Research Article

Pressure Relief and Permeability Enhancement with Carbon Dioxide Phase Transition Blasting: Fracture, Seepage, and Practice

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Coal seams are generally characterized by high pressure, low permeability, and strong adsorption in China. Moreover, carbon dioxide phase transition blasting (CDPTB) is an effective way to achieve pressure relief and permeability enhancement in high-gas pressure coal seams. Multiple fractures can be created in the coal body by CDPTB due to its characteristics of having a great impact stress and high energy efficiency. To determine the dual characteristics of coal fracturing and seepage after CDPTB, this paper developed a fluid solid coupling programme based on CDPTB cracking and permeability enhancement, which unifies the fracture and seepage of CDPTB. FLAC was used to determine the distribution characteristics of the stresses and fractures caused by CDPTB. The results showed fracture propagation from the initial fracture to multiple additional fractures or the main fractures over time. Then, the fractures were introduced into COMSOL software to simulate the characteristics of the gas flow field. The main fracture forms an effective channel for gas flow, which greatly reduces the gas pressure in coal. The successful application of CDPTB in the field induced the increase in the gas drainage effect by 10-20 times.

1. Introduction

The geological conditions of coalfields in China are complex, and coal seams here are generally characterized by high pressure, low permeability, and strong adsorption [1, 2]. The permeability of most coal seams is in the range of $0.1 \times 10^{-18} \sim 1.0 \times 10^{-18} \text{ m}^2$, which is four orders of magnitude lower than that in the United States and three orders of magnitude lower than that in Australia [3–7]. With the gradual depletion of shallow resources and increased mining depths in recent years [8, 9], the permeability of coal seams has decreased sharply, and the gas content and pressure have increased correspondingly, which has further increased the possibility of dynamic disasters, such as coal and gas outbursts [10]. Pressure relief and permeability enhancement of proactive seams are fundamental technical measures to control gas disasters [11, 12]. However, it is difficult to achieve this goal in single, low-permeability, and high-gas coal seams. At present, some technologies, such as deep hole presplitting blasting [13, 14], hydraulic fracturing [15–17], hydraulic slotting [18, 19], and gas injection displacement [20–22], have been used in single coal seams and have achieved good results. However, these methods are difficult to popularize due to the resulting workplace pollution caused by water contamination issues, misfire problems, and the difficulty associated with approving explosives.

Carbon dioxide phase transition blasting (CDPTB), which is a kind of nonexplosive safety blasting technology, utilizes the high-energy gas generated by carbon dioxide phase transitions to impact coal. Coal fracturing is caused
2. Coupled Fluid Flow and Solid Mechanics Aspects of CDPTB

A fluid solid coupling mode of seepage and fracture caused by CDPTB was established to evaluate the effect of fractures on seepage. As shown in Figure 1, the coupling between them is driven by the connection between permeability and coal state. First, the solid mechanics calculation is carried out in FLAC. Judged by the Mohr-Coulomb criterion, coal is endowed with different states (elastic zone or plastic zone) under the impact stress caused by CDPTB. Then, different state coal samples (intact coal or fractured coal) are given different permeabilities. Finally, the distribution characteristics of the gas flow field under the effect of drainage are calculated at different permeabilities.

COMSOL is employed to determine the seepage characteristics of coal gas drainage. In this paper, the original Darcy equation given by the software is used for secondary development. The Langmuir equation of gas adsorption in coal is embedded in the Darcy equation. Combined with the initial conditions and boundary conditions of gas drainage in coal, the corresponding problems can be solved.

The permeability of fractured coal rises sharply, while intact coal remains at a similar level [37]. Because the permeability of fractured coal is increased by an order of magnitude compared with that of the initial coal, the gas mainly flows along the fractures in the coal. Compared with fractured coal, the permeability of intact coal is not greatly impacted under stress. In this paper, the effect of stress on coal permeability is ignored. The permeability of different positions caused by CDPTB is introduced into COMSOL through MATLAB. Firstly, the grid position and state in...
FLAC are stored as data files in the form of array. Then, the array is read by MATLAB and changed into different permeabilities according to the state. Finally, COMSOL accepts the data in MATLAB as permeability.

3. Fracture Propagation Characteristics by CDPTB

3.1. Numerical Simulation Model. In the numerical simulation, it is acceptable to adopt semitheoretical and semiempirical exponential attenuation loads to simulate the blasting process due to the lack of a direct test method to determine the pressure-time history curve of the hole wall in the actual process [38, 39]. The pressure-time history function of blasting can be expressed as follows, and the specific parameters are selected according to the parameters of CDPTB [39].

\[ P_t = 4P_b \left( e^{-\beta t/\sqrt{2}} - e^{-\sqrt{2}\beta t} \right), \]  

where \( P_t \) is the dynamic pressure (Pa), \( P_b \) is the peak pressure (Pa), \( t \) is the time (s), and \( \beta \) is the damping coefficient determined by the pressure rise time, which is determined by the pressure rise time \( t_r \), \( \beta = -\sqrt{2} \ln (1/2)/t_r \).

The dynamic pressure curve generated by CDPTB can be directly determined according to the peak pressure and pressure rise time. In this study, the pressure rise time of CDPTB is 0.001 s and the peak pressure is 70 MPa.

As shown in Figure 2(a), a numerical simulation model, 4.0 m × 4.0 m, was established to study the fracture mechanisms and fracture distribution characteristics under the impact of CDPTB. The Mohr-Coulomb criterion was selected in FLAC, and the plastic zone in the coal seam was taken as the standard to judge the distribution characteristics of coal fractures. The numerical model has been generated with a borehole in rock mass with nonreflecting boundaries and without free surface parallel to the borehole. The parameters used to simulate the coal body are shown in Table 1. The impact stress applied around the borehole is shown in Figure 2(b). The dynamic calculation method is set in FLAC, and the local damping is set to 5%.

3.2. Simulation Results

3.2.1. Final Distribution of Fractures. The final shape of the coal body after CDPTB is shown in Figure 3. The fractures at different positions of the coal body are classified according to the distribution characteristics. The CDPTB results in cracks of different lengths extending from the middle of the borehole to the outside. The coal body is split into large blocks by CDPTB due to the small width and radial direction of the fractures. Near the borehole, a few radial cracks appear due to the high blasting energy. At the far end of the borehole, part of the fractures expands to form the main fractures running through the coal body under the action of decaying energy, which decreases with time and is consumed by the coal body fractures. The lengths of multiple fractures are similar, and the fractures in the whole coal body are approximately symmetrical due to the uniform stress and the neglect of coal heterogeneity.

3.2.2. Fracture Evolution Process. The fracture expansion of coal throughout the entire CDPTB process is plotted and shown in Figures 4 and 5. Some conclusions can be drawn from the figures.

(1) The initial multiple fracture expansion state of the coal body is mainly concentrated in the pressure rising stage, and the main fracture expansion is mainly concentrated in the pressure rising stage and the early stage of pressure reduction. As the main fracture runs through the whole coal body, the fracture development terminates in the later stage of pressure reduction.

(2) When the initial action time is 0.1 ms, the coal body is not damaged due to the short action time and small impact stress. When the initial action time is 0.2 ms, eight initial fractures appear around the
3.2.3. Stress Evolution Process. The evolution law of the maximum principal stress in the CDPTB process is shown in Figure 6.

(1) At the initial stage (0.1 ms), the stress wave propagates outward in a circular form, and the propagation range is small because the coal body is not destroyed by the initial shock wave.

(2) With increasing CDPTB time, the pressure produced by CDPTB increases continuously, and the tangential tensile stress will break the coal around the borehole, producing the initial fracture around the borehole. The initial crack breaks the stress circle, and the maximum principal stress propagates along the crack, while in the remote area where the crack has not yet occurred, the maximum principal stress still propagates along the circle.

(3) As the stress propagates outward, the crack also propagates and the maximum principal stress propagates in the crack. Finally, the main fracture continues to expand throughout the whole coal body, and the maximum principal stress is also distributed in four areas.

Similarly, according to the propagation characteristics of crack stress in the process of CDPTB, the distribution of principal stress in the initial stage and crack propagation stage is plotted, as shown in Figure 7.

(1) In the initial stage of CDPTB, the blasting pressure acts uniformly around the borehole and the principal stress distributes along the tangential and radial directions around the borehole, resulting in tangential tensile failure of the coal around the borehole and the formation of initial cracks.

(2) With increasing CDPTB time, the crack in the coal body continues to expand, forming a large stress state at the crack tip. The principal stress in the damaged crack presents a unidirectional tensile effect, and the value of principal stress at the crack tip is larger, which continues to inflict tensile damage on the crack.

4. Gas Seepage Characteristics in Fractured Coal

4.1. Numerical Simulation Model. On the basis of CDPTB, the gas seepage law of fractured coal is studied and a square model is established. The size of the model is 4.0 m × 4.0 m, which is consistent with the size of the CDPTB model. To obtain the accurate solution of the model, the possible area of coal fracturing is subdivided.

The Langmuir equation of gas adsorption in coal is embedded in the Darcy equation. The gas seepage equation can be expressed as [40]

$$\frac{M_c}{RT} \phi + \frac{abcM_c}{(1+b)p} V_m \left( \frac{\partial p}{\partial t} - \nabla \cdot \left( \rho - \frac{k}{\mu} \nabla p \right) \right) = 0, \quad (2)$$

where $p$ is the gas pressure (Pa), $M_c$ is the gas molar mass (kg/mol), $R$ is the gas constant (J/(mol·K)), $T$ is the absolute temperature under standard conditions, $\phi$ is the porosity of coal seam, $a$ and $b$ are the gas adsorption constant, $c$ is the corrected density of coal (kg/m$^3$), $V_m$ is the ideal gas molar volume (L/mol), $t$ is the gas migration time (s), $\rho$ is the gas density (kg/m$^3$), $k$ is the permeability (m$^2$), and $\mu$ is the gas dynamic viscosity (Pa·s).

The drainage characteristics of this part of the coal body are simulated, and the recharge effect of far-field gas is ignored; the boundary conditions of numerical simulation are as follows:

$$\begin{align*}
\frac{\partial p}{\partial x} &= 0, \quad x = 0, 4 \\
\frac{\partial p}{\partial y} &= 0, \quad y = 0, 4 \\
p(x, y, t) &= p_1, \quad x^2 + y^2 = r^2
\end{align*}$$

where $p_1$ is the gas drainage pressure (Pa) and $r$ is the radius of the gas drainage borehole (m).
The initial conditions in the numerical simulation are as follows:

\[ p(x, y, z) = P_0, \]  

where \( P_0 \) is the initial gas pressure (Pa).

In the numerical simulation of coal gas drainage, a transient analysis solver was used. The other relevant coal models and gas adsorption constants are shown in Table 2.

4.2. Simulation Results

4.2.1. Gas Pressure Distribution in Intact Coal. To evaluate the characteristics of gas seepage in fractured coal after CDPTB, we first analyse the effect of gas drainage in the original intact coal. In this model, a uniform original gas pressure is assigned and a negative pressure is adopted in the middle of the coal for gas drainage. After gas drainage, the gas pressure of the coal body at different times is shown in Figure 8, and the Darcy velocity vector

![Figure 4: Fracture development characteristics of the coal body in different periods of CDPTB.](image)

![Figure 5: Stress distribution characteristics and crack propagation lengths.](image)
distribution of the gas flow field is shown in Figure 9. Under the effect of drainage, the gas pressure is distributed in a circular shape, and the gas flows evenly to the borehole. The closer to the borehole the gas is, the greater its velocity. However, it only affects the area around borehole and has little influence on the original overall gas pressure in the coal.

4.2.2. Gas Pressure Distribution in Fractured Coal. The distribution characteristics of gas pressure at different times after the extraction of the fractured coal body are shown in Figure 10.

At the initial time of gas drainage, the gas in multiple fractures flows directly to the drainage borehole, resulting in a sharp reduction in the gas pressure of multiple fractures, which forms an effective channel for gas flow. The reason is that a large number of multiple fractures produced by CDPTB are distributed around the borehole, and the permeability of the coal body in the fracture area is much higher than that of the original coal body.

With the continuous increase in extraction time, the gas pressure reduction area gradually expands from the multiple fracture area to the main fracture part, and the gas in the fracture rapidly drills into the middle part. The fractures throughout the whole coal body form an effective channel for gas flow. Then, a new gas gradient is formed between the gas pressure throughout the whole coal body and those in the fracture, and the gas pressure in the whole coal body decreases with increasing extraction time. Finally, the gas distribution characteristics relying on CDPTB cracks are formed in the coal. The gas pressure in the cracks always exists in a low state, and the gas pressure increases from the cracks to the outside.

Multiple fractures with short lengths and a few main fractures with larger lengths are formed in the coal body after CDPTB. A polar coordinate system is established, and
the centre of the drainage hole in the middle is taken as the origin. The distribution characteristics of gas pressure in the coal body within the range of multiple fractures ($r = 0.3 \text{ m}$) and the range of the main fractures ($r = 1.0 \text{ m}$) are drawn, as shown in Figure 11.

According to the gas pressure curves at different positions, multiple fractures and the main fractures act as the dominant channels of gas flow. The gas pressure in the coal body drops sharply in areas where the fractures are distributed. In the multiple fractures close to the borehole, the gas pressure is obviously different from that in the coal body due to the large number of fractures and their close distance from the drainage borehole. In the main fractures, because the number of fractures is small, there are only four directions, and the gas pressure distribution in the coal body is divided into four identical parts, showing a symmetrical distribution. With increasing extraction time, the gas pressure in the coal body also decreases, but the decreasing amplitude is smaller than that in the multiple fractures.

### 4.2.3. Distribution of the Gas Flow Field in Fractured Coal

Fractures are the dominant channel of gas flow in the coal body. The distribution characteristics of the gas flow field...
different times of gas drainage in the fractured coal body are shown in Figure 12.

During the early stage of gas drainage, the presence of fractures only affects the gas characteristics near the borehole due to the short drainage time. The gas near the multiple fractures flows to the nearest fracture, and the gas in the coal body continuously converges to the fractures and then continuously flows into the drainage borehole. With the continuous increase in extraction time, the gas flow field throughout the entire fracture gradually reaches a stable state. The gas flow field in the coal body is divided into four symmetrical parts due to the effect of the main fracture. In each independent gas flow field, the dividing line of the gas flow field is formed from the corner point of the coal body and the centre of the borehole. The gas at the middle part of the boundary directly presents radial flow from the corner point to the borehole, while at both sides of the dividing line, the gas flows to the main fracture and then converges at the drainage borehole.

5. Field Practice of Permeability Enhancement by CDPTB

The Gaohe coal mine, a very large production mine with a design production capacity of 6.00 Mt/a, mainly mines 3# coal seam, which has a thickness of 6.22-7.35 m and an average thickness of 6.77 m. The gas content of coal seam is 10-15.49 m$^3$/t. The coal seam has poor permeability and is difficult to extract. The roof is composed of mudstone, sandy mudstone and siltstone, and local sandstone. The floor is composed of black mudstone, sandy mudstone, and dark grey siltstone. To improve the gas drainage efficiency of the E2307 belt transportation roadway, the CDPTB borehole is constructed in the belt transportation roadway. The driving face adopts a double air duct for air supply, and the ventilation rate is 1500 m$^3$/min.

5.1. CDPTB Scheme. The CDPTB boreholes are constructed within the gas drainage boreholes in the roadway. The spacing between each blasting borehole is 10 m. As for the
designed sealing length and the sealing pressure, they are 20 m and 8 MPa, respectively. Additionally, the construction azimuth of each blasting borehole is 175 degrees. The specific drilling layout is shown in Figure 13, and the specific drilling parameters are shown in Table 3.

5.2. Effect of Permeability Enhancement by CDPTB. The cracks caused by CDPTB play a role in reducing the pressure in the coal seam, providing a channel for the gas flow in the coal body, promoting the generation and analysis of the gas around the coal body, and continuously transforming the gas existing in an adsorption state into gas existing in a free state, which effectively reduces the gas pressure and gas content of the coal body. By monitoring the gas concentration in the air flow in the roadway, the relationship between the gas in the roadway and the related CDPTB is obtained. The

![Figure 10: Distribution of gas pressure in the fractured coal.](image1)

![Figure 11: Gas pressure distribution at different radii of the fractured coal.](image2)
monitored gas concentration in the roadway is shown in Figure 14, which indicates that CDPTB has an obvious disturbance effect on the gas in the roadway airflow. The coal body is disturbed by CDPTB, and a large amount of gas is resolved, which increases the instantaneous gas concentration of the roadway. The increase peak lasts for 3–5 hours and then returns to the normal level. CDPTB has an obvious effect on the gas resolution, but the action time for the gas resolution on the roadway surface is short.

The borehole is connected to the grid for drainage after CDPTB. The changes in the gas concentration and gas drainage purity in the gas drainage borehole are shown in Figure 15. However, the gas concentration increase before and after CDPTB is small, while the gas drainage purity increases significantly. This is because there are also many non-CDPTB drainage boreholes in the branch pipe. For a single CDPTB borehole, it is determined that the CDPTB obviously promotes the gas analysis and greatly improves the gas drainage efficiency.

In general, as shown in Figure 16, the new fracture system resulting from CDPTB greatly improves the efficiency of gas drainage in the coal seam and shortens the time of gas drainage:

1. The gas drainage concentration of the CDPTB borehole is increased from 15% to more than 50%, which is greater than a 3-fold increase.

2. From 0.00089–0.0284 m³/min-hm to 0.12–0.2 m³/min-hm, the gas flow per hundred metres of the borehole is increased 10–20 times.
The attenuation coefficient of gas flow is reduced from 0.1833~0.4389 d⁻¹ to 0.02~0.04 d⁻¹, which is a 10~20 time reduction, making the drainage coal seam more readily drained.

6. Conclusion

(1) Coupled fluid flow and solid mechanics aspects of CDPTB are established to determine the crack...
expansion range during CDPTB and the influence of coal cracks on the flow field distribution after CDPTB. The mechanical characteristics of CDPTB are coupled with seepage characteristics by taking the damage characteristics of coal as the medium.

(2) The initial multiple fracture morphology and fracture propagation state caused by CDPTB are mainly concentrated in the stage of pressure rise, and the cracks are mainly affected by the tensile stress produced by CDPTB around the borehole. The results show that the principal stress is of unidirectional tensile nature within the failure crack, and the value of principal stress at the crack tip is larger, which causes continuous tensile damage to the crack. With the attenuation of the stress wave, the main fracture and multiple fractures are formed in the coal body by CDPTB.

(3) The cracks produced by CDPTB form the dominant channel of gas flow. The gas in the coal body converges to the nearest crack and then flows into the drainage borehole through the crack. The gas flow velocity is highest, and the gas pressure is the lowest at the crack. With increasing distance from the crack, the gas flow velocity decreases and the gas pressure increases. The main fracture runs through the whole coal body, and the number of fractures is large, which greatly expands the gas drainage range of the coal body.

(4) The application to the Gaohe coal mine shows that CDPTB produces many cracks in the coal body, which promotes the analysis and flow of gas. The gas extraction concentration of the phase fracturing hole is increased from 15% to more than 50%, and the permeability coefficient of the coal body is increased by more than 10–20 times, which shows that the gas extraction efficiency is improved and the safe production of the mine is guaranteed.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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