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Study of Hydraulic Slotting Technology for Rapid Excavation of Coal Seams with Severe Coal and Gas Outburst Potentials

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Abstract: For coal seams susceptible to serious coal and gas outburst, numerous problems and issues, such as the low excavation speed and serious security risks, exist during the process of outburst prevention. Through on-site examinations, this study analyzes the effect of hydraulic slotting measures on changes in the coal-bearing assemblages and gas status and reveals the involved mechanisms that hydraulic slotting measures are applied to deal with coal and gas outburst. This study further proposes the rapid excavation technology with supporting equipment designed and integrated and establishes a comprehensive security system with hydraulic slotting as the core of the entire system. Therefore, the goals of achieving hydraulic slotting operated unattended to avoid personnel injury, implementing coal and gas control technology are achieved. The results of on-site examination indicate that the excavation speed using the proposed method could be two times faster than the excavation speed when boring and drilling method is applied and thus the goal of safely and efficiently carrying out excavation work in coal seams with severe coal and gas outburst potentials is realized.

Key words: Coal and gas outburst, hydraulic slotting, water jet, protection system, prevention measures

INTRODUCTION

Coal and gas outburst represents one of the most severe natural disasters within coal mines. It is a dynamic phenomenon accompanied by loud sound and violent force, which often manifests itself in the form of quick ejection of coal (rock) and gas towards the excavation working face during the process of excavation within coal mines (Yu *et al*., 2004; Litwiniszyn, 1985; Gray, 1980). In China, coal and gas outburst represents the major disaster that has plagued the effectiveness and production safety of coal mining enterprises. In particular, China ranks number one in terms of the number of gas outburst events and the frequency of gas outburst each year. Meanwhile, mortality rate caused by gas accidents remains high. For example, among all large-scale mining accidents with more than ten casualties during the years 2000-2009, deaths caused by gas accidents account for 79.9%. Since 1949, 22 major accidents related to gas outbursts have been reported, with more than 100 casualties for each accident, accounting for 91.67% of total reported accidents. Also, seven major accidents related to gas outburst events have been reported since 2003, with more than 100 casualties for each accident as well. For example, the major gas explosion accident trigged by coal and gas outburst on October 20, 2004 claimed the lives of 148 employees in Daping Coal Mine in.

Zhengzhou Coal Group and caused a direct economic loss of 39.357 million RMB. Also, the major gas explosion event on November 21, 2009 claimed the lives of 108 employees in Hegang Coal Mine and caused a direct economic loss of 56.146 million RMB. This series of shocking accidents imposed huge negative impacts on the economic activities of the entire country and the lives of local people.

Based on the statistical analysis of outburst occurrence locations, the majority of outburst events happen in coal excavation working face, which account for 66.2% of all outburst events, with an average intensity of 66.9t/times (Yu, 1992; Liu *et al*., 2007). The high frequency of outburst events during the process of coal excavation has become the major threat that endangers the life safety of working personnel. Meanwhile, the complicated excavation procedures, the long-term construction process and limited time in effective excavation have led to slow excavation speed and thus seriously constrained coal production. According to related survey, borehole drilling ahead of emissions

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remains the most common local prevention practice in China during the process of coal excavation, with an average excavation speed as 40 m per monthly only and a serious imbalance of excavation proportion. Especially, borehole drilling is difficult to carry out within coal outburst seams and events such as collapse and orifice occur frequently during the process of borehole drilling, resulting in short drilling distance, small drainage and relief coverage range and slow excavation speed. For many mining wells with severe outburst potentials, the excavation speed could be limited to 30-40 m per month only.

In order to effectively prevent the occurrence of coal outburst, borehole drilling ahead of emissions, shallow holes blasting, deep holes blasting, high-pressure water injection, gas pre-pumping gas and associated measures, together with comprehensive outburst prevention measures, have been applied and proved effective for some cases (Yu and Wang, 2002; Li, 1998; Fu, 2005; Lu and Liu, 2006). The major problem of bore drilling prevention measures lies in that when working staff is put in the hazardous environment with high potentials of coal and gas outburst, once the outburst event occurs, high-energy coal gas flow is bound to impact human body and thus causes suffocation and burying accidents.

Hydraulic slotting measure is a new technology that has been applied in recent years in China for outburst prevention purpose and this technology is based on the principle of hydraulic punching outburst prevention measures (Wei *et al*., 2008; Xue, 1998; Liu *et al*., 2005, Wang and Fang, 2007). The major step is the application of high-pressure water jet before carrying out excavation work. Because a number of holes with relatively large diameters are formed in coal seams by high-pressure water jet, which allow the emission of large amount of gas and the discharge of certain amount of coal so that pressure within certain regions would be released and the occurrence of coal and gas outburst might be avoided. The entire process of hydraulic slotting measures is about the breakdown of coal body by high pressure jet, the release of large amount of gas and the change of stress state of coal seams. The breakdown of coal bodies starts with the crushing of coal seams with high-energy high-pressure jet so that small-diameter grooves could be formed. Then, under the influence of coal and gas pressure gradient and the reflected residual energy of the jet, surrounding coal bodies could be further crushed to form grooves wit large diameters. Due to the destruction of stability in the upper groove of coal grooves, rectangular groove holes could be formed substantially under the combining effect of hydraulic and gravity force.

This study considers outburst prevention mechanism of hydraulic slotting measures as the core of entire system and on-site examinations of hydraulic slotting coal deformation patterns, fracture distributions, gas emission characteristics and pressure change status are carried out to summarize hydraulic slotting procedures and explore gas outburst prevention mechanism. Also, based on the characteristics of coal deformation and gas emission during the hydraulic slotting process, factors that might induce the occurrence of coal and gas outburst are identified and a comprehensive prevention system is proposed and tested on-site in Jiaozuo mining area.

PROCESS OF HYDRAULIC SLOTTING MEASURES

Systematic equipment for outburst prevention measures

Water supply pumps: According to the physical properties of local coal, DG150-130×12 water pumps are used with motor speed as 2980 r min^{-1}, motor power as 1250 KW, pump rated flow as 2.5 m^3 min^{-1} and rated pressure was 20 Mpa.

Water gun: Selected SQ-type water gun was made by Tangshan branch of Coal Research Institute. According to the hardness of local coal, muzzle with the size range of 10 to 20 mm is chosen.

The water guns are installed in front of the excavation workface 500-1000 mm ahead and the layout parameters are: The angle between the near middle line and the middle line is 0 and so is the angle between the waistline and the middle line, with an inclination of 2°C. High-pressure water flow is producing impact force on coal walls for 25-30 min. Based on reading values displayed by installed gas concentration monitor, the validation check process starts when gas concentration drops down to 1%.

Hydraulic slotting parameters: DG150-130×12-type water pump is used with motor speed of 2980 r min^{-1}, motor power of 1250 KW, pump rated flow of 2.5 m^3 min^{-1}, hydraulic slotting pressure of 20 Mpa and the diameter of gun muzzle as 10~20 mm.

Hydraulic slotting technique: When the excavation workface is undergoing hydraulic slotting measures, the gun is fixed in the center of the tunnel and with the same direction as the center line. Also, the gun is put 2-3 m ahead of the coal body and 1.7 m distance from the roof board. After the gun has been fixed, all working personnel are required to stay inside of the refuge chamber and the operation of high-pressure pump for hydraulic slotting work could start then. After the operation of the pump for

4 min, pump pressure and flow amount could reach 16~20 Mpa and 2.5 m^3 min^{-1}, respectively. The slotting process ends 20 min later. In the case of Yanmazhuang Mine (beneath the seam roof there are soft coal layers of 0.5~0.6 m thick with the false roof as thick as 0.2~0.3 m), cave grooves with a height of 1 m, a width of 1.2 m and a depth of 15~20 m could be formed after hydraulic slotting process. Similarly, soft coal layers represent the major structure of the whole cross-section of Jiulishan Mine. As a result, the height of formed grooves could be as high as 2 m that is similar to the height of related tunnels. Also, the corresponding width is about 3.6 m and the depth is between 10 and 15 m.

Excavation work: SGW40T conveyor scraper conveyors are commonly selected for transportation purpose. Part of the scraper conveyors are designed as leaky tank bottom so that they could play dehydration function during the process of coal transportation. According to the safety requirements for the excavation of coal seams and the relatively low levels of mining machinery and equipment in Jiaozuo mining area, blasting excavation strategy has been chosen specifically so that long-distance blasting is possible without much equipment investigation.

After hydraulic slotting process is finished, gas could then be released. About 2 to 4 h later, clean-up operations are done within the working face and it usually takes about 6-10 h to finish such clean-up operations. After then, the effectiveness of used measures is evaluated. If such measures are proved effective, long-distance blasting and excavation work could start. In the case of large cross-section groove cave, only 1 to 2 boreholes with a depth of 1~2 m could help facilitate the following extension work. On the other hand, if the groove cave is small, then the size of blasting drill holes should be decided based on the shape of the groove cave under study.

Roadway support: Construction trials are compared when either bolting support or steel shed support is applied. Under similar geological conditions, because steel shed method requires larger materials and longer excavation time compared to the bolting method, the latter is preferred so that the integral of the roof board could be maintained. However, when the roof board is not intact, intensive steel shed is required for support purpose.

After hydraulic slotting and blasting events, temporary stands need to be installed timely to help protect the top part. Hydraulic cylinders with steel frame are used to build temporary stands, which have the beam length as 2.2~2.4 m and pillar type as DZ 2.2~2.5. A beam with two or three columns is commonly used with 3~4 full cross-sections.

After hydraulic slotting measures have been applied for excavation purpose, two approaches are taken for roadway support. One is steel shed support approach with supporting specifications as 2.6×2.6 m, roadway height as 2.2 m, cross-section area as 6.6m^2 and shed spacing as 0.5 m. Another is a combination of anchor net and steel ladder method. During the hydraulic slotting process, temporary stands are set up first and anchor net is then installed following the construction specification of 0.5 m $shed^{-1}$.

Advanced distance measures: After hydraulic slotting measures have been applied onto the excavation working face, in order to ensure the operational safety of the next cycle, each cycle needs to retain 5 m advanced distance measures. To ensure that the events of coal and gas outburst would not occur during the excavation process, this advanced distance is retained so that excavation work would not affect this specific zone. The gas pressure is kept below 0.7 Mpa within this zone and 5 m distance from the outside interface of the roadway. Therefore, gas concentration within this zone is 13 m^3 t^{-1} or less. The pressure within coal bodies is released and corresponding stress is not obvious. But if we take into account the effect of the size of groove cave cross-section and roadway support, the advanced distance is smaller when the size of the groove cave cross-section is larger.

Hydraulic slotting measures are used to prevent outburst accidents from occurring. This is because when high-pressure water flow through the water gun, high-energy steady-state flow jet is generated and then applied to break down coal bodies in the front. Within 13~20 min, a deep groove cave is formed with a width of 800~1200 mm, a height of 1.2~1.7 m and a depth of 10~22 m. After the hydraulic slotting process ends, coals from the upper and lower part of the groove caves are fully unloaded. Meanwhile, high amount of gas is released and the physical and mechanical properties of coal bodies are also changed. When the relief groove has a sufficient height, the stress could redistributed, gas pressure could be further lowed down and thus gas could be further transported away from the roadway. According to the coal rheology theory, once the coal belt is formed to lower down pressure and release gas, the outburst risks could be alleviated or even eliminated.

Due to the high strength of hydraulic slotting measures, the size of holes is usually 0.8×1.2 m or above, accounting for over 10% of entire excavation sections. The coal body is fully unloaded and gas is completely released. Within the control range, the effective stress that coal body could withstand redistributes and the loading pressure of roof boarder changes. In other word, the loading pressure increases. Consequently, the advanced distance becomes very large, which means safety risks potentially exist due to hollow roof and overhang events that could easily lead to the failure of support function.

During the hydraulic slotting period, more than 100 trials were carried out. When the area of groove cave cross-sectional is greater than 1m^2, outburst events did not occur within the advanced distance of 0~3 m. However, when the area of groove cave cross-section is 0.3 m^2 with an advanced distance of 1.5 m, one outburst event occurred during the process of blasting and the amount of coal outburst was 30 t.

The analysis based on the emission of gas, the effective radius of groove caves and the stress distribution around groove caves within 2000 m excavation roadway during the trial period shows that under current coal seam conditions in Jiaozuo mining area, when the hydraulic slotting area is less than 1.0 m^2, a 5 m advanced distance should be retained. When the supportive effect of roof board is considered, if the hydraulic slotting area is more than1.0 m^2 but less than 2.0 m^2, the advanced distance should be retained as 3.0 m. When the hydraulic slotting area is more than 2 m^2, the advanced distance should be retained as 1.0 m.

Specifications of groove cave: When both soft coal and hard coal are present together, the soft coal is found in the upper coal seams with a thickness of 0.5~1.2 m. Usually, the entire soft coal layers are taken out in irregular rectangle shape. When the entire cross-sections consist of either soft coal or hard coal, the shape of groove caves is usually circular. Due to the gravity of coal bodies, the events of coal body collapse could be found near the roof board and thus the upper part of the circular cave is flattened. If the structure of hard coal layers is clear (layered), the bottom part of the circular cave could also be flattened. However, under circumstances that when the location of 8 h groove cave is lack of support, the bottom of the groove cave and associated side parts would undergo deformation process.

ON-SITE TESTS OF THE PREVENTION MECHNANISM OF HYDRAULING SLOTTING MEASURES

Determination of the effective relief range of groove caves using displacement method: Effective range tests were done in the 22041 roadway excavation working space of Yanmazhuang mine after hydraulic slotting measures were conducted, with coal f values ranging between 0.6 and 0.8. Drilling holes and measuring points were arranged as shown in Fig. 1, there were totally 4 drilling

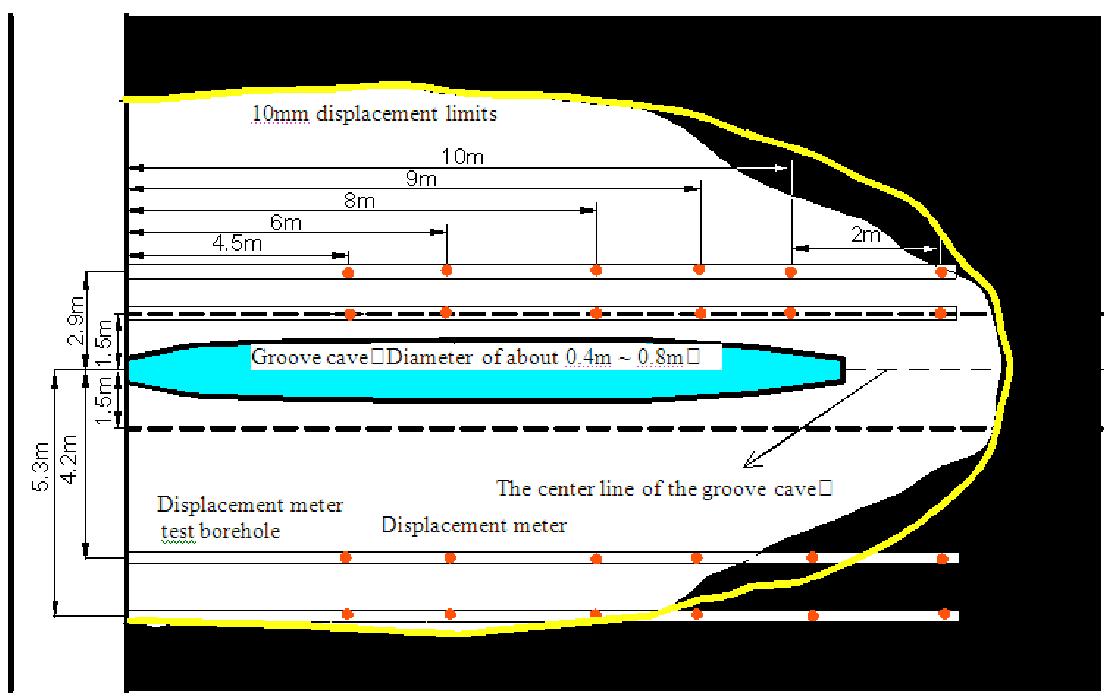

Fig.1: Hydraulic slotting coal displacement tested layout and pressure relief range

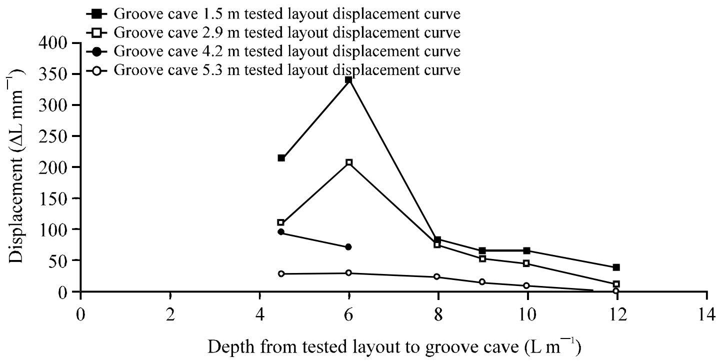

Fig. 2: Layout displacement curve after the hydraulic slotting tested

holes and 20 measure points. The slotting water gun was 2.5 m distance from the coal body and 1.1 m from the roof boarder. A groove cave with size of 0.8×0.8×10 m (width×height×depth) was formed after hydraulic slotting practice. The entire practice lasted for about 20 min with water jet pressure as 16 Mpa and flow volume as 2.5 m^3 min^{-1}. Two hours later after hydraulic slotting practice, the displacement level of each measured point was tested and the displacement status of all measured points with different depth within drilling holes was shown in the following figure.

It can be seen from Fig. 2 that the displacement level was below 350 mm after the hydraulic slotting practice. Along the depth direction of the hydraulic slotting measures, the displacement level was relative large within 4.5-6 m range, but gradually decreased afterwards. The displacement was within 50 nm range when the measured points were either 1.5 or 2.9 m distance from the center line of the groove cave. Also, the displacement was longer than 10 nm when the range was over 2 m depth of slotting groove. Therefore, the effective range of hydraulic slotting measures was within 2 m distance from the bottom of the groove cave. If 10 mm was used as the threshold value that evaluates the effective range of hydraulic slotting measures, along the direction that was perpendicular to the depth of slotting grove, the effective range was approximately around the range of 2.9-42, or 1.4-2.7 m distance from the contour lines of the roadway. In this figure, the 10 nm displacement zone could be considered as the effective relief zone after hydraulic slotting measures are taken.

Displacement method determination of the effective relief range using borehole gas flow measurement: During the daily forecast process of coal and gas outburst events, the amount of gas emission from drilling holes (initial emission speed) is an important parameter and prediction index of coal outburst risks, with its value and variation patterns depending on the physical and mechanical properties of coal, coal seam gas content, coal seam gas pressure and the stress-strain state.

During the Implementation of hydraulic slotting measures, with the formation of groove caves, the steady state of coal and gas surrounding groove caves is destroyed; the closed fissures are forced to open to absorb gas, with the occurrence of communication and movement activities. Therefore, gas emission process from drilling holes locally would be affected and the corresponding emission amount would vary significantly before and after hydraulic slotting work. The effective influence radius of hydraulic slotting measured could be determined by testing changing amount of gas emission.

The influence radius of hydraulic slotting measures is measured by drilling flow method, with the layout of drilling holes and test procedures shown as following:

- Drilling holes are set up along the two sides of the roadway with certain distance from the center line. The diameter is 42 mm and the hole depth is 8~9 m. The distance between each drilling hole and the center line of the roadway is measured
- Polyurethane is used to seal each drilling hole and the depth of sealing hole should be 2 m or above than that of residual groove cave from last loop. Also, the length of measuring chamber should be no less than 1 m
- After the drilling holes are sealed, the amount of gas flow through each drilling hole should be recorded immediately and the measurement should continue every 10 min
- During the process of hydraulic slotting measures, the initial and ending of slotting process should be recorded. Meanwhile, the change of the amount of gas flow through each drilling hole over time should be measured as well

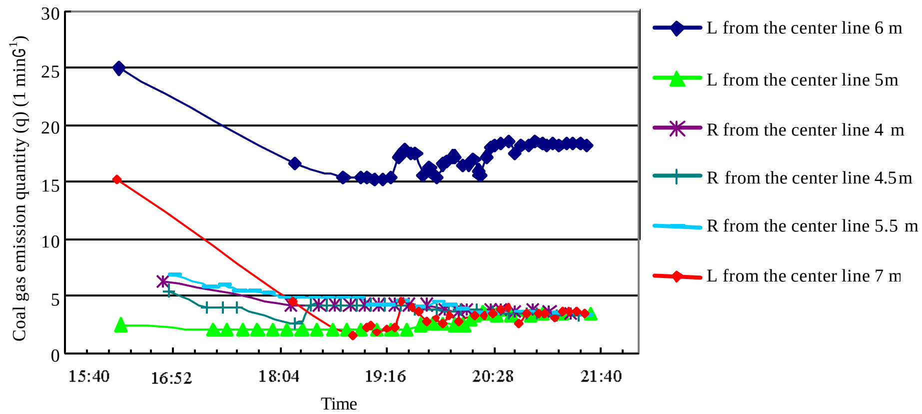

Fig. 3: Method of coal gas emission quantity research on the radius of validity effect using the hydraulic slotting in 24011 haul road. The groove cave width×height×depth is 2×1.5×9 m

- Gas flow amount within each drilling hole should be measured every 5~10 min within 2 h of hydraulic slotting process. Also, the curve of gas flow amount from each test hole should be plotted
- If gas flow amount from each test hole is 10% higher for three consecutive measurements, it is considered that these test holes are within the effective influence range of hydraulic slotting measures. Therefore, the maximum distance between the test holes and the center line of groove cave is referred as the effective radius of hydraulic slotting measures

In accordance with the inspection method, the effective influence radius of hydraulic slotting measures is tested during the trial period in Yanmazhuang mine roadway 22041 and 22011, with the results shown as follows:

It can be seen from Fig. 3 that within the influence range of the groove cave, gas flow amount from drilling holes significantly increases somewhere along the center line of the groove cave. According to the judgment index, the maximum influence range within the two sides of the roadway is about 5~5.5 m, which is 3~5 times of the width of the groove cave.

In sum, it could be concluded based on displacement measurement, plastic destruction zone calculation and gas flow amount estimation that hydraulic slotting measures could generally cause obvious displacement of coal body within 4~4.5 m range around the groove cave. Under this influence, the relief and loose level of coal body could be 3.0~5.3 times of that of the groove cave.

The statistics regarding roadway excavation in Jiaozuo mining area show that when conventional prevention measures are taken, the occurrence of roadway outburst is around 4~6 times for an average excavation distance of 4000 m. However, when hydraulic slotting measures are taken in the Jiaozuo mining area during the trial period, the occurrence is just two times for an excavation distance of 2000 m. One occurrence event occurs during the process of inspection the operation safety of hydraulic slotting measures and another occurs during the operation period (the excavation face encounters geographic faults and all coal seams are softy layers. After drilling work, severe outburst event occurs. To ensure construction safety, hydraulic slotting measures are taken afterwards). Judged from the occurrence frequency for every excavation distance of 1000 m, the application of hydraulic slotting measures doesn’t decrease or increase the occurrence frequency of outburst events.

CONCLUSION

Hydraulic slotting technology is proposed to deal with coal and gas outburst problem during the excavation process with ancillary equipment explicitly considered as well. The aim is to solve the quick and safe excavation issues in regions with sever outburst potentials and to provide technical basis for the safety operation within coal wells with severe coal and gas outburst potentials and for the sustainable development in these regions.

A comprehensive security system with hydraulic slotting technology as core of the entire system is established to server the purpose of ensuring the absolute security for working personnel under catastrophic environment, to realize hydraulic slotting work with unattended operation, to ensure the safety and efficiency of coal seam operation.

The feasibility of hydraulic slotting measures onto the prevention of coal and gas outburst is tested in Jiaozuo mining area. The results show that after hydraulic slotting prevention measures are taken, the excavation speed is greatly improved compared with conventional methods such as high-pressure injection and advanced borehole drilling. Actually, the speed could be enhanced two times or more.

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