INTRODUCTION

The coalbed methane, which is a significant potential source of energy, is facing notable challenges in exploration and production, especially degasification in low permeability coal seams with high gas concentrations. However, permeability is a critical factor controlling degasification and coalbed methane production. According to the safety operation specifications of China, the coal seam will be defined as outburst-prone coal while the methane concentration of coal seam...
The permeability of the targeted layer. Gidley and Murdoch have both conducted detailed research studies on permeability improvement technology and gas drainage methods in low permeability coal seams to prevent and eliminate disasters, such as coal and gas outburst. As the most serious area of coal-gas disaster in China, Guizhou continuously has special heavy gas accidents, resulting in serious casualties and property losses. At present, most coal mines adopt the in-seam gas drainage method to control the gas concentration. However, the labor production efficiency, including the replacement efficiency of working face, is notably low because of the poor gas permeability of coal seam, the low concentration and efficiency of gas drainage, even the long preparation period of the working face. Therefore, improving the gas drainage efficiency of gassy and soft coal seam becomes increasingly urgent.

In recent years, the enhanced gas extraction method has been widely used to solve the problems regarding gas drainage in a low permeability coal seam, including extraction with dense boreholes, hydraulic flushing, fracturing and slotting. The enhanced extraction with dense boreholes was proposed for gas drainage according to the seepage theory of Professor Zhou Shining, the key point to increase the amount of gas drainage is reducing both the borehole intervals and the negative pressure of extraction hole. Although those methods can improve the gas drainage effect in a short time, the permeability of soft and gassy coal seam is yet low with weak gas drainage performance and long drainage time.

Initially, the hydraulic fracturing technology was successfully applied to the Keipper 1 well in the Hugoton gas field, Kansas, USA in the 1950s. A large amount of drilling fluid with proppants was injected into the targeted strata by drilling holes, and fractures were subsequently generated and interconnected in the reservoir, thereby facilitating the improvement on the permeability of the targeted layer. Gidley and Murdoch have both conducted detailed research studies on the technology and principles of hydraulic fracturing, which is widely used in the development of low permeability oil and gas well fields. To increase the permeability of high gas concentration and low permeability coal seam, the hydraulic fracturing technology has been previously applied to the gas drainage borehole by the former Soviet Union. However, the damage caused by high-pressure hydraulic fracturing of coal roof urgently requires a solution.

The hydraulic flushing and slotting techniques were also proposed by the Soviet Union in the early 20th century, and the hydraulic coal mining technology has been successfully applied to the gas control and prevention of coal and gas outburst. However, hydraulic coal mining technology can only break the coal seam by jet flow within a certain distance. Although the jet flow within this distance is highly efficient, the coal breaking efficiency is dramatically decreasing, while the distance is beyond the assigned scope. As a consequence, the pressure loss along the hydraulic path is dramatically increased.

To improve the gas drainage of a coal seam with high methane content and low permeability, the hydraulic-controlled blasting of a single deep hole was conducted to increase the permeability. Moreover, the enhanced mining by protective roof has been extensively employed to reduce the pressure and increase the permeability of coal seams in China, especially in the deep coal extraction of coal seams with high methane content. With respect to the improved permeability of crushed and soft coal seam, superior technologies need to be optimized to improve the permeability of targeted coal seam.

At the early 1970s, the presplitting and blasting technology emerged, the use of this technology has a positive effect in increasing the permeability of a soft coal seam. However, this technology was restricted by the technical equipment and other aspects at that time. Thus, the control of explosive energy, deep hole charge, long distance hole sealing and blind shot treatment cannot be effectively solved, resulting in the low success rate and high risk of permeability improvement. Therefore, determining how to improve the gas extraction efficiency and the labor productivity of coal mining enterprises appear particularly important in the current depressed situation of serious coal loss.

In present work, the numerical theory and field experimental research on the permeability improvement in soft and gassy coal seams was conducted through presplitting and blasting technology with multiple boreholes. Moreover, the permeability variation of a low permeability coal seam under different borehole intervals and sealing lengths was obtained. The research results will contribute to promoting the prevention and control of coal-gas outburst in low permeability and high gas concentration coal seams.

2 MECHANISM OF PRESPLITTING AND BLASTING IN DEEP BOREHOLES

Compared to common boreholes in complete and stable coal seams, the depth of the blasting borehole in soft and outburst-prone coal seam is determined by the physical and mechanical properties of the coal, the depth is usually <70 m. The basic working process of presplitting and blasting with multiple deep boreholes consists of three stages: explosive charging, borehole sealing, and blasting. The onsite schematic diagram of the explosive charges is shown in Figure 1.

Once the explosive is loaded into the borehole with a certain depth and general geometric shape, the explosion with deep boreholes will be accomplished using a detonator. The
explosion and fracture process primarily included the following: the compressive stress first crushes the coal mass, and the hoop tension stress and strain wave continuously break the coal mass, eventually, the expansion of explosion gas expands cracks in coal mass. The above processes occur in three stages: (a) the initial cracks formed by instantaneous stress, (b) the further development of coal cracks with the expansion of the initial crack and the formation of the second crack, and (c) the increased coal volume caused by the movement of coal mass.

The presplitting and blasting in a gassy coal seam with multiple deep boreholes are different from the opencast blasting technology. The opencast blasting approach involves breaking the coal-rock mass for subsequent stripping. Alternatively, the presplitting and blasting in deep boreholes aims at the formation of fractures inside the coal seam, the process is completed by the noncoupling charging and blasting in the coal seam. Hence, the gas extraction rate is increased, and the permeability of coal seam is enhanced. To simplify the gas extraction process and reduce the production cost, the use of the three-dimensional fracture network along the center axis of the blasting boreholes is strongly recommended. The effect of explosion on the borehole wall is affected by the loading density of the charge, the uncoupling value between the blasting hole and the charge. Afterwards, the surface of the coal-rock body is subjected to a sudden high pressure, which facilitates the formation and expansion of the fractures in the coal mass. Through the rapid attenuation of explosive gas, the residual explosive wave still has fairly high energy along with pressure pulses, and it continuously propagates through the coal-rock body in the form of a shock wave, eventually the strain wave gradually attenuates to the sound wave level.

3 | NUMERICAL SIMULATION ON PERMEABILITY IMPROVEMENTS PERFORMANCE OF PRESPLITTING AND BLASTING WITH MULTIPLE DEEP BOREHOLES

Compared to the original permeability of soft and outburst coal seam with high methane concentration, the simultaneous blasting technology with multiple deep boreholes can increase the fracture density of the fractured zone, thereby enhancing the permeability improvement effect. However, the energy concentration effect will occur near the superimposed area of blast wave and the extraction borehole. This effect not only affects the stability of the extraction hole but also affects the strength of the top and floor coal. Therefore, the numerical simulation analysis with various borehole intervals on the inseam fracture distribution is conducted in the present work.

According to the field test conditions, the ANSYS/LS-DYNA was used to build a numerical simulation model with dimensions of 24 m × 24 m × 48 m, and the semi-symmetric structure was also utilized. The symmetric constraint in the Z direction is applied on the axial direction, and no reflection boundary condition is applied on all sides. Both the diameter of the blasting borehole and the diameter of the extraction hole are 73 mm, simultaneously the borehole interval ranges from 5 m to 7 m. The *MAT_HIGH_EXPLOSIVE_BURN is usually defined as the explosive material model in LS-DYNA. Likewise, the HJC model (No. 111 material model * MAT_JOHNSON_HOLQUIST_CONCRETE) is assigned as the material model of coal seam. The basic physical and mechanical parameters of coal are shown in Table 1.

The numerical model is meshed by SOLID164, and *MAT_ADD_EROSION is added to control the failure of coal-rock cell, which is used to generate explosive cracks. As the explosive stress waves in coal reach up to the dynamic compressive strength of coal, the failed cell will be deleted. According to the determining method of the loose zone, it can be considered that all cells within the range of loose zone will be deleted when reaching the failure criterion. The established numerical model is shown in Figure 2.

3.1 | Influence of the borehole interval on the permeability improvement performance

The fracture density in blasted zones obtained by blasting technology with multiple boreholes is shown in Figure 3. Compared to the original permeability, the fracture density in the computational area was dramatically improved by
simultaneous blasting technology with multiple deep boreholes, and the large-scale cracks gradually increased and propagated with the increase of detonation time, this behavior is beneficial to improve the permeability of the coal seam. Likewise, it can be implied that the main cracks still go through the extraction borehole for the borehole intervals of 5 m and 6 m. According to previous research results, the main cracks going through the extraction borehole only appears in the single borehole for the borehole interval of 4 m, as shown in Figure 4.

It can be indicated that the extraction borehole has a certain effect on the permeability improvement of blasting technology with multiple boreholes. Furthermore, such an effect will become increasingly obvious with the increased borehole intervals. Comparing the fracture distribution of Figure 3, it can be inferred that the crack density near the extraction hole decreases with the increased borehole intervals. Thus, the existence of the extraction borehole will induce the deflection of the formed crack, and the deflection degree will decrease with the increase of borehole interval.

**TABLE 1** Physical and mechanical parameters of coal

| Property                        | Value               |
|---------------------------------|---------------------|
| Density (kg/m³)                 | 1.4E3               |
| Elasticity module/MPa           | 3.1E3 6E4 0.21      |
| Critical energy release rate (kg/m) | 28 75 200           |
| Compressive strength/MPa        | 6.9 30 9.8          |
| Tensile strength/MPa            | Static load         |
| Static force                    | Dynamic load        |
| Dynamic force                   | Geologic stress/MPa |
| Static load                     | Dynamic load        |
| Static load                     | Dynamic load        |

**FIGURE 2** Numerical model of presplitting and blasting with multiple deep boreholes
3.2 Influence of the sealing length on the permeability improvements performance

To investigate the influence of the sealing length on the blasting effect of multiple boreholes, a semi-symmetrical structure and symmetric constraint condition were applied, and the numerical calculation model of blasting under different sealing lengths is shown in Figure 5. A total of three sealing lengths are included in present work: 5 m, 7 m, and 9 m, respectively. While the sealing length of the blasting borehole is 5 m, the stress distribution surrounding the blasting borehole at different times is shown in Figure 6. The maximum stress appears at the emulsion explosive section, and the stress induction zone gradually propagates with the increase of blasting duration time. While the explosive force is increasing, the soft coal matrix near the generated stress field becomes crushed. The heavier the explosive stress imposed on the coal matrix, the more severe the coal matrix will be crushed.

**FIGURE 3** The fracture growth process with various borehole intervals
Thereby, it can be indicated that the fractured range of the coal seam is also increased.

With the sealing length increased to 7 m, the Von-Mises stress contour surrounding the blasting borehole at different duration time is shown in Figure 7. With the increase of sealing length, the fractured area around the blasting borehole gradually decreases, indicating that the cracked zone of the coal seam accordingly decreases.

With the sealing length of the blasting borehole increased to 9 m, the stress distribution contours surrounding the blasting borehole is shown in Figure 8. It can be indicated that the reflection and stretching attenuation of explosive stress waves is weakened because the sealing material in blasting borehole is looser than the coal. With respect to the attenuation during blasting process, the air cavity has obvious advantages on the attenuation of stress wave propagation according to the Von-Mises stress contours at blasting duration time of 1200 µs.

Comparing the Von-Mises stress values of the blasting borehole with different sealing lengths, it can be concluded that the blasting borehole results in the formation of small free surfaces inside the borehole, and the reflection and stretching of stress waves on the free surface is beneficial to the attenuation of explosive energy, which, in turn, contributes to reducing the probability of breaking blasting boreholes. However, the total explosion energy can never be significantly decreased in the airtight cavity, as a result, the breaking of the blasting borehole still occurs, while the stress wave in the coal body and the compression wave in the air column reaches to the sealing cavity. Moreover, a large number of fractures emerge in the extraction borehole during blasting with two deep blasting boreholes at borehole intervals of 5 m and 6 m, and such fractures may result in the collapse of extraction boreholes. Hence, the optimal sealing length of blasting borehole is in the range from 7 m to 9 m. Numerical simulation results provide significant guidance to the subsequent field tests in gassy soft coal seam.

4 | FIELD TESTS ON THE PERMEABILITY IMPROVEMENTS PERFORMANCE OF MULTIPLE PRESPLITTING AND BLASTING HOLES IN THE OUTBURST COAL SEAM

The field test site is located in the X10901-3 mining head face of the Dawan west coal mine. The tested coal seams of the extraction site were original coal, and the average thick of targeted coal seam ranges from 0.83 m to 2.4 m. The methane gas content of original coal seam is 14 m³/t, and the pressure is 3.6 MPa, thereby the field tests site belongs to outburst-prone coal mine. Based on the geological data and the roadway layout of the working face in the rail roadway of X10901-3, the presplitting and blasting technology with deep blasting boreholes was conducted. Moreover, the permeability improvement performance of targeted coal seam was analyzed according to the field measurement and statistical analysis. According to the survey suggestions, three blasting boreholes and four extraction boreholes were arranged in front of working face in the rail roadway of the X10901-3, and the borehole layout is shown in Figure 9.

The permeability coefficient, the extraction concentration, the pure volume, and the methane gas content before and after blasting were investigated in the present field tests. The borehole parameters are shown in Table 2. After the blasting boreholes have been completed, the extraction boreholes can
FIGURE 6  The Von-Mises stress contour with the sealing length of 5 m
FIGURE 7  The Von-Mises stress contour with the sealing length of 7 m
FIGURE 8  The Von-Mises stress contour with the sealing length of 9 m
be normally performed in gas extraction. In the end, the gas extraction concentration and the purity volume can be daily measured, which is considered to be the improved extraction concentration and pure volume by presplitting and blasting technology with multiple deep boreholes.

5 | RESULTS AND DISCUSSION

5.1 | Permeability coefficient

According to the calculation method proposed by the China University of Mining and Technology, the gas permeability coefficient of coal seam can be obtained by the methane gas content. First, the assigned parameter $A$ can be calculated by

$$A = q \cdot r / (P_2^2 - P_1^2)$$

simultaneously another assigned parameter $B$ can be calculated by $B = 4 \cdot T \cdot P_1^{1.5} / (ar_1^2)$. Eventually, the permeability can be obtained by $\lambda = A^a \cdot B^{1/b}$, where $a$ and $b$ are assigned as constant value. The installation and sealing of gas pressure gauge must be completed once the extraction borehole drilling is completed, which ensures to monitor the methane gas flow rate of extraction borehole in real time while the pressure is stable. The obtained natural gas flow rate of targeted coal seam is shown in Table 3.

It can be found that the maximum natural gas flow rate of targeted coal seam is 1.52 L/min after blasting with multiple deep boreholes, and the variation of measured gas flow is slight. Thus, the permeability of gassy coal seam is improved. Moreover, the calculated average permeability of fractured coal seam is 0.043 md, which is 2.5 times higher than that of the original permeability of 0.017 md.

5.2 | Average extraction concentration and pure volume

As shown in Figure 10, the extraction concentration and pure volume of the 1$^{st}$ borehole has been increased by 210% and 320% compared with the original concentration and the pure volume obtained from previous permeability enhancement methods, respectively. During extraction over 14 days, the total volume of produced methane gas is 1643 m$^3$. It can be found that the extraction performance

![FIGURE 9](image_url) Layouts of blasting and extraction boreholes in the field test site

| Series No. | Depth (m) | Inclination (°) | Azimuth angle (°) | Length of pre-splitting (m) |
|------------|-----------|----------------|------------------|---------------------------|
| 1# extraction borehole | 98 | 2 | 91 | – |
| 2# extraction borehole | 96 | 2 | 89 | – |
| 3# extraction borehole | 90 | 7 | 83 | – |
| 4# extraction borehole | 95 | 7 | 97 | – |
| 1# blasting borehole | 80 | 0 | 90 | 72 |
| 2# blasting borehole | 83 | 4 | 86 | 63 |
| 3# blasting borehole | 78 | 4 | 94 | 50 |

![TABLE 2](image_url) The structural parameters of blasting and extraction boreholes

| Test time (d) | 1# measuring borehole (L/min) | 2# measuring borehole (L/min) |
|---------------|-------------------------------|-------------------------------|
| 1             | 1.48                          | 1.52                          |
| 2             | 1.46                          | 1.49                          |
| 3             | 1.44                          | 1.47                          |
| 4             | 1.42                          | 1.45                          |
| 5             | 1.040                         | 1.44                          |
| 6             | 1.39                          | 1.43                          |
| 7             | 1.39                          | 1.42                          |

**TABLE 3** The measured natural gas flow rate of coal body after presplitting
of the 1# borehole is remarkably decreasing within the 14 days’ period, and the maximum extraction concentration is shifting from 40% to 18%, which represents a drop with percentage of more than 55%. Likewise, the maximum extraction pure volume of 1# extraction borehole ranges from 0.12 m³/min to 0.06 m³/min, representing a decrease of more than 50%.

Compared with original data obtained from previous permeability enhancement technology with single blasting boreholes, the extraction concentration and pure volume of 2# extraction borehole is approximately increased by 240% and 264%, respectively. As shown in Figure 11, the total obtained methane gas volume of the 3# borehole is 1339 m³, and the extraction concentration and pure volume dramatically decreases after the 5th day of extraction, eventually remaining in the stable stage.

It can be concluded that the permeability of fractured coal seam is remarkably improved within the initial 6 days, and the maximum extraction pure volume is approximately 0.19 m³/min, which is equal to 273 m³ per day. Because of the continuous fractures exist in the deep extraction boreholes, the extraction capacity of drilled boreholes was absolutely improved. Moreover, the existed fractures will expand with the degasification process, thereby facilitating the connection of fractures inside the coal seam. However, once the methane gas has been extracted out of the coal seam, the strength of the coal will be gradually reduced. Hence, the fractures must be closed. When the extraction period exceeds 6 days, the accumulated closure of fractures results in the severe reduction of permeability.

The extraction concentration and pure volume variation of the 4# extraction borehole is shown in Figure 13. Compared to the original permeability of targeted coal seam, the average extraction concentration and purity volume of the 4# borehole were found to be improved by 250% and 298%, respectively. Moreover, the total gas extraction volume of the 4# borehole is 2104 m³ within 14 days. The extraction purity of the 4# borehole dramatically increases after the extraction of 8th day. However, the extraction concentration and pure volume of the 4# extraction borehole reduce to the minimum. Because of the disturbance of mining and excavating of the roadways, the coal and rock near the extraction borehole will be tamped step by step, resulting in the closure of the existed fractures inside the coal.

Once the fractures were definitely compacted, the minimum extraction concentration and purity volume will be obtained at 7th day. When the mining and excavation of roadways were subsequently proposed, the stress concentration will be lost, thus the extraction concentration and pure volume will eventually rise, as shown in Figure 13.

5.3 Variation on methane gas content of soft coal seam

The original gas content of tested coal seam is shown in Table 4. To investigate the residual gas content of the fractured coal seam, an investigation borehole has been drilled after the presplitting is finished. During the drilling process of the investigation borehole, the methane gas content W can be timely measured by the DGC gas detector. According to

As shown in Figure 12, the extraction concentration and pure volume of the 3# extraction borehole is increased by 100% and 84%, respectively, compared with the original data obtained from conventional permeability enhancement methods. Within 14 days of extraction, the total obtained methane gas volume of the 3# borehole is 1339 m³, and the extraction concentration and pure volume dramatically decreases after the 5th day of extraction, eventually remaining in the stable stage.

FIGURE 10 Variation on the average extraction concentration and pure volume of the 1# borehole before and after presplitting
the drilling and extraction operation in front of the working face of 60 m, no coal or methane gas was ejected out of the coal seam, which indicates that the methane gas content is extremely low. The residual gas content of the fractured coal seam is shown in Table 5.

At the first day of blasting, the residual gas content of measured coal seam was reduced by 1.62 m³/t, and the total residual gas content was reduced by 4.37 m³/t within 6 days of extraction, thus the methane content in the roadways of the Dawan coal mine was remarkably reduced by blasting with deep boreholes. It can be inferred that the methane content decreases with the extension of extraction time. Nevertheless, when the distance between the heading face and the investigation borehole is >70 m, the coal near the investigation borehole will be excluded in the fractured zones. Thereby, at least 7 days of extraction is required if the gas content should be reduced from 10.15 m³/t (original gas content) to 7 m³/t (safety and qualified gas content).

It can be concluded that the high-pressure gas formed from an explosion interacts with the surrounding coal-rock mass, simultaneously the coal and rock will be crushed by the instantaneous compressive stress produced by the explosion, causing the coal

![Figure 11](image1.png)

**Figure 11** Variation on the average extraction concentration and pure volume of the 2# borehole before and after presplitting

![Figure 12](image2.png)

**Figure 12** Variation on the average extraction concentration and pure volume of the 3# borehole before and after presplitting
body to be initially fractured. While the coal body is impacted, the surface of the coal is subjected to a sudden high pressure, and it will be exponentially attenuated with the extraction time. Meanwhile, the residual stress waves continue to form the pressure pulse, and then, the pressure wave will propagate forward as the form of shock waves. Afterwards, the strain wave will be gradually generated. The stress from the strain waves crushes the coal mass to form further fractures, and the initial fractures will be extended to form the new cracks. The formation and evolution of cracks in the coal seam facilitates the connectivity of new generated inseam fractures, eventually leading to the increase of permeability coefficient. As a result, the permeability of gassy coal seam is enhanced, which guarantees the mining safety and the extraction of underlying coal sources in turn.

6 | CONCLUSIONS

1. The permeability of a gassy coal seam is improved to be 2.5 times by using presplitting and blasting technology with multiple deep boreholes.
2. Within 6 days of extraction, the average extraction concentration and pure volume of the extraction borehole were 40.13% and 0.113 m³/min, respectively, which are 2.9 times and 4.1 times higher than the original data, respectively. Likewise, the average extraction concentration and purity of the extraction hole were 21.75% and 0.063 m³/min after being extracted within 14 days, which is twice and three times higher than that of the original average extraction concentration and purity volume, respectively.
3. Numerical simulation results show that the optimal sealing length of blasting borehole ranges from 7 m to 9 m, and the borehole intervals with 5 m and 6 m will ensure the main cracks go through the extraction borehole.
4. It can be concluded that at least 7 days are required to reduce the gas content to the qualified level, which provides significant guidance for the safety mining and efficient extraction of gassy coal seams.

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**TABLE 4** The original gas content of coal seam

| Borehole number | Position of 35 m | Position of 70 m |
|-----------------|-----------------|-----------------|
| 1# blasting borehole | 8.95 | 10.21 |
| 2# blasting borehole | 8.24 | 9.83 |
| 3# blasting borehole | 8.56 | 10.42 |
| Average gas content | 8.58 | 10.15 |

**TABLE 5** The residual gas content after permeability improvement and continuous extraction

| Investigation borehole | Extraction time (d) | Residual gas content (m³/t) |
|------------------------|---------------------|---------------------------|
|                        | 35 m | 70 m |
| 2#                     | 1 | 6.96 | 9.22 |
| 1#                     | 2 | 6.25 | 8.86 |
| 5#                     | 3 | 5.74 | 8.58 |
| 3#                     | 4 | 5.32 | 8.14 |
| 4#                     | 5 | 4.93 | 7.56 |
| 6#                     | 6 | 4.21 | 7.23 |
CONFLICT OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. Meanwhile, the founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

Changguo Huang and Jiangfu He conceived and designed the experiments; Yuebing Zhang and Fakai Wang performed the experiments; Yongjiang Luo and Zhongguang Sun analyzed the data; Yongjiang Luo and Jiangfu He wrote the paper.

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