Research on the Development of Hydraulic Flushing Caverning Technology and Equipment for Gas Extraction in Soft and Low Permeability Tectonic Coal Seams in China

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ABSTRACT: Soft and low permeability tectonic coal seams (SLPTCSs) are widely distributed in China. In SLPTCSs, because of the difficulty of gas extraction, coal and gas outburst accidents occur frequently. In this paper, with the principle of stress unloading and permeability enhancement in SLPTCSs analyzed, it is put forward that the key technology to realize stress unloading and permeability enhancement in SLPTCSs is caverning by hydraulic flushing. In addition, the development of hydraulic flushing caverning technology and equipment in China is also further systematically studied. Field tests on the application of highly integrated equipment for caverning by hydraulic flushing have been carried out in the Shijiazhuang coal mine and Pingdingshan no. 8 coal mine. The results show that the widely used drilling and hydraulic flushing packaged equipment and drilling and mechanical cutting packaged equipment for caverning in coal seams can efficiently enlarge caverns in SLPTCSs, reduce the amount of workload for hole-drilling in the coal seam, improve the permeability of the coal seam by 23.9 times, and increase the concentration and pure volume of gas extracted in boreholes by more than two times. Highly integrated hydraulic flushing caverning equipment can realize high-efficiency stress unloading and permeability enhancement of the coal seam, which provides beneficial guidance for gas control of SLPTCSs.

1. INTRODUCTION

Coal is a kind of fossil fuel formed from plant debris through long and complicated geological sedimentation. Coal has long been in a dominant position in China’s energy system structure. It is estimated that coal output will still remain at three billion tons by 2050 in China; therefore, the safe exploitation of coal resources plays an important role in ensuring energy security.

In addition to complex chemical changes, coal is generally affected by tectonic stress during its formation, which leads to the formation of soft and pulverized tectonic coal. In China’s coal resources, the proven tectonic coal reserves are about 457 billion tons, accounting for 23.5% of the total coal resources. Tectonic coal widely exists in Henan, Huaibei, Shanxi, Northeast China, Yunnan-Guizhou, and other mining areas in China, showing the characteristics of regional distribution, local distribution, and layered distribution. Tectonic coal features a soft structure, poor permeability, and high gas content, which makes it difficult to extract gas from the coal seams and poses a high risk of coal and gas outbursts.

The in situ stress increases continuously as coal mining gets deeper in recent years, which leads to the continuous decrease of permeability, difficulty in gas drainage, and increase in gas disaster potential. Because the gas in tectonic coal is difficult to effectively extract, gas may be released out suddenly under the disturbance of mining stress. Related research found that most coal and gas outburst accidents in the world are inseparable from tectonic coal. Therefore, effectively extracting gas from tectonic coal and improving coal seam permeability is an important way to realize the safe utilization of coal energy.

2. METHOD AND THEORY

2.1. Technology of Stress Unloading and Permeability Enhancement in SLPTCSs. The most effective technical means of coal seam stress unloading and permeability enhancement is protective coal seam mining. Mining the protective seam makes a large range of unloading damage in the targeted coal seam; thus, its permeability is greatly

Received: March 10, 2022
Accepted: June 2, 2022
Published: June 14, 2022
improved. By extracting through the holes at this coal seam and together with the high and bottom extraction gallery, the gas is effectively extracted out.

However, for coal seams where protective coal seam mining is not available, other measures for underground gas extraction are mainly hydraulic fracturing, hydraulic slotting, CO₂ deep-hole blasting, hydraulic flushing caverning, installing poly(vinyl chloride) (PVC) sieve pipe all the way down along the drilled hole.12–22 For soft and low permeability tectonic coal seams (SLPTCs), the fracture network formed by traditional hydraulic fracturing and hydraulic cutting will collapse and get blocked quickly because of the small firmness coefficient of their coal body, and the permeability enhancement effect is not good either. The CO₂ blasting technology requires very critical technological conditions, which may induce outbursts in SLPTCs with high gas content. Although installing a PVC sieve pipe all the way down along drilled hole may solve the hole collapse problem, once the hole is done drilling, it can do nothing to expand the range of stress unloading or permeability enhancement of soft coal.

The technology of caverning by hydraulic flushing is mainly to drill holes through or along the coal seams, and then use a high-pressure water jet to impact and break the hole wall. After the broken coal falls off the hole wall, a larger hole is formed, and after the hole diameter is significantly enlarged, a sieve pipe is installed, the holes are sealed, and extraction is carried out.

Experiments show that adopting the technology of caverning by high-pressure hydraulic flushing can effectively form large-size holes, expand the plastic damage range, and promote the stress release of coal body around holes. The large-size holes are favorable for coal body expansion, deformation, migration, and breakage and realize efficient stress unloading and permeability enhancement of soft coal body.21–23

2.2. Theory of Stress Unloading and Permeability Enhancement in SLPTCs by Hydraulic Flushing Caverning. Coal is a porous medium with simplified matrixes and a fractured network.28–33 After drilling, the stress and gas adsorption—desorption environment of the coal seam is broken. The gas will be desorbed from the matrixes into the borehole through the fractures network. The key factors that determine the gas flow in the fractures system are the opening and number of fractures, which is macroscopically expressed as the permeability of coal. Therefore, permeability is the key to improving gas extraction. According to the characteristics of coal under full stress and strain, a large number of fractures develop in the post-peak plastic stress unloading stage, the effective stress decreases, the fracture opening increases, and the permeability increases greatly as well.11 The development and change of coal permeability in total stress and strain follow the equation below:

\[ k = \begin{cases} (1 + \xi^p/\gamma^p) \exp[b_{\phi}(\Delta \Theta)]k_{\phi} & 0 \leq \gamma^p < \gamma^{p*} \\ (1 + \xi) \exp[b_{\phi}(\Delta \Theta)]k_{\phi} & \gamma^p \geq \gamma^{p*} \end{cases} \]  

(1)

where \( k_{\phi} \) is initial permeability of coal, mD; \( b_{\phi} \) is fracture compressibility of coal, MPa⁻¹; \( \Theta \) is volume stress on coal body, MPa; \( \xi \) is permeability mutation coefficient, which is determined according to the experimental results.

The increase of permeability is closely related to the plastic state. Therefore, bringing coal into a postpeak plastic stress unloading state is the fundamental way to improve coal permeability. After drilling, the stress state around the drilled hole is disturbed, and some coal undergoes plastic yield failure under the action of concentrated stress, and finally gets into the postpeak plastic stress unloading state. Coal around the drilled hole can be divided into an elastic zone, a postpeak plastic zone, and a postpeak fracture zone.48–50 In the postpeak plastic zone, many new fractures develop, and therefore during the process, stress decreases significantly, and the permeability increases suddenly. In the postpeak fracture zone, the fractures continue to develop and the stress is completely released. The radius of the postpeak fracture zone where the coal body around the drilled hole is located is as follows:

\[ R_b = a \left( \frac{P_0 + c \cot \phi}{c \cot \phi} \times \frac{1 - \sin \phi}{1 + \sin \phi} \right)^{1 - \sin \phi / 2 \sin \phi} \]  

(2)

where \( a \) is the diameter of the drilled hole in m, \( c \) is the cohesion of coal in MPa, \( \phi \) is the internal friction angle of coal in \(^o\), and \( P_0 \) is the in situ stress in MPa.

In a coal seam, cohesion, internal friction angle, and in-situ stress are invariable, and the effective way to improve the plastic stress unloading zone of coal is to increase the diameter of the drilled hole. Therefore, adopting hydraulic flushing to expand the diameter of the borehole can get a wider range of coal into the postpeak plastic stress unloading state and greatly improve the permeability.

For a soft coal seam, its low firmness coefficient makes it favorable to use a high-pressure water jet to break the coal body, flush more coal out, and expand the radius of the drilled hole. Therefore, using hydraulic flushing to make a cavern is a very effective stress unloading and permeability enhancement measure for gas extraction out of soft outburst coal seams where protective coal seam mining is not available.24,43,44

3. TECHNOLOGY AND EQUIPMENT

3.1. Development of Hydraulic Flushing Caverning Technology and Equipment. The hydraulic flushing caverning technology was first introduced for coal mining in the Soviet Union, Poland, and China as early as the 1950s. In China, this technology was applied as a new outburst prevention technology for coal gallery excavation and rock cross-cut coal uncovering in Beipiao, Jiaozuo, and Nantong mining areas, where coal and gas outbursts were quite serious.49,56 In the 1980s, the technology of caverning by hydraulic flushing was used for good completion on a large scale in the development of coalbed methane in San Juan Basin, the United States.47,49 Since 2000, hydraulic flushing caverning technology has been applied as a rapid gas extraction and outburst elimination technology in many mining areas in China.49,56

Ever since the application of hydraulic flushing caverning technology in China, the corresponding equipment has experienced three stages of development and evolution.50–55 In the first stage, the equipment was low in integration and not easy or safe to operate. For example, in the hydraulic flushing operation carried out in Jilushan Coal Mine of Jiaozuo in 2004,44 the high-pressure seamless steel pipe was mainly used to connect the high-pressure water pump with the water gun, and the water gun was separately fixed 0.5 m away from the coal wall. When the hydraulic flushing operation was carried...
out, the workers at the excavation face had to evacuate themselves into the refuge chamber before the high-pressure water pump was turned on for the flushing operation, as shown in Figure 1.

This approach was backward a process, and it was inconvenient to move because of the seamless steel pipe connection. In the flushing process, the water gun was outside the coal seam, so it was difficult to fix and move the water gun, and there was a lack of a blowout prevention device, so the controllability of the flushing operation was poor. It required more in respect of manpower, material resources, and working environment, and the progress of hydraulic flushing operation was greatly limited.

In the second stage, the integration degree of hydraulic flushing technology and equipment has been improved. As shown in Figure 2, the previous way of directly fixing a high-pressure water gun outside the coal body for flushing has changed to ordinarily drilling into the coal body first. Once the drilling is done, the drill would be replaced with a special hydraulic flushing nozzle, and then high-pressure hydraulic flushing would be carried out inside the drilling hole. The flushing could be controlled by pushing the drill pipe by the drilling rig, and the use of a blowout preventer improved the safety of operators. The emulsion pump was connected to the high-pressure sealing flushing drill pipe in the drilling rig with a high-pressure resistant rubber hose, which greatly improved the flexibility of operation compared with using seamless steel pipe as the high-pressure pipeline.

However, it was difficult for the general drill pipe joint to keep the internal water pressure above 20 MPa when high-RPM drilling due to reliable drilling rig performance and drill pipe sealing were hard to achieve. Drill pipe leakage would lead to low flushing water pressure and poor coal breaking effect. Moreover, it was very likely to get the drilling bit stuck during the drilling process. Besides, the drill bits could not be flexibly switched between ordinary drilling and high-pressure water jet. Usually, only after the ordinary drilling was finished, the drill pipe can be withdrawn from the drilling hole, and after the special flushing bit was installed, the drill pipe can be pushed into the drilling hole again for flushing operation. However, the process of withdrawing the drill pipe for the first time may cause hole collapse and hole plugging.

The construction process used in the SLPTCSs could cause blowout accidents, resulting in equipment damage and even casualties due to the poor reliability of the collar blowout preventer in the flushing equipment. In addition, due to the lack of an efficient coal-water-gas separation device, the gas that rushed out of the collar during construction was directly discharged into the gallery, which could cause the gas concentration in the gallery to exceed the limit.

Although the second-generation hydraulic flushing equipment has been significantly improved compared with the first-generation, it still had obvious defects such as a low integration level, cumbersome and difficult operability, inconvenient construction approach, and certain operation-related safety risks. As a result, it was hard to popularize and apply hydraulic...
flushing and caverning technology in high outburst mines with SLPTCSs in China on a large scale.

On the basis of summarizing the previous experience of hydraulic flushing caverning technology, the third generation of hydraulic flushing equipment improved the process defects and became highly integrated hydraulic flushing caverning equipment. With the function of crawler linkage walking, the equipment is quite suitable for the underground working environment of a coal mine. The drilling and hydraulic flushing packaged equipment and drilling and mechanical cutting packaged equipment for caverning in coal seams are the two most representative categories. At present, these two have been widely popularized and applied in Henan, Shanxi, Shaanxi, Shandong, Inner Mongolia, Guizhou, Huaibei, and Northeast China mining areas, and presented quite a good gas permeability effect.

3.2. Characteristics of the Drilling and Hydraulic Flushing Packaged Equipment. As shown in Figure 3, the coal seam drilling and hydraulic flushing packaged equipment integrates the collar blowout preventer on the hydraulic drilling platform and makes the blowout preventer firmer through hydraulic power. The drill pipe can achieve a water seal under high-speed rotation. The drill bit can flexibly transform from the ordinary drilling mode to a high-pressure water jet. The crawler hydraulic drilling rig can do spherical hole distribution, which has obvious advantages for drilling holes in the low gallery or at the low position in a gallery.

In addition, the drilling rig is equipped with a high-RPM power motor with a rotating speed of 500 r/min, which ensures that the drill pipe can be provided with a high rotating speed and large torque when drilling a soft coal body, and prevents the bit from getting stuck. The crawler-type high-pressure water pump station integrates the water tank and pressurization device on the crawler-type walking platform, which can move and operate conveniently in the coal mine, greatly saving manpower and material resources.

3.3. Characteristics of the Drilling and Mechanical Cutting Packaged Equipment. Under certain working conditions, there are still many restrictive factors on the effective impact breaking distance of flushing coal. When accumulated water in the drilled hole forms a submerged jet, the resistance of water greatly reduces the effective impact breaking distance. The flushing effect also will be very low
when the Platts coefficient of coal near the flushing hole is very high.

As shown in Figure 4, the drilling and mechanical cutting packaged equipment was developed on the basis of the drilling and hydraulic flushing packaged equipment. The equipment applies mechanical cutters, assisted with high-pressure water jet coal breaking technology, which makes up for the deficiency of submerged jet.58

The hole enlarging cutters are closed in the groove of the equipment in the drilling process, and the water supply is pressured up when enlarging the hole. The cutter will open when the water pressure reaches 10 MPa. The drilling and mechanical cutting packaged equipment combines drilling and mechanical and hydraulic hole enlarging in one, which is very easy and efficient.

4. RESULTS AND DISCUSSION

The highly integrated drilling and hydraulic punching equipment has achieved good results in the field application with soft outburst coal seams in many places in China. At present, the field test research on the application effect of drilling and hydraulic flushing integrated equipment and drilling and mechanical cutting packaged equipment in mines has been carried out.

4.1. Application Effect of the Drilling and Hydraulic Flushing Packaged Equipment. 4.1.1. Overview of the Field Test Area. Yangquan mining area is a typical representative of mining areas with complex geological conditions and serious gas disasters in China. The test site was selected in the bottom rock gallery of the auxiliary transportation gallery in the north wing of the Shijiazhuang mine. Field measurement told us that the maximum gas content in this area was 10.38 m³/t, the maximum gas pressure was about 1.0 MPa, the coal seam permeability coefficient was as low as 0.973 m²/(MPa² d), the coal body was soft, and the lowest firmness coefficient was only 0.15. The coal seam in this area was at great risk of gas disasters, so it was necessary to take measures to eliminate outbursts in this section during gallery construction.

4.1.2. Design of Caverns by Drilling and Hydraulic Flushing. In the construction process of the auxiliary transportation gallery in the north wing, ordinary boreholes and hydraulic flushing caverning boreholes were arranged along the construction direction of the gallery. In the area of 50 m before coal uncovering, gas extraction was carried out through ordinary boreholes with cross-seam drilling and 5 m of borehole spacing. The length of this area was 65 m, and 14 rows of boreholes were arranged in total. Each row of boreholes contains nine gas extraction boreholes, and the control ranges on both sides of the gallery were 20 m and 15 m. The design layout of ordinary boreholes is shown in Figure 5.
The length of the hydraulic flushing caverning boreholes was 50 m, and the control ranges on both sides of the gallery were 20 and 15 m, respectively. Eleven rows of boreholes were arranged in this area, and the spacing of boreholes was 5 m between rows. In odd rows, 1#, 3#, 5#, 7#, and 9# boreholes were constructed for hydraulic flushing, while in even rows, 2#, 4#, 6#, and 8# boreholes were constructed for hydraulic flushing. The arrangement of hydraulic flushing caverning boreholes is shown in Figure 6.

4.1.3. Effect of Hydraulic Flushing Caverns. In the construction process, the water pressure was about 18 MPa, the flushing time for a single hole was 70−290 min, the coal output of a single hole was 6−19 t, and the average radius of a single flushed hole was 0.65 m.

The gas extraction time of ordinary boreholes and hydraulic flushing caverning boreholes was about 150 and 120 days respectively. The gas extraction data of ordinary drilled holes and hydraulic flushed holes were compared and analyzed.

It can be seen from Figure 7 that the gas extraction concentration above 30%, which is quite high, from hydraulic flushing caverning boreholes lasted for 80 days, while that from ordinary boreholes is only 27 days, indicating that the extraction days of high-concentration gas from hydraulic flushing caverning boreholes increased by 3.0 times.

The average pure volume of gas extracted from hydraulic flushing caverning boreholes is 0.52 m³/min, and that for ordinary boreholes is 0.23 m³/min, the former is about 2.3 times the latter. A total of 44,800 m³ of gas was extracted from ordinary boreholes after 150 days of gas extraction, and a total of 83,600 m³ of gas was extracted from hydraulic flushing caverning boreholes after 120 days of gas extraction, which was about 2.2 times that from ordinary boreholes.

4.2. Application Effect of the Drilling and Mechanical Cutting Packaged Equipment. 4.2.1. Overview of the Field Test Area. This test was carried out in Pingdingshan no. 8 coal mine, and the coal seam gas was pre-extracted before the excavation of the V9-10-21070 machine gallery. The average thickness of the coal seam was 4.3 m, and there had been 15 coal and gas outburst accidents in this coal seam’s history. The highest original gas content, gas pressure, and coal seam permeability in the test area were 10.66 m³/t, 1.7 MPa, and 0.0018 mD, respectively.

4.2.2. Design of Caverns by the Drilling and Mechanical Cutting Packaged Equipment. Downward boreholes were carried out in the high-level drainage gallery of the V9-10-21070 machine gallery. In the design, the borehole was 13−46 m in depth and 89 mm in diameter, and there were seven boreholes in each group at every 6 m. Each group of holes was distributed in two rows, and the boreholes were controlled to 15 m outside the upper side contour line and the lower side contour line of the V9-10-21070 machine gallery, respectively. The
4.2.3. Effect of Caverning by Mechanical Cutting. A total of 343 mechanical cutting caverning boreholes were constructed at the high-level drainage gallery in the V9-10-21070 machine gallery. During the construction of caverns, the average coal output reached 0.36 t/m, and the borehole radius reached more than 0.3 m. When the negative pressure was 3 KPa, the effective extraction radius for 30, 90, and 180 d were 2.5, 3.5, and 4 m, respectively. The permeability of the coal seam increased from 0.0018 to 0.0431 mD, which is an increase of 23.9 times.

A group of ordinary boreholes was constructed near a single group of mechanical cutting caverning boreholes at the same time, and the range controlled by the two groups of boreholes was the same. The gas concentration and net gas volume of each row of boreholes in the gas extraction period were monitored and counted.

As shown in Figure 9, the gas out of the mechanical cutting caverning boreholes is higher in concentration than that from ordinary boreholes during the whole extraction period, which indicates that a wider range of damage is produced around the holes after caverning, and the permeability of coal body is obviously improved. The initial concentration of gas from mechanical cutting caverning boreholes is about 80–90%, while that of ordinary drilled holes is about 40–50%. The high-concentration gas extraction period of mechanical cutting caverning boreholes with a gas concentration above 30% reached 127 days, while the high-concentration gas extraction period of ordinary boreholes is only 61 days, and the days of high-concentration gas extraction from the mechanical cutting caverning boreholes increases by 2.1 times.

The initial gas pure volume of a single group of mechanical cutting caverning boreholes and a single group of ordinary boreholes are 1.13 and 0.23 m³/min, respectively, indicating a 4.9 times improvement. With the prolongation of extraction, the net flow of gas from both groups of holes gradually decreased, but the former is always larger than the latter.

From the data of gas extraction by boreholes which are mechanically cut following normal drilling, compared with ordinary boreholes, the effect of stress unloading and permeability enhancement is significantly improved after caverning.

5. CONCLUSIONS

1. Hydraulic flushing caverning technology can effectively flush out the coal body in a soft coal seam, form larger size holes, promote a wider range of coal body around the drilled hole to get into the postpeak plastic stress unloading state, and greatly improve the coal seam permeability, which is an effective means to realize stress unloading and permeability enhancement in SLPTCs.

2. Since the introduction of hydraulic flushing caverning technology in China in the 1950s, through three stages of application innovation, it has developed from the initial simple and backward equipment to the current highly integrated hydraulic flushing equipment system, which makes the caverning easier to operate and more applicable, and suitable for various different working conditions.

3. The field test at typical mines shows that the coal seam has achieved a good stress unloading and permeability enhancement effect after adopting the highly integrated hydraulic flushing caverning equipment for caverning. The radius of hydraulic flushing caverning boreholes can reach more than 0.65 m, the average gas extraction pure volume is increased by 2.3 times, and the extraction period of high concentration gas is increased by 3.0 times. The radius of mechanical cutting caverning boreholes can reach more than 0.3 m, the coal seam permeability is increased by 23.9 times, the initial pure volume of gas extraction from the mechanically cut cavern is increased by more than 4.9 times, and the extraction period of high concentration gas is increased by 2.1 times.

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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This paper is supported by the Fundamental Research Funds for the Central Universities of Civil Aviation University of China (no. 3122019067).

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