).
3) The in-seam horizontal borehole pattern can be eliminated CBM faster than other methods of underground methane drainage (Twombly et al., 2004).
4) The borehole configuration can be modified at any time when required.
5) In-seam horizontal borehole pattern is the most effective strategy for methane drainage while coal extraction.

In-seam horizontal borehole pattern generally involves boreholes drilled from gateroads into the longwall panel, sometimes across over the panel 15m to 50m into the next longwall panel. Boreholes are usually drilled in fan patterns to reduce the relocation times of drilling rigs. The lateral spacing of boreholes differs based on the in-seam permeability, methane content, drainage plan, and other factors. The inherent restriction of in-seam horizontal borehole pattern is that the drainage period is significantly impacted by the development condition of gateroad and coal panels. Hence, the lead time of methane drainage decreases with the increase of gateroad or coal panel development condition. This is not a big issue for those coal mines or panels with high in-seam permeabilities and low methane contents; it would not take much time to reduce the methane content below the Threshold Limit Value. However, to the coal mines or panels with low in-seam permeabilities and high methane contents, if the methane content cannot be sufficiently eliminated before the extraction of next panel, it will delay the mining plan (Black & Aziz, 2008a).

A second inherent problem of in-seam horizontal borehole pattern is how to choose drilling pattern. Because most of the mines plan to achieve more production annually if possible, coal seams and panels are extracted fast, so that usually there is insufficient time to drill and drain methane to below the Threshold Limit Valve. In some regions with high in-seam permeability and high methane content, there are many cases that show that methane content cannot be reduced adequately, which leads to production delays. Furthermore, sometimes the longwall panel is extracted while production delay, which results in the high in-situ pressure and reduces the available drainage time. In some extreme cases, mine companies cut the longwall panels shorter and discard some coal reserves instead of waiting for adequate methane drainage to avoid critical production delay (D. J. Black & N. Aziz, 2009).

These controllable factors have dramatic influences on the production ability and effectiveness of a methane drainage system include:

a) Inadequate methane drainage period prior to boreholes termination while the coal panel extraction
b) Inadequate monitoring and management of boreholes performance to recognise those boreholes with low production rate and to dispose of the accumulations of water and coal fines within boreholes
c) Inadequate monitoring and management of boreholes blockages caused by water and coal fines, which dramatically constrict the flowability within boreholes
d) Poor quality of boreholes sealing which results in methane production with a low concentration and reducing the suction pressure (Zheng, Kizil, Chen, & Aminossadati, 2017)
e) Inadequate boreholes length and sealing result in air emission into boreholes and reduce the suction pressure
f) Borehole trajectory is not drilled along with the optimum orientation to achieve the maximum performance of methane production, and
g) Boreholes drilled down-dip orientation which results in the water accumulated in the boreholes to restrict the in-hole flowability while dewatering.

Some previous study shows the methane influence theory in coal seams, indicates that:

$$Q=\pi m\lambda^{0.9}P_0^{1.85}R_1^{0.2}\alpha^{0.1}t^{-0.1}$$

Q represents to the total methane volume produced from boreholes; m represents to the thickness of coal seam; P_0 represents to the in-seam methane pressure; λ represents to the in-seam permeability coefficient; R_1 represents to the diameter of boreholes; α represents to the in-seam methane content; t represents to the drainage time.

This equation indicates that: the total methane production Q increases with the thickness of the coal seam, with the in-seam methane content $P_0^{1.85}$ and the in-seam permeability coefficient $\lambda^{0.9}$. However, the diameter of boreholes is not the primary factor impacting methane production. Methane pressure and permeability coefficient are the dominant factors impacting the total methane production.

For the future work, the CBM drainage technology should develop regard to:

a) Connecting the surface wells and the underground fractured fissures to achieve the co-drainage from surface wells and underground boreholes;
b) Developing the drilling technology and drilling rigs of underground in-seam horizontal drilling, increasing the production rate of CBM drainage, and shorten the lead time to achieve the requirement of CBM drainage;

Developing the high vacuum and high diameter borehole drainage pattern, increasing the production rate of CBM drainage by increasing the effectiveness of pressure difference

3. Chapter 3

Simulation and optimization of inseam horizontal drainage for coalbed methane production in a china coal mine

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Brief Introduction

During underground coal extraction, coalbed methane is the primary factor causing gas outburst and explosion. With the mining depth increasing, methane is difficultly controlled during panel extraction because methane content usually increases with mining depth. The traditional method for methane elimination during panel extraction is drilling in-seam horizontal boreholes to eliminate methane from coal panel to surface. However, this method is inadequately to eliminate gas content below the threshold limit value within the required period while gas content is high, or coal permeability is low. This paper optimised the general methane drainage method, which is in-seam horizontal borehole pattern, to raise the performance of methane elimination.

3.1.Abstract

Coalbed methane (CBM) emission is the primary factor which can cause mining catastrophes worldwide. Recently, with the mining depth becomes deeper, the gas content becomes higher, which leads to higher CBM emissions from the active face areas. Since ventilation cannot supply sufficient air volume to dilute and control the underground gas emission, extra solutions are needed for reducing the gas explosion risk, such as in-seam horizontal CBM drainage. In-seam horizontal drainage is used to decline the gas content of the coalbed prior to or during mining. In this paper, an inseam horizontal drainage pattern will be modelled and optimized.

3.2.Introduction

Coal bed methane (CBM), which could also be named as Coal mine methane (CMM) during coal exploitation, contributes to the coal in-seam gases with other components such as carbon dioxide and nitrogen (Flores, 1998). At present, CBM is the primary factor which has affected not only underground working safety and productivity, but also the environment conditions (Flores, 1998; Keim et al., 2011). Most of the mining outburst catastrophes were caused by methane during underground mining (Anderson, 1995; Lama, 1995; Okten et al., 1995). In the US, more than 600 mining explosions have been recorded and killed thousands of people since 1830s (Thakur et al., 2014). Additionally, in China, over 50% of underground coal mines have gas outburst-risk (FU, 2005). Over 82% of mine accidents are triggered by gas explosion in China (Yuan,2004). For avoiding these catastrophes, lots of mining industry companies have developed many technologies. Generally, methane liberates into the underground working environment during the mining process and can be diluted by a practical amount of mine ventilation during coal production (Flores, 1998). If the volume of gas-in-air proportion makes up range between 5% and 15%, it could have a prone explosive risk, so that the underground gas proportion needs to be controlled below the prescribed Threshold Limit Value (TLV), which is usually less than 1% in China (Noack, 1998). If the ventilation cannot sufficiently dilute the gas below the TLV, other options is of necessity. Most companies prefer to drain the gas content below 6 m3/t to reduce the outburst risk. Additionally, methane is also a kind of greenhouse gas that has a global warming potential 25 times greater than carbon dioxide (Stocker et al., 2013). In China, there is 13 billion m3 methane released into the atmosphere annually, 95% is from ventilation air of underground mines (Su et al., 2006). Therefore, an effective application for underground CBM emission control and CBM utilisation can reduce its footprint and minimise the environmental impacts (D. J. Black & N. I. Aziz, 2009). Today, with more advanced mining technology, minable depth of a coal seam becomes increasingly deeper, and methane content increase with burial depth of the layer, conventional solutions such as ventilation can hardly deal with such huge volumes of methane emitted from the coal seam. Hence, a crucial development and utilisation of coal mine methane draining technology are of necessity (Keim et al., 2011).

Typically, there are several technologies of methane drainage and can be divided into two types, pre-drainage and post-drainage. Pre-drainage is to drain the methane prior to mine a coal seam of a coal panel, such as vertical boreholes drilled from the surface, long length of horizontal boreholes drilled from the surface of from development, and inseam drainage. Post-drainage is to drain the methane during or after mining, such as cross-measure boreholes drilled into overlying and underlying strata, old active goaf drainage (Lunarzewski, 2001a; Su et al., 2006). The methane elimination process typically takes four steps. At first, boreholes are drilled into coal seams or coal panels. Then coal seam would be dewatering the natural fracture initially so that the reservoir pressure in the fracture system will reduce to a point which is called the critical pressure. Finally, methane would be desorbed from coal surface while the reservoir pressure is below the critical pressure and transferred into boreholes by the pressure gradient. In this study, in-seam horizontal drainage pattern will be tested by numerical simulation, because it has a good performance in coal mines which have low permeability, less than 3md (3*10-15m2) (Keim et al., 2011).

Normally, in-seam horizontal methane drainage pattern design can differ from case to case as practice globally. Boreholes are drilled from tailgate to headgate direction in a panel and then form an integrated reticulation system. There are variety borehole configurations of the in-seam horizontal drainage system, such as fan pattern, parallel pattern, herringbone branching from the primary lateral pattern and hydraulic fractures from the primary lateral pattern (D. J. Black & N. I. Aziz, 2009). Among these patterns, the parallel pattern and fan pattern are the most simple and common mode to operate. However, there is no systematic acknowledge about how different patterns influence CBM drainage ratio. In this study, several pattern models will be examined and will result in an improved strategy. There are many factors contribute to the drainage efficiency, such as coal seam property, including seam depth, coal thickness, water saturation, fracture porosity, gas content, and drainage pattern parameters including borehole length, borehole lateral spacing, borehole diameter, borehole position, borehole configuration (Keim et al., 2011; Ried, Towler, & Harris, 1992). Although some previous studies investigate the underground gas drainage system regards to these factors (Frank et al., 2013; Karacan, 2008; Karacan et al., 2007; McInerney & Brown, 2016), however, studies indicated that not all drilling effort deliver benefit to gas content reduction, and sometimes drilling more boreholes may not increase the gas drainage rate as expected. Hence, to understand the process of the in-seam horizontal methane drainage system and impacts of different drainage patterns is of significance.

In this study, a specific coal mine site (A mine), which located in Shanxi province of China, will be involved in deeply investigation. This mine site contains 469.07 Mt coal with 945.42 Mm^3 methane; maximum gas content is $12m^3/t$, which has been defined as high gassy coal mine seam (Campoli et al., 1985). As a typical coal mine, the methane content of air needs to be controlled less than 1%, which is hard to achieve without methane drainage prior to and during mine. Although traditional ventilation air from shafts could offer part of the fresh air, the volume of air intake cannot be increased without limit for remaining the underground safety. This study aims to establish an improved CBM drainage system for coal mine A. The in-seam methane must be eliminated over 45% in total before coal production. By investigating different drainage patterns and comparing the influence of related factors, the effective drainage strategy will be determined to ensure a safe work circumstance and to achieve an improved economic outcome.

3.3.Basic information and methodology

3.3.1. Mine site information

There are six coal seams within the mine site. The No.03 is the main coal seam for the primary stage coal production. The thickness of No.03 coal seam is between 0.94m to 1.02m and 1m on average. The coal reservoir is full of bituminous coal, which is bearing high-level thermal energy and considered as power coal type. In addition, the coal reservoir is considered as gassy, with about maximum 10m3/t of gas concentration in the NO.03 coal seam. Table 2 shows the summary of mine site characteristics. Due to the high level of absolute methane emission rate which may result in gas outburst, a traditional method such as enlarge ventilation cannot dilute the gas-air ratio below the safety limitation, hence in-seam horizontal methane drainage is of significance.

Before CBM drainage pattern design, the coal reservoir must be evaluated. Differing from the US coal reservoirs, most of the coal reservoirs in China has been characterized as low permeability, low reservoir pressure and high anisotropy (H. Li, 2001; Song, Zhao, Liu, Wang, & Chen, 2005; Yijun & Jianqing, 2004). In this study, a comprehensive evaluation model is used based on other studies, which is established for complicated geological and engineering diversity especially in China (Yanbin et al., 2008). This reservoir evaluation model has classified and graded several parameters. Parameters are graded into three groups including reservoir physical property, reservoir storage, and geologic characters. In this study, these parameters will be given, and the reservoir will be under evaluated

The reservoir physical property contains important factors impacting CBM production results. Permeability is the fundamental parameter. Usually, permeability can be obtained by two methods, in-place permeability test and petrological permeability test. However, although in-place permeability is the most reliable method with accuracy and reflects the real formation condition, it is hard to obtain due to applying restriction. Petrological permeability is a common method when in-place permeability is hardly to obtain. In this study, the permeability of coal mine A is estimated by petrological permeability method.

Table 2 Summary of mine characteristics

Mine Location	Central of Shanxi Province in China
Mine Area	33.59km2
Coal Seams	6 minable seams
Mining Type	Longwall Mining
Panel Dimensions	180*1800m
Mine Classification	Gassy mine
Existing Drainage System	None

Reservoir storage capacity can be determined by gas content and reservoir pressure. Gas content can be obtained by both in-place tests or calculated by Langmuir volume (Moore, 2012; Ziarani, Aguilera, & Clarkson, 2011). In this study, gas content and Langmuir curve are gained from the library test. The gas content of the target coal panel is 10m3/t as measured. In addition, the gas pressure is also tested directly as in situ parameter, which is 0.4MPa in target coal seam. In addition, Geologic characters involve coal lithotype, coal structure, macerals composition, coal rank, and coal quality. In the target coal seam, as tested by coal specimen, the coal lithotype is clarain, vitrinite accounts for ranging from 57.7% to 88.9% by volume and inertinite ranges between 10.2% and 26% by volume. Moreover, as prospected and estimated, the coal rank of targets coal seam is 85.44Mt, and seam thickness is ranging from 0.94m to 1.02m.

3.3.2. Methodology

For investigating CBM production performance impacted by different in-seam horizontal methane drainage patterns, the numerical simulator is an important tool. There are three steps during simulation, creating a geological structure grid, building in CBM drainage patterns, finally outputting results. In this study, a 3D numerical model simulation is used, The Petrel E&P software platform brings disciplines together with best-in-class applied science in an unparalleled productivity environment (Manual, 2007). As the industry looks to accelerate reserves replacement and boost recovery in difficult reservoirs, increasing productivity is essential. The Petrel platform supports automated, repeat chart workflows, to capture best practices. The primary coal exploitation panel will be chosen as the main target during this simulation. In this simulation, a 33*180*1m grid size is determined to simulate the coal reservoir considering the repeatability of the whole coal panel.

In the target coal seams, inseam horizontal drainage pattern will be used to exploit methane from underground. This method drills drainage boreholes through coal seams or panels then form an integrated network system. This network system involves several important parameters, including borehole configuration, borehole length, borehole diameters and lateral borehole space. Any change of each parameter will result in a different gas production rate under the same geological condition. The borehole configuration is the most important factors which could impact the drainage performance. In this study, parallel pattern and fan pattern will be tested while other parameters and conditions are constant. Parallel pattern includes two types, including borehole drilled from tailgate to headgate, and from both sites to each other. The latter pattern is designed as the plan of A mine site as the original pattern. This design is restricted by the maximum drilling depth of rigs. Fan pattern also can be named multi-lateral pattern, is drilled in one point then disperses into several boreholes. Usually, fan pattern has tri-laterals and qual-laterals. In this study, these patterns will be investigated the performance and then compared.

During this simulation, at first step, the original methane drainage pattern based on coal mine methane drainage plan will be investigated the performance. In the primary exploitation coal panel of the No.03 coal seam, boreholes arranged to be drilled from tailgate into headgate direction and from headgate into tailgate direction as perpendicular to tailgate and headgate with 95m borehole length. The boreholes would be inter-crossed. The lateral borehole spacing is 3m. The diameter of each borehole is 113mm. Boreholes will be drilled 0.6m height above the underlying strata. Due to 1800m development length of working face, there will be 1200 boreholes in the primary coal extraction panel. The drainage pressure in borehole is -18kPa. The estimated CBM drainage duration is 270 days. This borehole configuration is shown in Figure 10. Table 3 and Table 4 show the summary of CBM project characteristics and important parameters for reservoir simulation. After the original pattern simulated, the boreholes configuration will be optimized based on the result of the first simulation. Hence, the configuration design, especially the lateral space and borehole configuration will be improved to achieve the safety requirement.

Table 3 Summary of CBM project characteristics

Study area description	Shanxi Block	Lateral Spacing of Boreholes	3m (original plan)
Study area size	23.7Km2	Borehole length	95m (original plan)
Coal seam dip angle	< 15 degree	Borehole Operation	In-seam pipeline
Target coal seam	No.03 Coal seam	Drainage Pressure in Borehole	-18kPa

Estimated GIP, Seam	55Mt

3.4.Simulation Results

In this study, the lateral space and borehole configuration are optimized to achieve better performance of CBM elimination. At the first step, the original pattern is simulated, the boreholes configuration is shown in Figure 10. As calculated, the accumulative methane production accounts for around 71% at 270 days, which achieve the target of at least 45% of methane elimination. However, although the original pattern may achieve the methane elimination target, it over-exceeds the elimination requirement. And this may result in high commercial waste, because of the high expenditure on drilling more additional boreholes and maintenance. Hence, the lateral space of the boreholes should be optimized. In this study, simulations at 9m, 6m and 4m lateral spaces without any other change are applied, the Figure 11， Figure 12 and Figure 13 shown the configurations with 9m, 6m and 4m lateral spaces, respectively. Figure 14 shows the cumulative results of parallel patterns, and Table 5 shows the cumulative production-total borehole length ratio. The cumulative production-total borehole length ratio is of significance because it can avoid the impact of the reservoir shape toward the borehole configuration. As can be seen from chart 2, the 6m lateral space of boreholes is the best choice because it achieves the 45% of methane elimination and also saves the budgets of boreholes drilling and maintenance.

Table 4 Input Parameters of the Reservoir simulation

Coal Seam Depth (m)	-598m	Langmuir Pressure (MPa)	0.4

Coal Seam Thickness, Average (m)	1m	In situ Gas Content (m^3/t)	10
Coal Density	1.40t/m^3	Cleat Permeability (mD)	1
Methane Content Gradient	1.98m3/t/100m	Porosity (Matrix)	0.95
Initial Reservoir Pressure	0.4Mpa	Porosity (Fracture)	0.05
Initial Cleat Water Saturation (fraction)	1	Sorption Time (days)	270

Table 5 Methane production per meter of parallel pattern boreholes

Lateral space of parallel pattern	Methane production per meter of boreholes
9m	27.21 m^3/m
6m	24.48 m^3/m
4m	20.93 m^3/m
3m	21.19 m^3/m

In the next step, fan patterns are simulated, which based on the results of parallel patterns. Fan pattern 1 has three laterals with 3m lateral space. Fan pattern 2 has five laterals with 3m lateral space. Fan pattern 3 has three laterals with 6m lateral space. Fan pattern 4 has three laterals with 4m lateral space. The boreholes configurations are shown in Figure 15, Figure 16, Figure 17 and Figure 18, respectively. Figure 19 shows the cumulative production results of fan patterns. The fan-2 and fan-4 have a similar production performance. So that, another parameter, the methane production per meter of borehole length will be compared, which is shown in Table 6 The methane production per meter is $16.65m^3$ of fan-4 pattern, which has a better performance than the fan-2 pattern.

Table 6 methane production per meter of fan pattern boreholes

fan pattern	Methane production per meter of boreholes
Fan pattern 1	15.08
Fan pattern 2	13.78
Fan pattern 3	21.03
Fan pattern 4	16.65

As comparison of the parallel patterns and fan patterns, although the fan pattern has less heads of boreholes to manage, it still has some demerits during methane elimination. the boreholes of fan pattern may collapse during borehole drilling, and the methane may fluid between holes rather than drained into pipelines during methane elimination. As to the design parallel pattern, because the boreholes are inter-crossed, they will be drilled to connect to both side due to improper borehole drilling. At the final step, the parallel pattern 3 will be refined to cut the length of each borehole to avoid the connection of boreholes. Figure 20 shows the final borehole configuration of parallel pattern, and Figure 21 shows the simulation result of the final parallel pattern. The accumulative elimination of methane accounts for 46% in total within 270 days, which achieves the production requirement.

3.5.Conclusion

The in-seam horizontal drainage system for coal bed methane elimination is of importance for 1) improving the underground safety, 2) reducing the methane elimination into the atmosphere, and 3) saving the energy fuel. This study constructed the original CBM drainage design by using a 3D reservoir simulator and then optimized the design of boreholes configuration. The basic conclusion of this numerical simulation can be summarized as follows:

- Accumulative methane production increases with increasing of drainage time. Among the parallel patterns and fan patterns, the original design of boreholes configuration has the highest CBM production, while the Final Parallel pattern with 6m lateral space and 90m per borehole length is the best choice for an economic reason and basic requirements.
- Although the accumulative production of CBM increases with the number of boreholes and increases with the total length of boreholes, the accumulative production cannot get expected value. After achieving the critical point, the increased volume of CBM drainage would gradually drop with the increase of boreholes.
- The fan pattern has fewer heads of boreholes which need to maintain during CBM elimination. However, the boreholes of fan pattern are easier to collapse than that of the parallel pattern — the closer to the head of boreholes, the closer of lateral space of boreholes. The boreholes would be connected close to tailgate and headgate, and the methane would cause fluid among boreholes, which reduce the CBM production rate.
- The original design of borehole configuration involves inter-cross of both sides of boreholes, which may result in an improper connection between boreholes during drilling. The length is optimized into 90m to fit the width of the longwall panel.

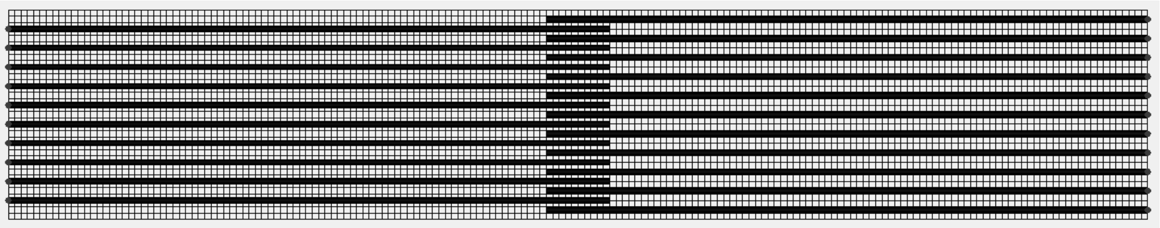

Figure 10 Parallel pattern 1 with 3m lateral space

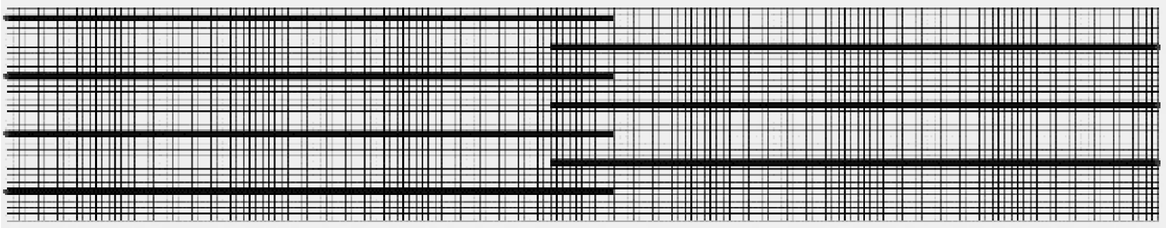

Figure 11 Parallel pattern 2 with 9m lateral space

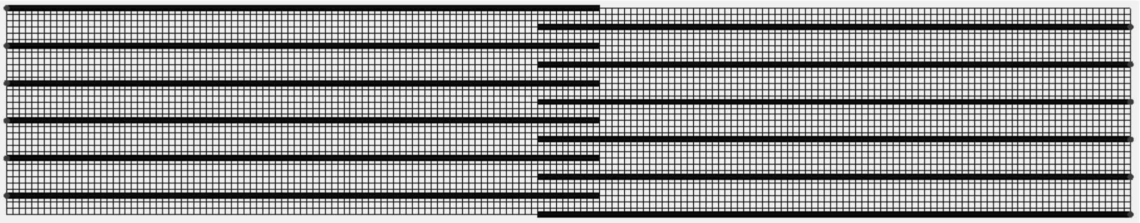

Figure 12 Parallel pattern 3 with 6m lateral space

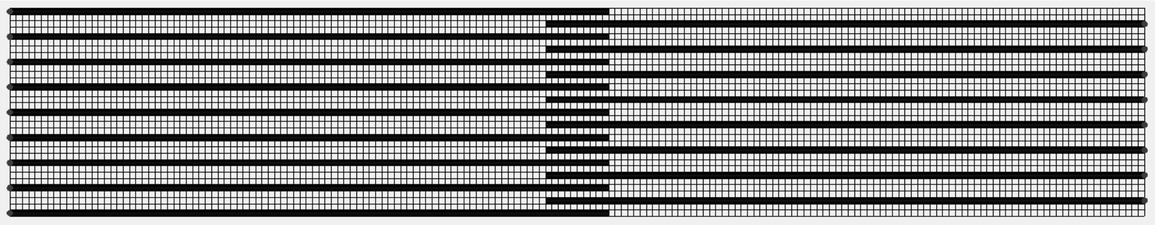

Figure 13 Parallel pattern 4 with 4m lateral space

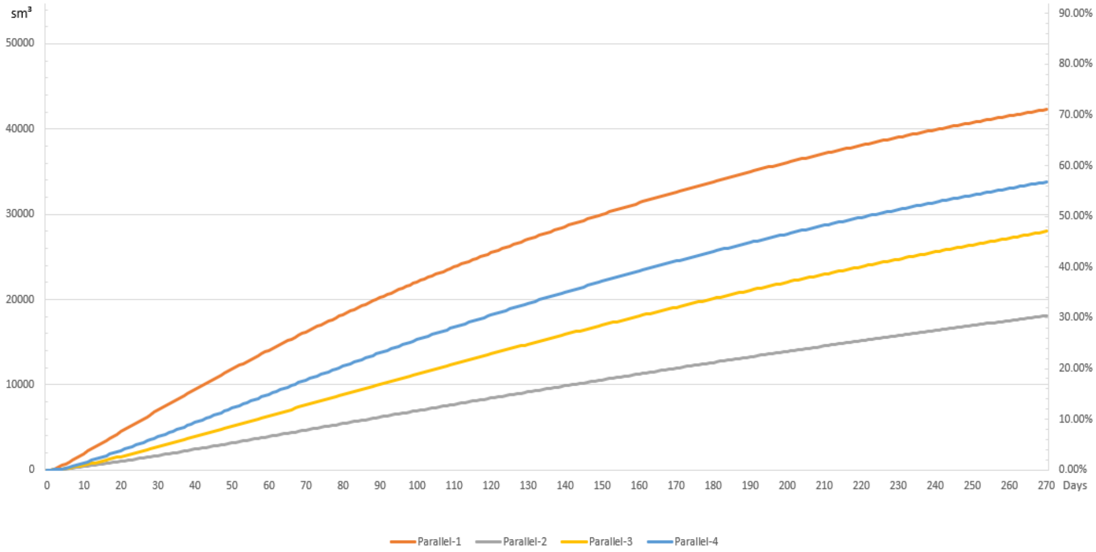

Figure 14 Cumulative production of parallel pattern

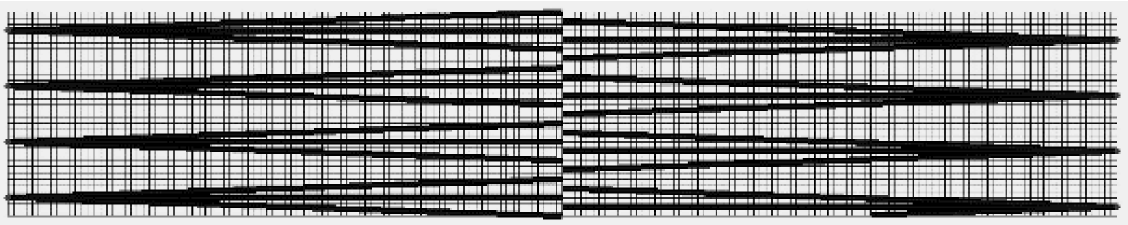

Figure 15 Fan pattern 1

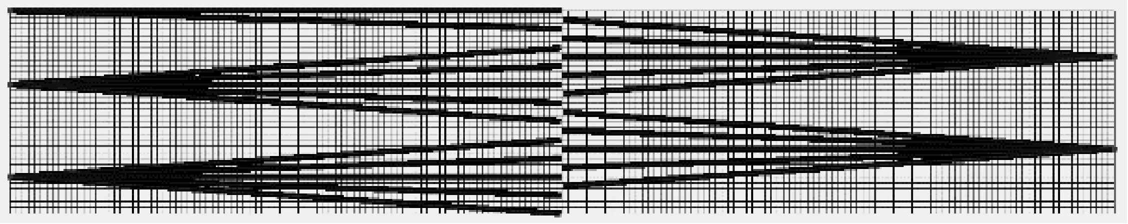

Figure 16 Fan pattern 2

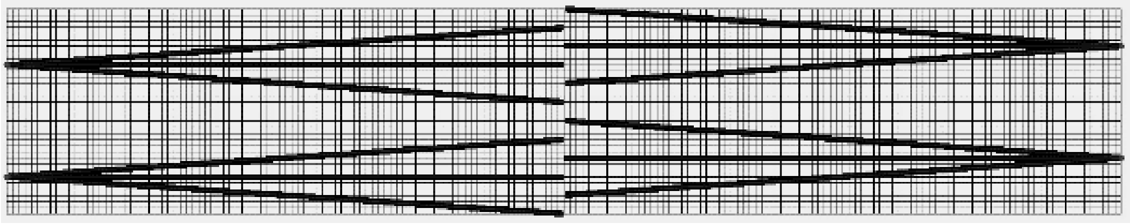

Figure 17 Fan pattern 3

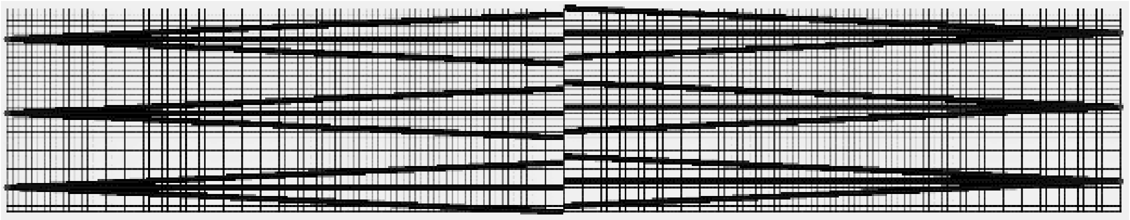

Figure 18 Fan pattern 4

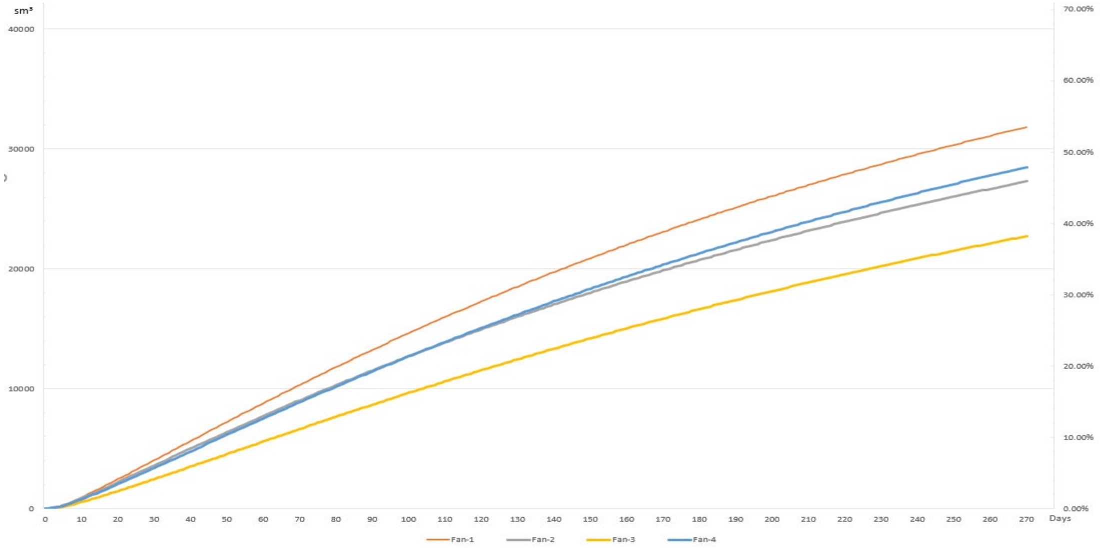

Figure 19 Cumulative production of fan pattern

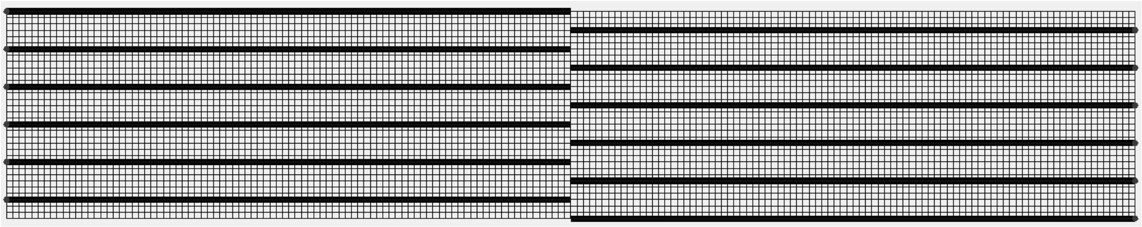

Figure 20 Final parallel pattern

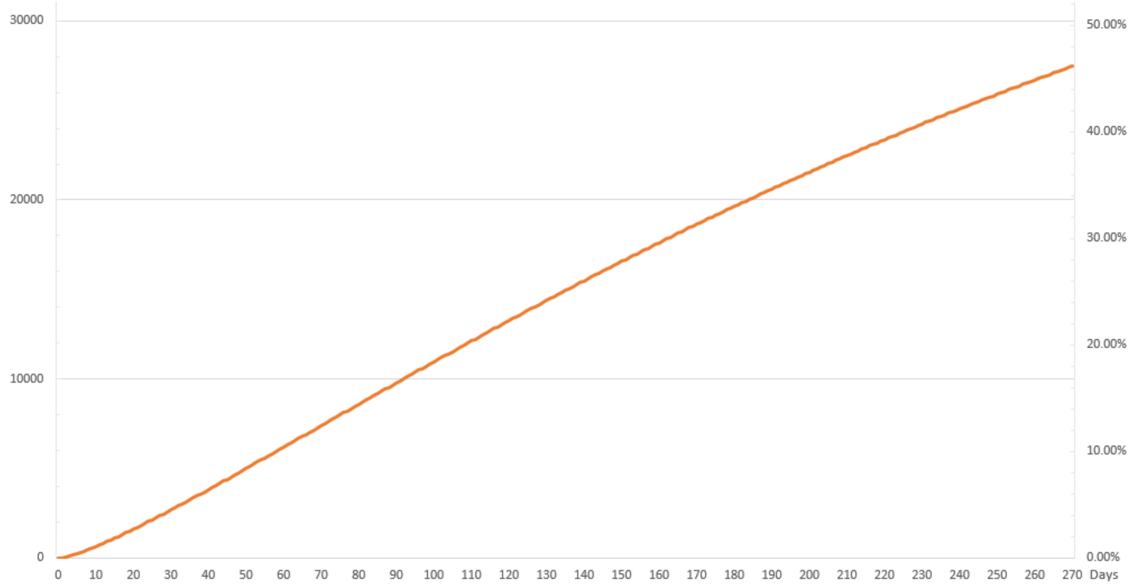

Figure 21 Simulation result of final parallel pattern

4. Chapter 4

Mechanism analysis of uncovering coal in crosscut and gas outburst based on Flac3D

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Brief Introduction

With the increase in mining depth of crosscut, the rate of gas outbursts is increasing, posing a vital threat to safe production. In China, 80% of the gas-related accidents occur in the course of uncovering coal in crosscut. As a result of coal and gas outbursts, the plastic zone penetration is a significant factor which caused by high-pressure gas storage and excavation disturbance. The mutation of velocity, displacement and stress in the potential outburst area are sufficient conditions for the occurrence of major disasters. This paper contributed to research value and engineering significance for the preliminary work of CBM control in underground.

4.1. Abstract

Gas outbursts occur frequently in the process of uncovering coal in crosscut, so it is of great significance to study the outburst conditions of coal and gas in the process of tunneling. By establishing the model of these gas outbursts, we can obtain the function of the thickness of stone gate, gas pressure and gas outburst. With or without high pressure gas, the impact of high pressure gas during gas bursts is analyzed through the numerical simulation method. Based on the velocity, displacement, maximum principal stress and time curve of coal and rock interface in the center of roadway under two kinds of working conditions, the main conditions of gas bursts have been successfully verified. According to the results, in coal and gas outbursts, necessary conditions include the plastic zone penetration caused by high pressure gas storage and excavation disturbance, while sufficient conditions include the mutation of velocity field, displacement field and stress field in plastic zones.

4.2. Introduction

With the increase in mining depth of crosscut, the frequency of gas outbursts is increasing, posing a great threat to the safe production. In our country, 80% of the accidents occur in the course of uncovering coal in crosscut. Coal and gas outburst is an extremely complicated phenomenon encountered in underground coal mining. However, in the outburst model, uncovering coal is one of the most common patterns (Fan, Zhang, Wang, & Chen, 2017; Li & Lin, 2010; Shining, 1990).Therefore, it is very important to analyze the factors in an gas outburst. A great deal of research has been done on the mechanism of coal and gas outburst by scholars both home and abroad. Using self-developed RFPA2D system, Tang Chun'an and others(C. Tang, Liu, & Liu, 2002) have analyzed the comprehensive effect of in-situ stress, gas pressure and mechanical properties of coal; using the folding catastrophe model, Tang Jupeng and others (J. Tang, Ding, Yu, & Lu, 2018) found the relation between critical effective stress and coal surface area and introduced the notion of effective stress; Xu Jiang and others(Jiang Xu, 2012) believe that the stress level change in stress-concentrated area plays an important part in coal and gas outburst. Polish scholar Sobczyk, J. et others (Skoczylas, 2012; Sobczyk, 2011) studied the relationship among uniaxial compressive strength, gas pressure and outburst risk by using two-dimensional loading test equipment. Bodziony, J. and others (Bodziony, Nelicki, & Topolnicki, 1989) studied the effect of porosity upon outburst velocity through simulation tests of coal and gas outbursts. Yin Guangzhi and others (Yin, Li, Jiang, Li, & Cai, 2010) simulate delayed outbursts under the constant vertical and horizontal stress by using the self-developed "large scale coal and gas outburst simulation platform". Results show that the outburst strength reflects the failure degree of delayed outbursts, which is positively correlated with critical gas pressure and negatively correlated with ground stress. Zhang Chunhua, Gao Kui and others (Kui, Ze-gong, & Jian, 2015; ZHANG, Ze-gong, & Jian, 2013) have performed similar simulation tests on outbursts, and acquired the law of mechanical properties of "tectonic inclusion". However, in terms of rough process description, the influence of structural factors still remains unclear. Preliminary research suggests that the main external factors are the influence of mining stress, while internal factors include the structure of coal body, the firmness of coal body and the gas occurrence pressure. Further clarification is the key to predict and prevent coal and gas outbursts.

4.3.Model of gas outbursts induced by uncovering coal in crosscut

In the process of seam exposure, the stress equilibrium of the original stratum is destroyed and the stress in the coal body redistributed. In general, in the short formation of mining spaces, higher stress is formed near the interface of the mining space. When the stress value reaches its limit, the first part of the coal body will yield and deform. The stress propagates to the deeper part of the coal body, after which form the pressure relief zone, the stress concentration zone and the original stress zone. The stress concentration area can be divided into plastic and elastic deformation zones, as shown in Figure 22.

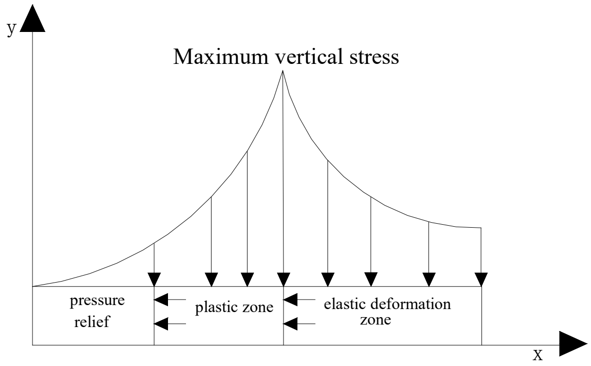


Figure 22 Stress distribution in coal body in front of working side

The complex phenomenon of stress wave propagation is generated in coal seam. Sparse wave may cause outbursts, but the internal factors of outbursts are still gas pressure and coal strength in coal seam. In order to study the distribution of gas pressure in the ultimate equilibrium zone, we may make the following assumptions:

（1）In the limit equilibrium region, the flow of gas is one-way, the adsorption and desorption of gas in coal are basically in equilibrium state, and the gas flow accords with Darcy's law.

（2）In the limit equilibrium, the coal body is homogeneous and isotropic, the permeability coefficient K of coal body changes from the negative exponent equation with the change of distance x, which satisfies the following empirical formula:

$$\mathrm{K} = \mathrm{K}_0 \mathrm{e}^{-\mathrm{bx}} \qquad （1）$$

The permeability of K-coal seam in formula （1）is m2 ； When K0——x=0, and the permeability coefficient of coal；b-empirical constant

On the basis of the above assumption, when gas penetrates through the coal body in the limit equilibrium zone, the gas pressure acting on the direction of mining space can be obtained from the ration flow equation.

$$q = \frac{AK}{\mu p_n} p \frac{dp}{dx} \qquad （2）$$

In the equation:

q——Flow rate of gas on 1m2 coal surface, （0.1MPa，t ℃），m3/(m2•d)；

μ——Gas absolute viscosity，Pa•s，take μ=1.08×10-6 Pa•s；

p_n——Atmospheric pressure，0.1Mpa；

p——Gas pressure at position x, MPa；

dp——Pressure difference within DX length，MPa；

A——Unit conversion correction coefficient.

In the limit equilibrium region, due to the effect of concentration stress, the coal body is compressed enormously and the permeability coefficient reduced. The change of permeability coefficient is the function of the distance of coal seam surface. According to the second assumption mentioned above, $\mathrm{K} = \mathrm{K}_0 \mathrm{e}^{-\mathrm{bx}}$. When coal gas permeability changes, the gas flow per unit in area is:

$$q = \frac{-AK}{\mu p_a} e^{-bx} p \frac{dp}{dx} \qquad （3）$$

$$\frac{q \mu p_a}{AK_0} e^{bx} dx = -pdp \qquad （4）$$

$G=\frac{q\mu p_a}{AK_0}$, substitute it into（4）to obtain：

$$-Ge^{bx}dx=pdp \qquad (5)$$

The differential equation can be obtained by solving the equation 5):

$$p=\sqrt{\frac{2G}{b}(1-e^{-bx})} \qquad (6)$$

Formula (6) is the gas distribution equation in the limit equilibrium region. In fact, because the coal is porous medium, the gas pressure p has only the n part action to exert on the roadway direction. According to Hododt's study, for the continuum with voids, the n value is close to the porosity. For the multi-space dispersive medium consisting of deformable spherical particles and closer to the actual coal mass, its n value can be calculated with the following formula:

$$n=\frac{1-bh}{1-3h^2}-n_0 \qquad (7)$$

In formula（7）h——The height of the spherical solitary body is (equal to the degree of flattening); n_0——porosity of coal.

As a result, the gas pressure acting on the roadway direction is as follows:

$$\mathrm{p}=\sqrt{\frac{2\mathrm{G}}{\mathrm{b}}(1-e^{-kx})} \qquad (8)$$

Judging from formula（8）we can see：The smaller the x value is, the thinner the pressure zone is, so it is easy to penetrate. The greater the gas pressure gradient is, the greater the danger that the unloading zone will be broken through. Therefore, the breakthrough of plastic zone is closely related to high gas pressure, an important factor in coal and gas outbursts.

4.4.Numerical simulation analysis of gas outbursts

Using the FLAC3D software, the distribution map of plastic zone of coal and rock mass is respectively obtained under the condition of no gas (0 MPa) and 3MPa. In roadway excavation and coal uncovering, when the thickness of coal is 4 m, 2 m and

0 m, the distribution of the plastic zone of coal and rock mass is obtained. The influence factors of gas outburst should be further analyzed.

4.4.1. Analysis of 4m plastic zone and gas outburst in crosscut

Figure 23, Figure 24 and Figure 27 show the distribution of plastic zone of coal and rock mass when the thickness of crosscut is 4 m, 2 m and 0 m under the condition of no gas (0 MPa) and high gas pressure 3 MPa.

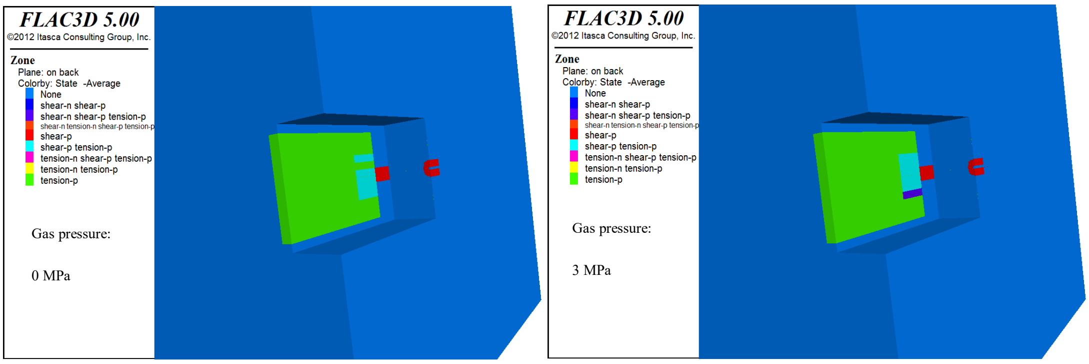


Figure 23 Distribution of plastic zone of surrounding rock of roadway under different working conditions with 4 m thickness of coal in crosscut.

As shown in Figure 23, under the action of high-pressure gas, when the uncovering thickness is 4 m, there is no obvious plastic yield in the roadway section.

4.4.2. Analysis of 2m plastic zone and gas outburst in uncovering coal in crosscut

By using Flac3D software, we can see that when the thickness of uncovering coal in crosscut is 2 m, the plastic zone distribution of surrounding rock of roadways is as in Figure 24.

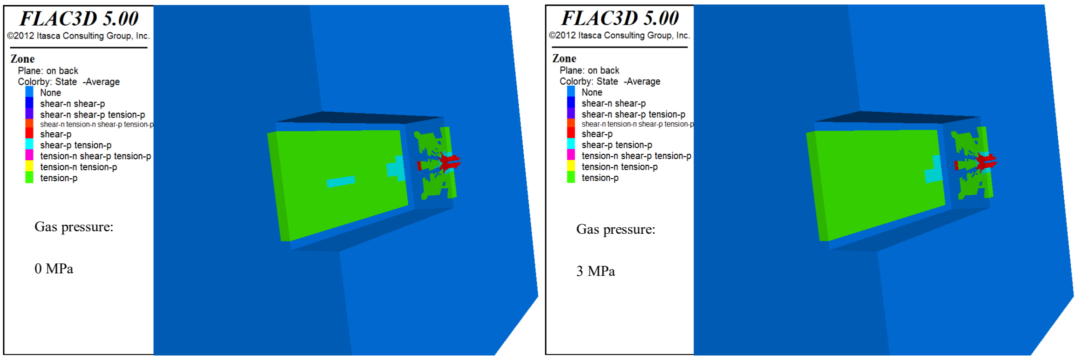
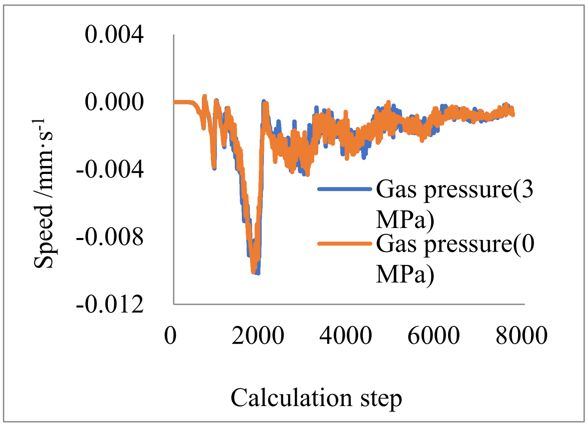


Figure 24 Distribution of plastic zone of surrounding rock of roadway under different working conditions with 2m thickness of uncovering coal

As shown in Figure 24, when the thickness is only 2 m, plastic yield occurs in the 70% section of the roadway, regardless of whether there is high pressure gas in the coal seam. Moreover, the distribution of plastic zone is basically the same under two working conditions, so if the plastic zone penetration is taken as the prominent index, the outburst may occur at this moment.

Therefore, when the thickness of uncovering coal in crosscut is 2 m, the variation of velocity, we analyze displacement and maximum principal stress at a certain monitoring point at the center of coal / rock interface roadway under the condition of no high pressure gas (0 MPa) and high pressure gas (3MPa). Thereby it is clear that gas outburst is caused by stress redistribution after exposing coal or under high gas pressure. Then we obtain the speed and displacement of monitoring point and the curve of maximum stress, as shown in Figure 25 and Figure 26.



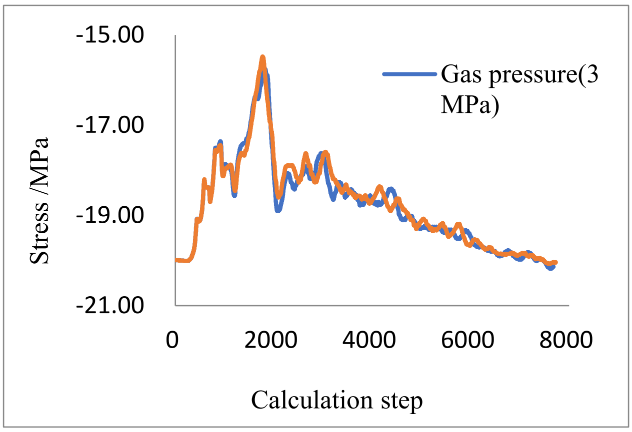


Figure 25 the variation curve of velocity and displacement with calculation step at the interface between coal and rock in the center of roadway

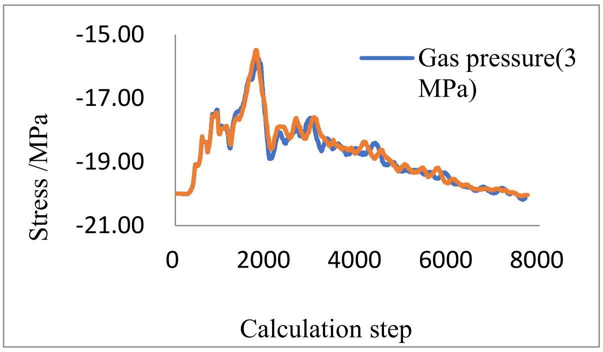


Figure 26 the maximum principal stress variation curve at the coal-rock interface in the center of roadway during coal uncovering in crosscut

As shown in Figure 25 and Figure 26, the mechanical response of the roadway center is monitored by curve. Furthermore, when the thickness of uncovering coal is 2m, the calculated steps are basically consistent with the curves of the velocity, displacement and maximum effective stress of monitoring points, with or without high pressure gas. When the calculation model converges, the monitored velocity time history curve almost coincides with the horizontal axis, and the velocity is close to 0. This indicates that a 2m thick stone gate can guarantee the stability of rocks surrounding the roadway. Although the displacement curve of the monitoring position increases with the augmentation of the calculation step, the curves under two working conditions coincide completely. The displacement is the result of stress redistribution caused by the tunnel excavation, not by high gas pressure. Moreover, the effective stress under these two conditions can be restored to the initial state when the model converges, proving that no outburst happens when the thickness of the stone gate is 2 m.

4.4.3. Analysis of plastic zone and gas outbursts with 0 m coal uncovering thickness

In order to further explore the main cause of outbursts, software simulation reanalyzes the plastic zone distribution of rocks surrounding the roadway excavation when the thickness of uncovering coal is 0 m, as is shown in Figure 27.

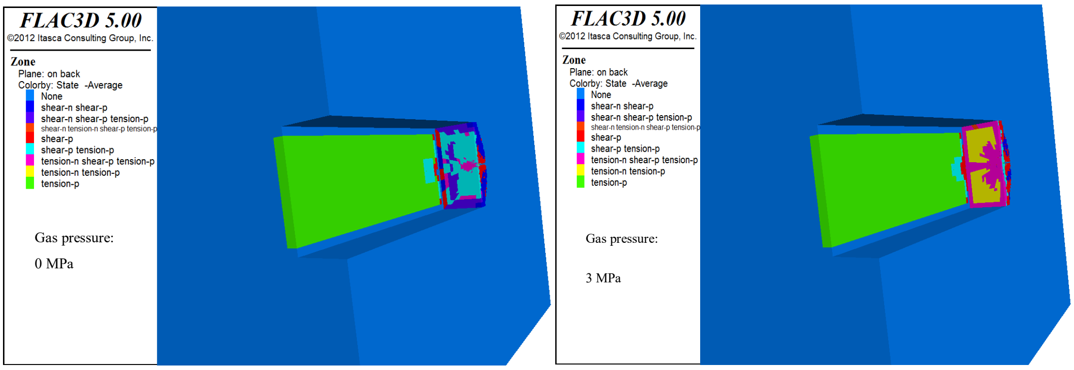


Figure 27 Distribution map of surrounding rock plastic zone of roadway under different working conditions with the thickness of uncovering coal of 0 m

At this time, the thickness of the stone gate is 0 m, or full exposure of the coal body. It can be seen from Figure 27 that under two different working conditions the coal body of the excavated surface is basically in a state of plastic yield. Moreover, the distribution area of plastic zone under high pressure gas is slightly larger than that without gas. Therefore, it is preliminarily indicated that the gas pressure of coal seam has an increasing impact upon the plastic zone of coal body. Moreover, it indicates potential gas outbursts when the gas bearing coal seam is completely opened while uncovering coal.

In order to verify the accuracy of the above theory, we retest and reanalyze the velocity, displacement and maximum principal stress of the monitoring point at the center of the coal / rock interface roadway when the thickness of uncovering coal is 0 m, obtaining the velocity and displacement of the monitored point. The curves of the maximum stress are shown in Figure 28, Figure 29 and Figure 30.

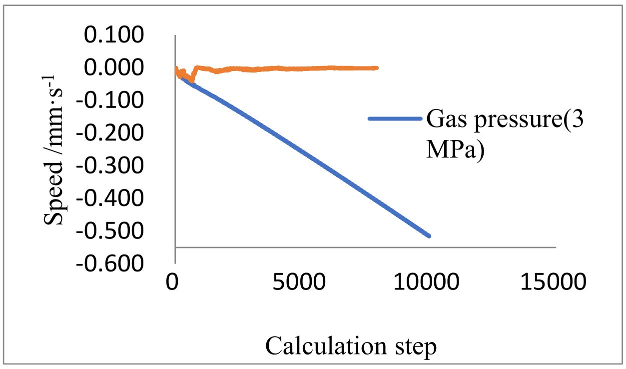


Figure 28 Velocity variation curve at coal-rock interface in the center of roadway during coal uncovering in crosscut

The velocity-calculation time curve in Figure 28 shows that when the uncovering coal is completely opened, the velocity of gas-free coal seam almost almost remains unchanged when calculation steps increase, and the velocity amplitude is close to zero. However, the velocity of gas seam monitoring points under a high pressure of 3 MPa increases linearly with the augmentation of calculation steps and shows a trend of non-convergence. Therefore, combined with the distribution pattern of plastic zone under 3MPa high pressure gas, it can be judged that an outburst of gas-bearing coal seam has occurred.

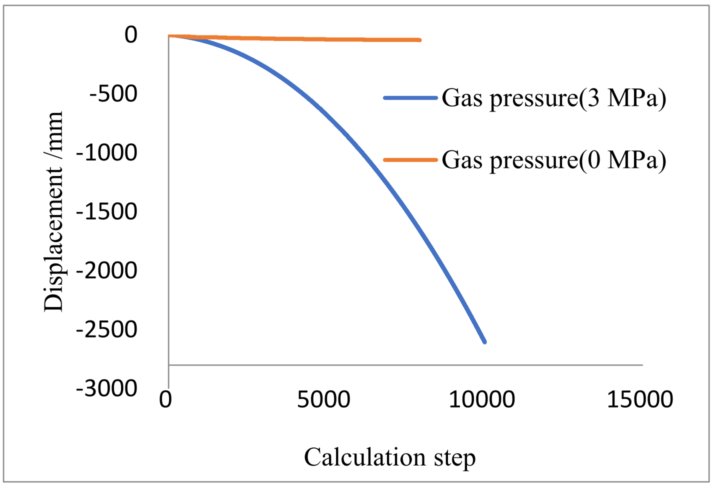


Figure 29 Displacement curve of coal and rock interface in the center of roadway during coal uncovering coal in crosscut

The law of velocity in Figure 29 is similar to that in Figure 28. From the displacement time curve given in Figure 29, the displacement with high pressure gas presents a trend of nonlinear increase with the increase in calculation steps, and the displacement gradient becomes larger and larger. Therefore, when the thickness of uncovered coal in crosscut is 0 m, there is no outburst without gas, but the disaster has already occurred under high pressure gas containing 3 MPa.

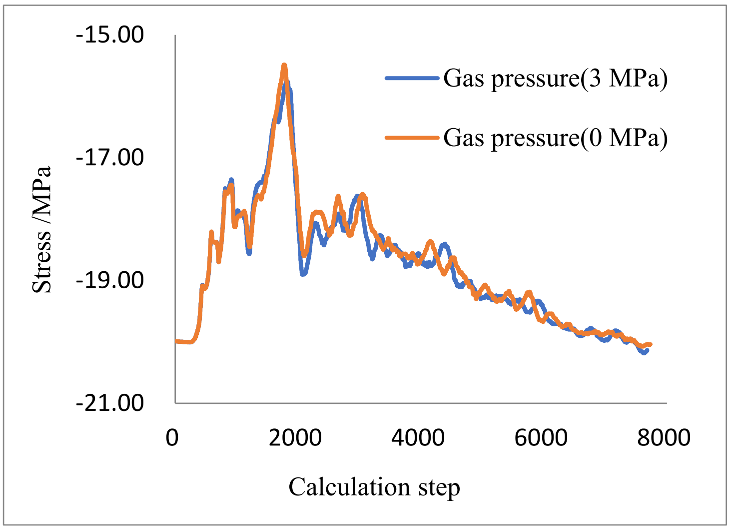


Figure 30 Maximum principal stress variation curve at coal-rock interface in the center of roadway during coal uncovering in crosscut

The time curve of effective stress in Figure 30 further shows that when coal is completely exposed, the largest main force of the gas-free coal seam (0 MPA) passes through about 5000 steps before the coal body reaches the tensile strength and enters into the plastic yield state. The maximum effective stress of the coal seam containing rich gas reaches the tensile strength in an instant, which indicates the occurrence of coal and gas outbursts.

We have summed up as follows by the numerical simulation analysis of whether there exists high pressure gas of uncovering coal: Gas under high pressure and the penetration of plastic zone caused by excavation are the necessary conditions for coal and gas outbursts. The mutation of velocity field, displacement field and stress field in plastic zone are the sufficient conditions for the occurrence of outbursts. In practical engineering, the monitoring of information before excavation should be strengthened, so that scientific and reasonable technical measures be taken in advance in order to minimize major disasters in the process of uncovering coal in crosscut.

4.5.Conclusion

a) The plastic zone generated by excavation disturbance and the original high pressure gas are the necessary conditions for the occurrence of dynamic disasters of coal and gas outburst. The mutation of velocity, displacement and stress in the potential outburst area are sufficient conditions for the occurrence of major disasters.

b) In practical engineering, we should strengthen the monitoring of physical and mechanical parameters and geological structure of coal and rock mass in advance, and take adequate technical measures so that coal and gas outburst should be reduced or even eliminated to the greatest extent.

c) Through the comparison and analysis of coal and gas outbursts induced by the breakthrough of plastic zone and the original high pressure gas, the prediction outbursts is improved. This has contributed a lot in terms of research value and engineering significance for guiding rational and scientific coal excavation while ensuring safe production.

4.6. Acknowledgment

This work was financially supported by the National Science and Technology Major Project (Grant No. 2016ZX05067).

5. Chapter 5

Conclusion and Future Work

Conclusion

This thesis includes a series of research papers and reviews paper which aims to establish a better understanding of in-seam horizontal boreholes for methane drainage. As methane is drained more effective, any production delays and the rate of gas-relative catastrophes are reduced.

In the first paper, there are two necessary factors had been found out which can cause dynamic disasters of coal and gas outburst including the plastic zone generated by excavation disturbance and the original high-pressure gas. The mutation of the velocity field, displacement field and stress field in plastic zones are adequate for the occurrence of primary disasters. By the comparison and analysis of coal and gas outburst induced by the breakthrough of the plastic zone and the initial high-pressure gas, the prediction of outburst is enhanced. This has devoted to guiding rational and scientific coal excavation while remaining a safe production environment.

The second paper is optimizing the original methane drainage pattern for a particular coal mine in China. Under the same conditions of underground structure and drilling rigs, optimizing the parameters of drainage pattern can significantly increase the performance of methane drainage. The original drainage pattern was designed based on the experience and drainage plans applied at nearly coal mines. Due to the high gas content and low permeability conditions, the original drainage pattern would insufficiently eliminate the methane to a safety level within the required duration. Moreover, as the boreholes drilling rigs are not changeable, the length of boreholes is unextendible. Optimizing the boreholes configuration, lateral space of boreholes and the boreholes orientation can achieve a better performance of methane drainage. Through the numerical simulation, an optimized drainage pattern is gained and achieves the required goal of methane elimination.

The third paper is a review of the application of in-seam horizontal boreholes pattern for methane drainage worldwide. An integrated pattern involves six primary parameters including boreholes length, boreholes configuration, boreholes orientation, lateral space of boreholes, leading time, and drainage pressure. Within these parameters, the leading time has the most influence to impact the accumulated volume of methane drainage. However, the leading time usually is restricted by the mining plan. Normally, a panel is drained only within the life of a panel extraction. A longer leading time would result in coal production delays then impact economics. Boreholes length is constricted by the drilling rigs. The Lateral space of boreholes, boreholes configuration and boreholes orientation are more controllable for engineers to optimize the methane drainage pattern. Also, parameters can be regulated for any special requirement. It is of importance to understand how parameters affect the performance of methane drainage.

Limitations and Future Work

Although this thesis researches the influences of several parameters of in-seam horizontal boreholes and presents a method to optimize the pattern to achieve better performance, there are still some aspects that need to be improved.

The optimizing method primarily aims to solve methane drainage problems within pre-developed coal panels. The shapes of panels are usually regular, which is easy to organize boreholes pattern. Methane drainage of irregular panels requires special organization. Besides, the normal in-seam horizontal boreholes pattern is not good at draining methane from coal seams with low permeability. Optimizing the parameters of this pattern can hardly increase the methane permeability in coal seams.

For solving this problem, there are other methods to increase the permeability such as injecting nitrogen or water into the fractures of coal seams. This method can enlarge the old fractures and make new fractures, which can promote the transition process from adsorbed methane to free-state methane and increase the fluidity of methane.

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