Analysis of Existing Research on Permeability Improvement Technologies for Gas-rich and Low-permeability Coal Seams and Design of the Technical Plan for Integrated Hydraulic Pressure Relief and Permeability Improvement

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Abstract

There fully aware of the grave situation of gas disaster management in China, the authors point out that the current gas drainage technologies fall short of the demand of gas prevention and control. According to the “three lows and one high” features of gas-rich and low-permeability coal seams in China, the authors hold that the theoretical and technical research on coal seam pressure relief and permeability improvement is the right way to achieve standard gas drainage. After systematic introduction of the research and application of permeability improvement technologies for gas-rich and low-permeability coal seams in China, and analysis of the advantages, disadvantages and applicability of various technologies, the authors suggest researchers to explore integrated hydraulic pressure relief and permeability improvement technology based on regional gas control.

Keywords: gas-rich coal seams, low permeability, coal and gas outburst, pressure relief and permeability improvement, stress distribution.

1. INTRODUCTION

I since the turn of the century, China’s coal mining industry has developed rapidly. The coal production rose from 1.1 billion tons in 2001 to 3.7 billion tons in 2013. However, every silver lining has a cloud. In the same period, 52,329 people died in 30,487 fatal mining accidents across the country. Among them, 16,936 fatalities were caused by 3,985 gas accidents, taking up 32.4% of the total number of fatalities. The data show that coal mine gas disaster still poses a great hidden threat to work safety in coal mines. Apart from insufficient work safety management, the root cause lies in backward gas drainage technology, which is not enough to prevent gas accidents.

The overall gas drainage rate is pretty low because most of coal fields in China feature complex geological structure and low coal seam permeability. In over 95% of outburst mines in China, the permeability coefficient of mineable coal seams is as low as 0.04~0.004 m²/(MPa²·d) (Wang and Liu, 2005). As the permeability coefficient stays below 0.1 m²/(MPa²·d), it is very difficult to drain gas from the coal seams. Gas-rich and low-permeability coal seams are characterized by “three lows and one high”, namely low pressure, low permeability, low saturation and high heterogeneity. Low pressure leads to insufficient air flow driving capacity, low permeability hinders the formation of a broad desorption-diffusion-percolation cycle around drainage boreholes, while low saturation is the combined effect of a series of factors, such as temperature, pressure and surrounding rock. All these features make it immensely difficult to carry out gas drainage in gas-rich and low-permeability coal seams (Cheng et al., 2009). Long-time theoretical research and practical experience demonstrate that protective layer mining is an effective way to relieve pressure and improve permeability in eligible coal seams. However, it is very difficult to promote gas drainage through permeability improvement in single coal seam of high gas content and low permeability and long-distance coal seam group (Hu and Zhao, 2012). Therefore, this paper mainly analyzes the progress of the research on permeability improvement technologies for gas-rich and low-permeability coal seam in China, and designs the integrated hydraulic pressure relief and permeability improvement technology.
2. EXISTING RESEARCH ON PERMEABILITY IMPROVEMENT TECHNOLOGY FOR GAS-RICH AND LOW-PERMEABILITY COAL SEAMS IN CHINA

In China, the first gas drainage operation took place in 1938, when Fshun Mining Bureau successfully carried out gas drainage in worked-out section of Longfeng Mine. Since the founding of the PRC, researchers have developed various pressure relief and permeability improvement technologies according to local geological conditions, and widely applied these technologies in coal mining. The main technologies are drilling (reaming), deep hole blasting, hydraulic cutting and hydraulic fracturing. Despite the progress, researchers of gas drainage and permeability improvement technologies are facing with an embarrassing situation in which theory lags behind technology and technology lags behind engineering practice (Chen and Zhao, 2012).

2.1 Drilling drainage

As an effective measure to prevent outburst, advanced drilling is widely used. To a certain extent, the increase of borehole diameter and borehole density can reduce the tangential stress and increase the radial cracks of the coal mass around the borehole, thereby improving the gas drainage rate of the coal mass. According to the percolation theory of Academician Zhou Shining, after drilling drainage has been carried out for a period of time, the gas flow tends to be stable. In this case, the gas flow Q of the borehole mainly depends on the gas pressure and permeability coefficient of the coal seam, which is directly proportional to the 0.2-th power of borehole diameter. Therefore, expanding borehole diameter can effectively increase gas drainage, but only in the short term. During intensive drilling, sticking and borehole crossing is likely to occur due to the huge amount of work. As numerous problems emerge in the construction process, the technology of intensive drilling cannot significantly improve permeability. It can only be used as an outburst prevention measure under certain conditions (Sun et al., 2012). Use FLAC3D software to simulate and analyze the stress distribution of surrounding rock mass with different depths, diameters and number of boreholes and different rock stress conditions. The results indicate that the surrounding pressure relief area is not large as the borehole is relatively small, and that stress concentration occurs between the boreholes in intensive drilling, which should be eliminated by expanding the effective impact area of boreholes with further pressure relief and permeability improvement measures.

2.2 Deep hole blasting permeability improvement technology

To improve permeability, deep hole blasting permeability improvement technology releases coal mass stress and increases coal seam porosity by creating cracks and rupture zones on coal mass around blast holes with the blasting stress wave and the dynamic pressure of denotation gas, coupled with the gas pressure in the coal seam. By the process, deep-hole blasting permeability improvement technology can be divided into four types: deep hole loosening blasting, deep hole cumulative blasting, deep hole pre-split blasting and gas explosion permeability improvement (Zhai et al., 2011).

Wu Dingzhou conducts numerical simulation of the loosening blasting process of low-permeability coal seams with RFPA2D-Flow solid-gas coupling system. The results show that the drainage quantity of the drainage hole and the gas pressure both drops significantly, but the effective drainage time is short. It is necessary to improve gas drainage by increasing drilling diameter, and improving borehole density. Shang Dengying carries out a deep hole cumulative blasting experiment at Songshuzhen Coal Mine, and analyzes the drainage effect of the technology. With the combined effect of the jet flow and explosion energy, deep hole cumulative blasting prevents excessive grinding of coal mass, increases the number and depth of coal fractures in specific directions, and forms a broad fracture network. Through numerical simulation analysis of deep-hole pre-split blasting, Liu Zegong holds that the technology is an effective solution for gas drainage in gas-rich and low-permeability coal seams.

Thanks to the progress in coal mining, drilling and blasting, the deep hole pre-split blasting technology has been widely applied, particularly in mines with high potential of rock burst, coal outburst and gas outburst. The technology has been put into use by the following entities: Hebi Coal Industry Group, Tiefa Coal Industry Group, Fuxin Coal Industry Group, Yima Coal Industry Group, Shanxi Lu’an Coal Mining (Group) Co., Ltd., Pingdingshan Tian’an Coal Mining Co., Ltd, Xinwen Mining Group Co., Ltd, Jiaozuo Coal Industry Group, Huainan Mining Group, Huainan-Zhejiang Coal Power Co., Ltd., Shenhua Group Co., Ltd., Guizhou Pannan Coal Development Co., Ltd, Zhengzhou Coal Industry Group, and Chongqing Tianfu Mining Bureau (Wang, 2012).
However, these entities also encounter many problems during the application. For example, the cartridge cannot be recharged for blasting, the sticking and blowout issues affect borehole formation rate, the charging process falls short of the requirements of deep hole blasting, and the explosion energy does not reasonably acts on permeability improvement process. These factors restrict the application of deep-hole blasting. Moreover, as a large number of coal mines in China enter the phase of deep mining, further study and demonstration are needed to judge whether the lessons learned in deep hole blasting of middle and shallow mining still apply to the high stress condition in deep mining.

2.3 Hydraulic permeability improvement technologies

When hydraulic technologies are used, the water has a two-fold effect on the coal seam: one is “suppression” effect, and the other is “dredging” effect. The suppression effect comes from the technology called coal seam water injection. As it moistens the coal mass, the water suppresses gas desorption and blocks the gas migration channel, and thereby removes dust, increases plasticity and prevents outburst. However, the technology has little effect on permeability improvement. The dredging effect comes from such technologies as hydraulic cutting, hydraulic fracturing, hydraulic slotting and hydraulic flushing. The water is used to drive fracturing or cutting, which damages the stress state of the coal mass and increases the permeability of the coal seam.

2.3.1 Hydraulic cutting pressure relief and permeability improvement technology

Similar to the pressure relief and permeability improvement technology of protective layer mining, hydraulic cutting cuts out cracks of a certain length in the coal seam so that the coal mass collapses and the stress is redistributed. With the increase in the number and scale of cracks, the coal seam will have a better permeability. As a relatively mature technology, hydraulic cutting has a unique advantage, that the location, direction and scale of the cracks are all controllable.

In April 1982, Hunan Baisha Mining Bureau held a meeting to discuss the improvement of gas drainage rate with hydraulic cutting. After listening to the report, 86 representatives from 41 research institute across China agreed that hydraulic cutting improved coal seam gas drainage rate and shortened the gas drainage time, and could be promoted to the mines facing difficulty in gas pre-drainage. Since then, a lot of researchers have studied the technology. Among them, Qu study the theories on hydraulic cutting, Feng (2011) carries out experiments and explores the theories on gas dynamic phenomenon of hydraulic cutting, and Zhao Lan conducts experiments on coal seam permeability improvement with hydraulic cutting. Based on the engineering application of the technology by Hunan Hongwei Mining Co., Ltd. in coal seam 6# of Tanjaichong Coal Mine, Zhao et al., (2011) point out that the advancing cutting technology is suitable for thin coal seams with ultralow permeability and high outburst hazard, but the operation process is hard to control and the gas is likely to exceed the limit, while the retrograding cutting technology is suitable for thick coal seams with high gas content, and is easier to control and manage despite that it has a poorer effect of pressure relief and permeability improvement than that of the advancing technology. Zhao and Wang (2012) indicate that hydraulic cutting is, on the one hand, an effective way to improve permeability with twice the impact radius of commonly used drilling pressure relief technology, and, on the other hand, not applicable to high hardness coal seams and likely to cause borehole blowout during the operation. Analyzing experiment data, Fu et al., (2014) mention that the shortcomings of hydraulic cutting include complex operation, heavy workload, and high hazards. The disadvantages are also illustrated by the numerous boreholes to be drilled before cutting, and non-compliance with the principle of “regional outburst prevention comes first”.

2.3.2 Hydraulic fracturing pressure relief and permeability improvement technology

Hydraulic fracturing technology was first used in the oil and gas industry, which has effectively raised the production capacity of oil and gas wells. In 1954, the technology was applied to coal mine gas drainage for the first time in Walker County, Alabama (Corvaro et al., 2015). The basic principle is to pump high-pressure water flow through boreholes into the coal seam so as to extend the primary cracks in the coal mass and promote the growth and extension of cracks. Meanwhile, the proppant added to the water is used to support the cracks, which promotes regional separation of the internal structure of the coal mass, increases the space volume of the weak surface of the cracks, and expands the migration channel of the gas. In this way, the technology helps improve coal seam permeability, achieve regional pressure relief, realize rapid desorption of absorbed gas, thereby fulfilling the purpose of pressure relief and permeability improvement.
The key to the success of hydraulic fracturing is crack initiation and expansion. The existing theoretical research is mainly based on the assumption that the rock is brittle, linear elastic, homogeneous, isotropic and impermeable. Nevertheless, coal rock mass has strong heterogeneity and permeability. The primary crack development of coal seam has a dual effect on the effect of hydraulic fracturing effect. On the one hand, good fracture development reduces the strength of coal rock, and facilitates the interconnection of primary cracks. On the other hand, the well-developed crack system is liable to cause the loss of fracturing fluid. When the top floor or the fault structure is encountered, the phenomenon of “pressure relief” might occur, resulting in failure of fracturing. At present, the experimental study of crack initiation and expansion is most targeted at rocks. Little research has been done on coal rock mass. Xu et al., (2014) points out that hydraulic fracturing is likely to cause a high degree of stress concentration. After the coal seam cracks under hydraulic fracturing, the saturation of the coal mass will continue to grow with the increased moisture content. High stress and water content greatly suppress permeability of the coal seam, which impedes gas desorption and affects drainage effect. According to Zhang et al., (2016), although hydraulic fracturing has the advantages of large pressure-relief range and high initial gas flow, it also has many disadvantage: first, the gas drainage flow rate decays rapidly and generally returns to the original level after one week; second, the crack initiation and extension locations follow no obvious law and the fracturing effect might be affected if the cracks extend to the roof and the floor.

3. INTEGRATED HYDRAULIC PRESSURE RELIEF AND PERMEABILITY IMPROVEMENT TECHNOLOGY BASED ON REGIONAL GAS CONTROL

Superstition Through the above analysis, large-diameter drilling and intensive cross-drilling are not suitable for soft coal seams because of small permeability improvement range, poor borehole formation rate, and high probability of collapse and borehole plugging. Neither are they suitable for deep buried high stress coal seams because of heavy workload and difficulty in drilling deep and long boreholes. Despite good permeability improvement range and effect, deep hole blasting is not suitable for soft coal seams because it involves complex process and high economic cost, raises strict requirements on borehole formation rate and quality, and faces potential hazards like blown-out shot and spark. Moreover, as the detonation gas boosts the pressure in microseconds, generating a shock wave with peak value much higher than the strength of the coal mass, most of the explosion energy is consumed by the crushed area, in which coal powder might plug the cracks.

As for hydraulic technologies, each measure has its own features. Apart from improving permeability, the hydraulic measures can also remove dust and prevent outbursts. However, when a hydraulic measure is used independently, it has many limitations. For example, if coal seam water injection is adopted alone, the increase in water content suppresses the gas desorption and migration, affecting gas drainage; Hydraulic cutting is not suitable for hard coal seams or coal seams which may encounter borehole blowout during the drilling process. Sometimes, it is difficult for water to return through the cracks and the amount of gas discharged from the coal seam is rather small. Hydraulic fracturing is even more complex. High pressure water is liable to cause secondary pollution of coal seam. Some coal seams are more sensitive to water, which will constrain desorption of coal bed gas and increase the time required for fracturing.

In short, the gas drainage process involves complex technologies and heavy workload. Since every existing permeability improvement measure has significant limitations, the permeability improvement should be treated as a systematic work. Researchers should conduct a comprehensive and in-depth study of permeability improvement theory and technology, improve the gas drainage of low permeability coal seams, and promote the safe and healthy development of coal mining.

Based on the comprehensive analysis of the mechanism, and advantages/disadvantages of various permeability improvement technologies and in accordance with the principle of “regional outburst prevention comes first” in the Regulations for Coal and Gas Outburst Prevention and Cure issued by State Administration of Work Safety, it is necessary to develop an integrated hydraulic pressure relief and permeability improvement technology based on local gas control, and reasonably integrate drilling, cutting and water injection measures with hydraulic fracturing technology in field application. To remove gas outbursts through pressure relief and drainage in local areas, the integrated technology should overcome the disadvantages of a single hydraulic measure and exploit the advantages of various measures. This train of thought leads the authors to put forward an integrated pressure relief and permeability improvement equipment and workflow which combines pulsed hydraulic flushing, cutting and fracturing for coal seams.

(1) Prepare the drilling construction plan: Set the locations and spacing d (normally 10m) of boreholes on the roadway rib of the coal seam on the excavation surface. Firstly, drill 2 control holes at the spacing of 2d,
Secondly, use pulsed hydraulic cutting-fracturing technology to drill in the middle of the two control holes and in the middle of coal seam roof 3 and coal seam floor 4.

(2) Conduct non-uniform pulsed hydraulic radial cutting of the 3 pulsed hydraulic cutting-fracturing holes. After fracturing holes are drilled, connect the central water guiding hole of the drill pipe 14 to the pulsed water pressure system through water pipe 7, and then start the pulsed water pressure system. The pulsed water pressure in generated in the following steps: issue a command from console 5, which starts water injection pump 15 via the data line 16; water injection pump 15 converts the water in tank 6 into high pressure water with a certain pressure; the high pressure water flows to pressure-holding vessel 9 via the overflow valve 8; the water pressure in pressure-holding vessel 9 is monitored by console 5; when the water pressure in pressure-holding vessel 9 reaches the desired water injection pressure, start solenoid valve 10 at the set frequency on console 5 to complete the generation of pulsed water pressure. When the pulsed water flow reaches the multi-function rotor 12 via drill pipe 14, start rig 13 and let it rotate slowly. Segment by segment (0.3~0.5m), the cut moves gradually from the bottom of the fracturing holes. Stop the rig when the cut location arrives at the location of the pulsed hydraulic cutting-fracturing holes. In order to prevent secondary disasters caused by cracks extending to coal seam roof and floor in the next step of hydraulic fracturing, non-uniform radial cutting should be performed in both horizontal and vertical directions during the pulsed hydraulic cutting process. The horizontal depth of the slot L2 should be greater than the vertical depth L1. In other words, the slot 19 should be approximately elliptical so that the cracks will extend further in the horizontal direction than in the vertical direction during pulsed hydraulic fracturing, thereby preventing secondary disasters to the roof and the floor.

(3) Conduct pulsed hydraulic fracturing. After the completion of the pulsed hydraulic cutting, remove rig 13, and seal up the fracturing holes and the control holes with sealing material 18. In the meantime, bury water injection pipe 17. Connect the pipe to the pulsed water pressure system, and start the pulsed hydraulic fracturing immediately. The pulsed hydraulic fracturing water pressure is generated in the same steps with those of pulsed hydraulic cutting water pressure in (2). During pulsed hydraulic fracturing, closely observe the two control holes. The fracturing is completed when water comes out of either of them, indicating that it is the time to stop the pump and drain the water of the fracturing holes.

(4) After the completion of all the processes of pulsed hydraulic cutting-fracturing permeability improvement technology, include the fracturing holes and the two control holes into the gas drainage pipe network to study the drainage effect. Record and analyze the gas drainage data.

Figure 1. Layout of Boreholes

Figure 2. Workflow of Pulsed Hydraulic Cutting
Figure 3. Workflow of Pulsed Hydraulic Fracturing

Figure 4. Shape of Cutting Slot

4. CONCLUSION

(1) Thanks to the joint efforts of researchers and field workers, a variety of permeability improvement processes and technologies have been developed for low permeability coal seams and have been successfully applied to coal mines in China. However, these processes and technologies generally lack enough applicability. Plus, the theoretical study lags behind technical application.

(2) Through comparison and analysis of existing permeability improvement mechanisms and processes, the authors point out the advantages, disadvantages, and applicability of each technology. Analyzing the practical process of gas drainage in several mines, the authors believe pressure relief is an effective way to improve the permeability of low permeability coal seams.

(3) Based on the systematic analysis of various hydraulic measures and in accordance with the coal gas control principle of “regional outburst prevention comes first” in China, the authors put forward an integrated pressure relief and permeability improvement equipment and workflow which combines pulsed hydraulic flushing, cutting, and fracturing for coal seams.

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