A Novel Hydraulic Mode to Promote Gas Extraction: Pressure Relief Technologies for Tectonic Regions and Fracturing Technologies for Nontectonic Regions

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Abstract: Extraction of gas (coalbed methane) produces clean energy and can ensure that coal mines maintain high-efficiency production. The currently available coal seam permeability enhancing technologies and modes have certain application restrictions. Therefore, a novel mode is proposed to promote gas extraction. This mode divides complex coal seams into tectonic regions and nontectonic regions based on geological structures. Then, the characteristics of different regions are matched with the advantages of different hydraulic technologies; thus, pressure relief technologies are proposed for tectonic regions, and fracturing technologies are proposed for nontectonic regions. The permeability of coal seams will be sharply increased without leaving unfractured areas. This mode will promote the effectiveness of gas extraction, shorten the extraction time, and ensure safe and efficient production in coal mines. A field application shows that this mode has a better effect than slotted directional hydraulic fracturing technology (SDHFT). The gas concentration and pure gas flow were increased by 47.1% (up to 24.94%) and 44.6% (up to 6.13 m³/min), respectively, compared to SDHFT over 9 months. The extraction time was reduced by 4 months. This mode reduced the number of times that gas concentration exceeded government standards during coal roadway excavation, and the coal roadway excavation speed was increased by 16% (up to 158 m/month).

Keywords: gas extraction; permeability enhancement; coal and gas outburst; hydraulic technology; complex coal seam

1. Introduction

Coalbed methane is a type of clean energy that has a high calorific value and clean combustion products [1–3]. Many countries, including the United States, China, and Australia, are producing gas to optimize their energy structure. The gas production in the United States is declining because of shale gas. However, the production in other countries is increasing, and these countries will continue to focus on developing gas resources in the future [4–6]. Additionally, coal mines that contain gas have the possibility of coal and gas outburst (CGO) accidents in the mining process, and gas extraction can solve this problem [7,8]. Therefore, efficiently extracting gas and eliminating the potential for CGOs is an urgent problem that needs to be solved.

To promote gas extraction, scholars from different countries have proposed various methods to increase coal seam permeability. For most coal mines, dense borehole gas extraction technology is initially used [9–11]. The effectiveness of this technology in low permeability coal seams is poor. Additionally, this technology requires a substantial amount of work and long extraction times, which...
affect the subsequent production process. Some researchers have proposed a series of pressure relief technologies, such as hydraulic flushing technology and hydraulic slotting technology \[12,13\], to improve the effectiveness of gas extraction in cross-measure boreholes and shorten the extraction time by approximately 20% to 30%. To some extent, these technologies play a role in promoting gas extraction. However, the influence radius of a single cross-measure borehole is limited (usually 3 m to 5 m), and a large amount of work is required for extraction. Additionally, cross-measure boreholes easily collapse and become blocked, which reduces the final extraction efficiency. Some researchers have proposed using hydraulic fracturing technology (HFT) in coal mines. After years of improvement, traditional HFT in coal mines has developed into directional HFT, pulse HFT, tree-type HFT, etc. \[14–18\]. Additionally, some new types of fracturing fluid have been proposed \[19\]. The effect of these HFTs is significantly improved compared with the pressure relief technologies mentioned above. These HFTs can significantly increase the influence radius (generally 30 m to 60 m) and shorten the extraction time by approximately 50%. However, these HFTs have certain application limitations. For example, the roof and floor must be intact because coal seams with geological structures cannot hold pressure and cannot be fractured. Additionally, in many multi seam coal mines, protective seam mining technology is used as an auxiliary technology to ensure extraction effectiveness \[20,21\]. Protective seam mining technology applies to only the seams below the first seam in multi seam areas with appropriate coal seam intervals.

For the first seam in multi seam or for single coal seams, one of the abovementioned permeability enhancing technologies (usually HFT) is generally used to promote gas extraction. In fact, for many coal mines, the local conditions will not be fully considered when implementing HFT. When HFT is used in a tectonic region, an unfractured area will be produced around geological structures; otherwise, CGO accidents or water inrush accidents will occur. For example, a hydraulic fracturing project in an area with secondary faults triggered a CGO accident in the Hongyan coal mine (Chongqing, China) on 31 August 2017. For some coal mines with multiple geological structures, HFT is not used for fear of causing accidents. These mines use only dense borehole gas extraction technology or pressure relief technology, which results in poor extraction efficiency. Additionally, imperfect permeability enhancement leads to a long extraction time, which affects the coal mine production. The above phenomena occur because there is no perfect technology or mode to guide the vast majority of coal mines to increase permeability and promote gas extraction, especially in high gas coal mines that have multiple geological structures.

Therefore, a novel mode for applying hydraulic technology to complex coal seams to promote gas extraction is proposed in this paper, and a schematic diagram is shown in Figure 1. This mode divides complex coal seams into tectonic regions and nontectonic regions based on geological structures. The advantages of different hydraulic technologies are then matched with the characteristics of different regions, such as hydraulic oscillate slotting technology (HOST) for tectonic regions and SDHFT for nontectonic regions. The permeability of coal seams will be sharply increased by pressure relief or fracturing methods without leaving unfractured areas. The use of this mode will promote gas extraction and ensure that production is safe and efficient in coal mines.
2. Introduction of the Novel Hydraulic Technology Mode

2.1. Background of the Novel Hydraulic Technology Mode

A large amount of field data indicates that different coal seams (especially when they contain geological structures) need to have different permeability enhancing technologies applied. Because tectonic zones have abnormal changes in stress and gas distribution, the location of gas accumulation in these areas cannot be accurately predicted [22–24]. However, the gas content and pressure are balanced in nontectonic zones. Additionally, coal seams in tectonic zones are fractured and store a large amount of elastic energy [25–27]. The gas storage conditions are complicated. For example, a partition is formed by a fault in the fracture zone and a gas accumulation area. This partition will help store more gas and make the distribution of gas more complicated, whereas the type and physical properties of the coal and rock seams remain almost the same.

Permeability enhancing technologies have been applied and researched throughout the world in recent years and have been summarized [4,12]. These technologies can be divided into pressure relief technologies and fracturing technologies. Pressure relief technologies manufacture spaces in coal seams by methods such as drilling holes or flushing out coal. Stress in the coal seam will then be relieved, and the permeability of the coal seam will be increased. Examples of these technologies include dense borehole technology, hydraulic slotting technology, hydraulic flushing technology, and HOST. Fracturing technologies produce fractures in the coal seam by injecting high-pressure fracturing fluid or using other methods to produce fractures (or prop up natural fractures) in the coal seam and drastically increase the permeability. Examples of these technologies include traditional HFT, pulse HFT, SDHFT, tree-type HFT, and deep-hole blasting technology.

In the present study, a novel mode is proposed by considering and summarizing the characteristics of coal seams, the difficulties in increasing coal seam permeability, and the advantages of different permeability enhancing technologies. The main idea behind this mode is to adopt different permeability enhancing technologies in different regions. Because a tectonic region stores a great amount of elastic energy and gas, the coal and rock seams are broken and cannot bear more energy input. Any injection of energy may easily cause CGO accidents. Therefore, pressure relief technologies are appropriate (HOST is one of the best technologies available at present). Coal and rock seams in nontectonic regions are stable and can accommodate some energy; therefore, using permeability enhancing technologies is appropriate.

Figure 1. Schematic diagram of the novel hydraulic technology mode.
regions are stable and can accommodate some energy; therefore, using fracturing technologies is better because they are highly efficient and effective. SDHFT is one of the best choices because of its balanced permeability enhancing effects.

2.2. Technological Processes of the Novel Hydraulic Technology Mode

2.2.1. Components of the Novel Hydraulic Technology Mode

HOST and SDHFT are used as examples of the novel hydraulic technology mode. The mode contains two systems: a hydraulic oscillate slotting system and a hydraulic fracturing system. The hydraulic oscillate slotting system includes the following components: a high-pressure pump, a high-pressure hose, a drilling rig, a high-pressure rotary joint, a high-pressure drill pipe, and an automatically switching drill bit. Additionally, the hydraulic fracturing system requires a pressure-flow control device and a hole sealing device. During the slotting process, high-pressure drill pipes and automatically switching drill bits are used as the drill pipe and drill bit, respectively, and as the water delivery pipe and slotting nozzle, respectively. A schematic diagram of the two systems is shown in Figure 2.

![Figure 2](image-url)

Figure 2. Systems used in the novel hydraulic technology mode.

2.2.2. Implementation Steps

The hydraulic technology mode includes the following three steps: the preparation stage, implementation stage, and testing stage. The details are shown in Figure 3.
The preparation stage contains the preparation work for hydraulic technology implementation, such as determining the original gas content and pressure and detecting the details (the type, location, and extent) of the geological structure in the coal seam. The coal seam is then divided into tectonic regions and nontectonic regions. The presence of geological structures, such as folds and faults, nearby and within 100 m classifies the area as a tectonic region. The remaining areas are classified as nontectonic regions. Due to errors in current geological exploration techniques, it is not easy to divide the coal seam into tectonic and nontectonic regions. However, the aforementioned problems will be solved by improving the geological exploration techniques. Additionally, the effective radii of HOST and SDHFT must be tested. The radii provide the basis data for determining the layout of the cross-measure boreholes (for slotting or hydraulic fracturing). The test method is to determine the moisture content and the gas pressure around the cross-measure borehole after implementing the hydraulic technology. The test point will be within the radius if the moisture content increases and the gas pressure decreases; otherwise, the test point is outside the radius.

The systems used in the novel hydraulic technology mode during the implementation stage are shown in Figure 2. The steps in the tectonic region are as follows. First, a cross-measure borehole is drilled from the specified position (in a gas tunnel) to the roof of the coal seam. Second, a slot is cut in the middle of the coal seam using an automatically switching drill bit. The shape of the slot is disk-like, and the radius is approximately 2 m. Third, extraction boreholes are drilled and connected to the extraction pipe. In nontectonic regions, the first and second steps are the same as those in tectonic regions. The third step is to seal the cross-measure borehole and carry out hydraulic fracturing. The fourth step is to maintain the pressure for 2 weeks. Then, extraction boreholes are drilled and connected to the extraction pipe.

The gas concentration and gas production from the extraction pipe are recorded in the testing stage, and the gas content and gas pressure are measured after 6 months. If the gas content and pressure meet the national standards, coal roadway tunneling can be started. In addition, monitoring...
and recording the gas concentration in the return air way are necessary during the coal roadway excavation and mining period.

2.3. Characteristics of the Novel Hydraulic Technology Mode

a. Good applicability. This hydraulic technology mode is designed for complex coal seams. The technologies described in this mode can be changed based on the geological conditions for most coal mines. Therefore, this mode can guide the vast majority of coal mines in preventing CGO accidents.

b. More advantages. This mode draws on the advantages of different hydraulic technologies (pressure relief technologies and fracturing technologies) and can eliminate some shortcomings in these technologies.

c. Improved effectiveness. The extraction efficiency of this mode is better than that of others, and effective CGO prevention can be ensured in a relatively short time. Then, the working face can continue on schedule.

d. Economic rationality. This model can reduce the amount of work, shorten the extraction time, ensure the continuity of production, and increase the economic benefits of coal mines.

3. Test Site and Field Testing

A field test was implemented in the Datong First Coal Mine (Chongqing Yuxin Energy Co., Ltd.) to verify the applicability of this hydraulic technology mode.

3.1. Introduction to the Coal Mine

The Datong First Coal Mine is a high gas coal mine located in the southern Qianjiang District, Chongqing, China (shown in Figure 4). The approved production capacity is 1.5 million tons/year. The three minable coal seams (M6, M7, and M8) have average thicknesses of 0.74 m, 1.10 m, and 2.85 m, respectively. In addition, folds and faults are present in this mine. The Yutiao anticline (the main geologic structure) is located in the middle of the mine, and the trend is 50° to 60° to the northeast. The F35 reverse fault is the largest fault, and it decreases significantly with increasing depth and forms some smaller faults at depth.

The target coal seam in the test is M7, with an average dip angle of 8°. The gas content of the M7 coal seam is 19.41 m³/t, and the original gas pressure is 5.73 MPa. There have been 235 CGO accidents in this mine, and more than 90% of the accidents occurred in the M7 coal seam [28].

Figure 4. Location of the Datong First Coal Mine.
The target coal seam in the test is M7, with an average dip angle of 8°. The gas content of the M7 coal seam is 19.41 m³/t, and the original gas pressure is 5.73 MPa. There have been 235 CGO accidents in this mine, and more than 90% of the accidents occurred in the M7 coal seam [28].

3.2. Working Design

The test working faces are W2708N (920 m long) and W2708S (830 m long). The width of the working face is 140 m. The bottom gas tunnels are under the middle of the working faces. The Yutiao anticline, Fw-7-70 fault (normal fault, offset of 0.4 m) and Fw-7-71 fault (normal fault, offset of 1.7 m) are in the coal seam. The working faces and roadways are shown in Figure 5a. First, the coal seam is divided into tectonic regions and nontectonic regions based on the presence of geological structures. Next, a construction plan is designed according to Section 2. The W2708S working face is a comparison working face. To ensure the effect of permeability enhancement, SDHFT was used on the W2708S working face (the effect of SDHFT is approximately 1.8 times that of traditional HFT [29]). Then, the effective radii of HOST and SDHFT were tested and found to be 5 m and 60 m, respectively. To ensure that the entire coal seam was enhanced, the distance between the fracturing boreholes was 110 m, the distance between the slotting boreholes was 10 m, and the distance between the extraction boreholes was 5 m. The details are shown in Figure 5b.

Figure 5. Diagram of the working face design: (a) Diagram of the working faces, roadways, and geological structure; (b) Diagram of the fracturing boreholes and slotting boreholes.
4. Results and Discussion

4.1. Gas extraction Effectiveness

To analyze the effectiveness of extraction, the gas flow and gas concentration in the main extraction pipe were recorded each day. The changes in gas flow and gas concentration are shown in Figure 6.

The gas concentration curves shown in Figure 6 are wavy. The results of the W2708N working face decrease with time, whereas the peaks of the W2708S working face decrease first and then increase mainly because the extraction boreholes are drilled and connected to the main extraction pipe by subareas. The working faces are divided into five (W2708S) or six (W2708N) subareas. The extraction boreholes in a subarea are connected to the main extraction pipe at the same time after they are all drilled. For each subarea, the gas concentration will gradually decrease as the gas content and gas desorption rate decrease, and the rate of decline becomes increasingly lower. For the entire working face, the gas concentration in the main extraction pipe will increase when a new subarea (with a high gas concentration) is connected. The peaks in concentration become increasingly smaller because the gas flow in the pipe becomes increasingly larger in the first 3 months. The curve for the W2708S working face is a “U” type curve because HFT has poor effectiveness in tectonic regions but good effectiveness in nontectonic regions.

The gas concentrations of the W2708N and W2708S working faces were quite different in the first 45 days because SDHFT was used in the tectonic region of the W2708S working face. When a hydraulic fracture meets a structural plane, the fracture may not be able to pass through the structural plane and will extend along the plane (Figure 7), leaving some areas unfractured. Additionally, the hydraulic fractures that extend along the plane may connect to the roadway and draw in air during the extraction period, which may lead to low gas concentrations. HOST was effective and resulted in high gas concentrations in the tectonic region of W2708N. SDHFT was used in the nontectonic regions of both working faces. Therefore, the gas concentration curves are similar. However, the gas concentration for W2708N was approximately 3 grades higher than that of W2708S over the final 6 months. The average gas concentration from W2708N over 9 months was 24.94%, which was 47.1% higher than that of W2708S (16.96%). This result occurred because of the reduced effectiveness of the employed technology in the W2708S tectonic region.

The gas flow curves in Figure 6 are also wavy. The curves have multiple peaks that became higher with time. This phenomenon likely occurred because the subareas are progressively connected. For each subarea, the gas flow rapidly increased to peak values within one day. The gas flow then started to decline after several days. The rate of decline decreased over time. For the entire working...
face, the gas flow increased when each new subarea was connected. The gas flow then slowly decreased after all of the subareas were connected. When the extraction boreholes were connected, the gas content and gas pressure were relatively high, and the fracture morphology was good. These conditions are beneficial for gas migration, desorption and extraction. The gas content and gas pressure gradually declined as extraction progressed and ultimately produced a negative impact on gas extraction.

The average mixed and pure gas flows for the W2708S working face were 22.01 m³/min and 4.24 m³/min, respectively, and those for the W2708N working face were 22.16 m³/min and 6.13 m³/min, respectively. The mixed gas flows were similar. However, the pure gas flow of W2708N was 44.6% higher than that of W2708S because some air may have been drawn into the W2708S tectonic region during the extraction period. The W2708N working face had a better permeability enhancing effect and a higher gas concentration than the W2708S working face. Additionally, the W2708N working face was 90 m longer than W2708S. Therefore, the mixed gas flows of the two working faces were similar.

4.2. Gas Content after Extraction

To determine the gas extraction effectiveness and whether the coal seam meets the standards for mining in China, some cross-measure boreholes were drilled to test the gas pressure and content of the coal seam after 9 months of extraction (including the drilling period). The government of China stipulates that a coal seam cannot be mined if the gas pressure exceeds 0.74 MPa or the gas content exceeds 8.0 m³/t. The average gas pressure after extraction in the W2708N working face was 0.31 MPa, which was 5.42 MPa lower than the original gas pressure. The average gas content was 6.44 m³/t, 12.97 m³/t lower than the original gas content. The gas pre-extraction rate was 66.8%, and the gas contents in the nontectonic region and the tectonic region of the W2708S working face were 6.61 m³/t and 10.52 m³/t, respectively, which did not meet the requirements of the standard. After 4 months of additional extraction, the gas content in the tectonic region was 7.13 m³/t (12.28 m³/t lower than the original gas content), and the gas pre-extraction rate was ultimately 63.3%. The average gas pressure after extraction was 0.51 MPa, which was 5.22 MPa lower than the original gas pressure.

4.3. Gas Concentration in the Return Airway

During the coal roadway excavation period, the gas concentration in the return airway was monitored in real time. The gas concentration curves are shown in Figure 8. The government stipulates that electric drills are prohibited when the gas concentration in the return airway exceeds 1%, and construction work is prohibited when the concentration exceeds 1.5%.

As shown in Figure 7, the gas concentration exceeded 1% 16 times and exceeded 1.5% twice during the time that the W2708S working face coal roadway was excavated. In comparison, the number of times that the gas concentration exceeded 1% in the W2708N working face coal roadway was 2 (87.5% less than W2708S). No CGO accidents occurred on either working face. We found that the gas
The novel hydraulic technology mode shortened W2708S and W2708N coal roadways were 5.8 months and 6.1 months, respectively. This mode will ensure that the working faces continue on schedule and help the coal mine reap more economic benefits.

4.4. Time Required to Meet Government Standards

The time required for gas extraction to meet government standards includes three parts: the time for permeability enhancement, the time for drilling extraction boreholes and the time for extraction, as shown in Table 1.

Table 1. Details of the time required to meet government standards.

<table>
<thead>
<tr>
<th>Working Face</th>
<th>Time for Permeability Enhancement (months)</th>
<th>Time for Drilling Extraction Boreholes (months)</th>
<th>Time for Extraction (months)</th>
<th>Total Time (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2708S</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>W2708N</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

The time for permeability enhancement at the W2708S working face included drilling cross-measure fracturing boreholes (3 days), the hydraulic fracturing time (7 days) and the pressure holding time (20 days). The time for permeability enhancement in the W2708N working face included drilling cross-measure fracturing boreholes (2 days), the hydraulic fracturing time (5 days) and the pressure holding time (20 days). During the pressure holding time, HOST was simultaneously performed in the tectonic region.

In addition, if the gas concentration in the coal roadway exceeds the government standard, then work on the coal roadway should be put off for approximately 8 h. The excavation speed in the high gas concentration area is approximately half of the normal speed. The excavation times for the W2708S and W2708N coal roadways were 5.8 months and 6.1 months, respectively.

In summary, the time required to meet government standards at W2708N was 4 months shorter than that at the W2708S working face, and the excavation speed at W2708N (158 m/month) was 16% faster than that at W2708S (136 m/month). The novel hydraulic technology mode shortened the time required to meet government standards and improved the coal roadway excavation speed. This mode will ensure that the working faces continue on schedule and help the coal mine reap more economic benefits.
5. Conclusions

1. A novel mode for applying hydraulic technology to complex coal seams is proposed in this paper to promote gas extraction. This mode divides complex coal seams into tectonic regions and nontectonic regions based on geological structures. The advantages of different hydraulic technologies are matched with the characteristics of the different areas, such as HOST for tectonic regions and SDHFT for nontectonic regions. The permeability of coal seams can be sharply increased by pressure relief or fracturing methods, without leaving unfractured areas, and can promote gas extraction and ensure that coal mine production continues safely and efficiently. Additionally, this mode has the following characteristics: good applicability, more advantages, better effectiveness, and economic rationality. This mode will also be more mature with the development of the geological exploration techniques.

2. Application of this mode on adjacent working faces in the Datong First Coal Mine shows that this mode has better effectiveness than SDHFT. The gas concentration and flow of pure gas used in this novel mode were increased by 47.1% (from 16.96% to 24.94%) and 44.6% (from 4.24 m³/min to 6.13 m³/min) compared with SDHFT over 9 months. The extraction effectiveness was better, and the extraction time was reduced by 4 months. The pre-extraction rate for this novel mode was 66.8% over 9 months, and the pre-extraction rate for SDHFT was 63.3% over 13 months. This mode will reduce (or even eliminate) the number of times that gas concentration exceeds government standards during coal roadway excavation (from 16 to 2). In addition, this mode increased the coal roadway excavation speed by 16% (up to 158 m/month).

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References


