INTRODUCTION

More than 95% of the coal seams mined in high gas, and outburst mines belong to low-permeability coal seams in China, and the difficulty of extracting coal seam gas has become a coal seam feature of most coal mines.¹ To improve the gas drainage efficiency and increase the permeability of coal seams, researchers at home and abroad have conducted much research on appropriate technologies for studying these parameters and have achieved some useful results, such as the use of a regional predrilling pump,²,³ hydraulic fracturing,⁴,⁵ hydraulic flushing,⁶,⁷ and deep hole...
presplit blasting. However, these technologies have their own limitations, or higher costs or they may require a large amount of engineering or improvements in safety. and CO₂ presplitting blasting is a new blasting method that uses the physical characteristics of gas, loosening and crushing. Compared with the violent chemical reaction associated with explosives, CO₂ presplitting blasting has better safety and applicability, and better prospects for commercialization and application.

Currently, at Chinese coal mines and in many engineering practices, carbon dioxide is used to blast coal and rock mass in many engineering practices, with little experimental and theoretical research. According to the principle of detonation, the increase in the free surface not only saves energy, but also generates more detonation cracks. The free surface provides a good guiding effect for bursting cracks and achieves good results in practice. This effect of empty holes is called the “empty hole effect”. Combining the empty hole effect with CO₂ presplitting blasting, the guidance effect of the empty hole and the free surface effect are used to fully develop cracks and further improve the permeability of the coal seam. Scholars at home and abroad have performed much research on the stress field distribution around the cavity. In terms of theory, Dally used dynamic photoelasticity to study the distribution of the explosion stress wave around the cavity. Liu theoretically obtained the stress concentration effect of empty hole. Li used the theory of elastic mechanics to deduce the calculation formula of void hole effect under the action of blasting stress. Meng established a tension-compression constitutive model of rock mass damage.

In terms of experiment, Yue used a new digital laser dynamic caustic line to study the effect of hole-hole on the behavior of primary crack propagation. Chen explored the fracture direction of rock when the void holes are located in different action zones. Yue explored the experimental study of crack propagation in polymethyl methacrylate material with double holes under the directional controlled blasting. Yang explored the experimental investigation on the influence of different diameter empty holes on the crack growth behavior of blasting. Li explored the stress concentration effect of empty hole was investigated by experiment.

In terms of numerical simulation, Bian explored the damping effect of empty holes on blasting vibration by numerical simulation. Wang used numerical simulation to explore the propagation characteristics of explosive crack under different working conditions. Li used numerical simulation to explore the effect of empty hole between adjacent blast holes in the perforation process of blasting. In order to study the effects of different diameters of empty holes on the blasting effect of first-ring cut, Zhu used numerical simulation method to carry out a comparative analysis of the cutting scheme of single empty hole under different diameters of empty holes.

However, under the effect of CO₂ presplitting blasting, not enough research was performed on the antireflection effect of the empty holes in the coal seams and the controlling mechanism, and it is difficult to reveal the principles of crack development under the influence of the “empty hole effect.” To study the antireflection effect of the “empty hole effect” on coal seams, this paper studies the damage and crack growth principles of coal and rock mass through theoretical and laboratory CO₂ presplitting blasting experiments, then, this paper compares the results of LS-DYNA numerical model to analyze the influence of the empty hole effect to guide cracks propagations, and explore the antireflection effect of coal seams under CO₂ presplitting blasting.

2 | THEORETICAL

To study the empty hole effect on crack propagation, a physical model is established as shown in Figure 1. This model has empty holes arranged on the upper and lower sides of the blast hole and provides a limited volume of the coal and rock mass to replace the actual infinite coal seams. To prevent the stress wave from generating a boundary effect on the left and right boundaries, it is assumed that setting a nonreflective boundary on the left and right boundaries can solve this problem.

The blasting stress wave propagates in two media; and reflection occurs at the interface, and the reflected wave will cause the superposition of stress and displacement. When the blasting stress wave is perpendicularly incident,
its propagation direction is perpendicular to the interface; the stress wave has a reflection effect at the free surface, as shown in Figure 2.

The propagation law of the incident wave in the medium can be obtained as follows:

\[ \sigma_i(x, t) = \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{x}{C_p} \right) \right) \quad t > \frac{x}{C_p} \]  

(1)

The reflected wave in the propagation medium is:

\[ \sigma_r(x, t) = f_r \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{x + L}{C_p} \right) \right) \quad t > \frac{x + L}{C_p} \]  

(2)

The superposition of the incident and reflected waves can be seen Figure 1, \( x = L - x' \); therefore:

\[ \sigma(x, t) = \sigma_i(x, t) + \sigma_r(x, t) = \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{x}{C_p} \right) \right) - f_r \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{2L - x}{C_p} \right) \right) \]  

(3)

when \( t > \frac{2L - x}{C_p} \), and substituting (1) into (3) gives:

\[ \sigma(x, t) = \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{x}{C_p} \right) \right) - f_r \sigma_0 \sin \left( \frac{\omega}{C_p} \left( t - \frac{2L - x}{C_p} \right) \right) \]  

(4)

From Equation (4), the magnitude of the stress wave after superposition depends on \( \sigma_0, f_r, L, C_p, \) and \( \omega \), so the local position stress superimposition will appear in the medium.

When the stress wave propagates in the coal rock, the energy \( E \) transmitted to the coal rock per unit area is:

\[ E = \int_0^t \sigma(t) u(t) dt \]  

(5)

where \( u(t) \) is the function of particle velocity over time.

In the area where the stress wave acts, the shock wave formed by the expansion and extrusion of the explosive material acts on the wall of the blast hole. Because the tensile stress load of the shock wave far exceeds the dynamic tensile strength of the coal and rock mass, the solid skeleton of the coal and rock mass deforms and fails. The dynamic tensile strength of the coal and rock mass is used as its failure criterion. Simultaneously, the dynamics of the action of the shock wave during the initial damage reaction of the coal and rock mass are considered. The damage variable \( D \) is introduced. The effective dynamic tensile strength of the coal and rock mass is used to describe the crushing of the coal and rock mass as follows:

\[ \sigma_e = (1 - D_0) \sigma_d \]  

(6)

where \( \sigma_e \) is the radial tensile stress of the blasting shock wave; \( D_0 \) is the initial damage value of the coal and rock mass; and \( \sigma_d \) is the dynamic tensile strength of the coal and rock mass.

The stress intensity factor of the macrocrack tip under the action of explosive gas is:

\[ K_1 = \frac{2}{1 - D} \int_0^L \frac{P(x, t)}{(a + r_h)^{1.5} - x^2} dx \]  

(7)

where \( K_1 \) is the effective stress intensity factor; \( a \) is the angle between the crack and the maximum principal stress in the far field; \( r_h \) is the explosion hole radius; \( P(x, t) \) is the pressure of the explosive gas on the crack surface; and \( L(t) \) is the length of the explosive gas penetrating into the crack.

When using elastic constitutive forces, the stress can be calculated from the strain, elastic modulus \( E \), and Poisson's ratio \( \mu \). The equation is as follows:

\[ \sigma = Q \cdot \varepsilon \]  

(8)

\[ Q = \frac{E}{1 + \mu} \begin{bmatrix} 1 - \mu & \mu & \mu \\ 1 - 2\mu & 1 - \mu & 1 - 2\mu \\ 1 - 2\mu & 1 - 2\mu & 1 - \mu \\ \end{bmatrix} \begin{bmatrix} 1 - \mu & 1 - 2\mu & 1 - 2\mu \\ 1 - 2\mu & 1 - \mu & 1 - 2\mu \\ 1 - 2\mu & 1 - 2\mu & 1 - \mu \\ \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{2} \\ \end{bmatrix} \begin{bmatrix} 1 - \mu & \mu & \mu \\ 1 - 2\mu & 1 - \mu & 1 - 2\mu \\ 1 - 2\mu & 1 - 2\mu & 1 - \mu \\ \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{2} \\ \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & \frac{1}{2} \\ \end{bmatrix} \]

In the equation, \( \sigma \) is the stress tensor; \( \varepsilon \) is the strain tensor; \( Q \) is the elastic constitutive parameter; \( E \) is the modulus of elasticity; and \( \mu \) is Poisson's ratio.

CO₂ presplitting blasting of a coal and rock mass with empty holes is completed under the combined action of stress waves and explosive gases. If the tangential tensile stress derived from radial displacement exceeds the tensile strength of the coal and rock mass, it will generate radial cracks in the coal and rock mass; then, the explosive gas is filled the initially formed radial crack, and the crack propagates under a
gas-driven mode. The physical model of CO₂ blasting in the entire empty hole of the coal and rock mass is expressed by Equations (4)-(8). The equations are shown below:

\[
\begin{aligned}
\sigma(x,t) &= \sigma_0 \sin \left[ \omega \left( t - \frac{x}{C_p} \right) \right] - f_R \sigma_0 \sin \left[ \omega \left( t - \frac{2L-x}{C_p} \right) \right] \\
E &= \int_0^{t_f} \sigma(t)u(t)dt \\
K_1 &= \frac{2}{1-D} \sqrt{\frac{\sigma_0}{\pi}} \int_0^{r_b} \int_{L_0}^{L+L_0} \frac{P(x,t)}{\sqrt{(a+r_b)^2-x^2}} dx \\
\sigma &= Q \cdot \varepsilon
\end{aligned}
\]

\[ (9) \]

3 | EXPERIMENTAL

3.1 | Experimental platform design

To carry out CO₂ presplitting blasting experiments on coal and rock mass containing empty holes, a CO₂ presplitting blasting experimental platform was independently established that consists of a loading system, a blasting system, and an observation system. The loading system is a high-frequency pulse meter, which is intended to achieve the effect of adding a specific axial pressure to the coal and rock mass, and the basic physical parameters of the sample are measured at the beginning of the experiment. The blasting system consists of a CO₂ gas cylinder, a pressure reducing valve and an explosion-proof gas pipe. The blasting system can release CO₂ gas at a specific pressure value in an instant, to achieve the effect of blasting. The observation system includes two instruments: VIC-3D and an ultrasonic wave. The VIC-3D was used to observe the coal and rock mass and to observe the displacement and strain changes on the surface of the sample during the blasting process. The ultrasonic wave can collect the wave amplitude and analyze the internal damage of the coal and rock mass based on the characteristics of the different wave propagation speeds and amplitudes in different media. The whole experimental platform design is shown in Figure 3.

3.2 | Preparation of samples

Due to the large number of cracks on the surface of the drilled samples, there is a relatively large error in the speckle image acquisition of the sample surface, and the strain change on the surface cannot be observed. Therefore, the coal blocks were immediately crushed and molded into 70 mm * 70 mm * 140 mm cuboid standard sample briquettes, the specific shape of the sample and the positions of the blasting hole and empty holes are consistent with the model diagram shown in Figure 1, so that their physical and mechanical properties, such as the strength of the raw coal sample, were approximately the same. Three groups of samples were prepared and recorded as A1, A2, and A3; B1, B2, and B3; C1, C2, and C3.

The sample preparation process mainly solves the problem of pore preparation. First, the position of the explosion hole is reserved in the center of the coal sample, and then, the empty holes are placed on the two sides of the hole 3.5 cm away from the explosion hole. The hole was allowed to stand for 5 hours, and then, the samples demolded after it formed. After demolding, the raw was prepared materials according to the previous ratio, and then, the holes were sealed according to the calculated ratio to achieve the effect of an empty hole with an interior length of approximately 1 mm. Finally, the sample was placed in a room to care for 28 days.

After the sample completely dried, the prepared coal sample was polished with sandpaper to adjust the upper and lower ends of the sample to 140 ± 0.5 mm. The final samples are shown in Figure 4.

3.3 | Experimental procedure

Before the test, to better observe the blasting effect, the samples were first tested for strength. The results are shown in Table 1. The compressive strength of the sample was approximately 8 MPa.

To eliminate the influence of the sample ends on the test, petroleum jelly was applied to the upper and lower ends of the coal samples to cause the coal sample to contact the loading probe well, and then, the ultrasonic probes were fixed on the left and right sides of the sample. (a) At the beginning of the experiment, according to the test results, the high-frequency pulse meter was first adjusted to a constant
pressure of 2 MPa. (b) After the pressure reached the set value, the high-frequency pulse was no longer be pressurized. At this time, the carbon dioxide cylinder switch was turned on and the pressure reducing valve was adjusted. Then, the gas in the gas cylinder is passed into the blast hole. (c) While introducing carbon dioxide into the explosion hole, VIC-3D was used to observe the surface strain change in the sample during the gas explosion process, and the ultrasonic wave was used to analyze the damage inside the sample according to the different changes in the amplitude. The most critical issue during the experiment is the sealing problem. If the seal is not good, the sample will leak, and the effect of blasting will not be achieved. Therefore, to prevent the sample from leaking, the connection between the cylinder and the gas pipe installed with fixing clips and the air pipe was tightly connected to the sample with hot melt adhesive to achieve the effect of sealing. The experimental process completed by the test platform is shown in Figure 5.

3.4 Experimental results and analysis

3.4.1 Effect of stress on crack propagation control

During the experiment, VIC-3D was used to observe the crack propagation changes on the surface of the sample through digital speckle measurement technology. Since the holes were set on the upper and lower sides of the explosion hole, based on the principle of symmetry, cracks developed in the sample similarly. Here, we took the upper half of the sample as the research object.

During the test, the strain on the surface of the sample was measured with VIC-3D. When using the elastic constitutive, the stress can be calculated from the strain, the elastic modulus $E$, and the Poisson's ratio $\mu$. The equation is shown in (8). From the calculation of the stress-strain curve, Poisson's ratio $\mu$ can be obtained from the calculation of the strain. The main stress estimation process is shown in Figure 6.

After the three groups of samples were blasted, the explosion chamber will be quickly filled with a large number of compression waves. When the compression waves propagated to the holes, due to the free surface provided by the holes, the compression waves will reflect to form reflected waves. The compression wave propagates along the path of the cavity to form a main crack channel. At this time, we can obtain the strain change curve at the main crack according to VIC-3D, as shown in Figure 7.
It can be seen from the above figure that the strain on the sample surface reaches the maximum at 0.13 seconds, at this time, the main crack channel is formed between the blast hole and the empty hole. In addition, according to the stress-strain relationship in Equation (5), it can be seen that the more strain changes, the greater the stress at this place. Through the abovementioned guiding empty hole effect, a compression wave is generated at the blast hole, and a reflected wave is formed after passing through the free surface. When the compression wave and the reflection wave are superimposed, a radial tensile stress is formed between the blast hole and the empty hole. Therefore, the stress at the main crack is the largest. Figure 8 shows the stress and strain cloud diagrams obtained from the different samples. From the figure, when the main crack channel is formed between the blast hole and the empty hole, the strain of the sample surface reaches the maximum. The corresponding stress also reaches the maximum.

This phenomenon further verified that after the CO₂ presplitting blast, radial tensile stress was generated due to the superposition of waves, so that an obvious crack channel was formed between the two holes.

In order to better understand the incident wave passing through the free surface, we established a system of Equations (9), which clearly expressed that the superposition of the waves would form a main crack channel similar to a straight line between the blasting hole and the empty hole. During the test, some samples will be split from the middle after the blasting process. We use a more complete and representative sample for observation and analysis as an example, as shown in Figure 9 on the left. The processing is shown in the right of Figure 9.

There is an approximately straight main crack channel between the blast hole and the empty hole. When the compression wave reaches the free surface and generates a reflected wave, the reflected wave will be centered on the empty hole and diffuse in a circular shape to the surrounding area. The wave will form different angles with the free surface. The larger the angle, the smaller the stress formed. Therefore, only the radial tensile stress that forms an approximate straight line between the two holes will form the main crack channel.

### 3.4.2 Effect of energy on crack propagation control

Equation (5) shows that the energy dissipation can also reflect the internal crack growth of coal rocks. To better explore the free surface effect caused by empty holes on crack propagation control, ultrasonic tests were used during the test. The change in the first wave amplitude was recorded.
to analyze the energy dissipation in the coal and rock mass during the blasting process. The change in the amplitude of the CO$_2$ blasting ultrasonic detection over time is shown in Figure 10.

Figure 10 shows that, there is a large fluctuation in the amplitude of the sample is observed during the period of 0-0.13 seconds. Because the propagation speed and frequency of the sound wave in different media are different, it can be seen that the internal damage of the sample during this time is most severe. It can be seen from the strain change observed by using VIC-3D that the strain reached its peak at 0.13 seconds, and it can be analyzed by combining the ultrasonic amplitude map that the main crack channel formed at this moment.

The ultrasonic attenuation coefficient $\alpha$ can reflect the degree of ultrasonic energy loss. Therefore, this coefficient can indirectly reflect the degree of deformation damage and fracture evolution in the coal and rock mass. The calculation formula for the attenuation coefficient $\alpha$ is:

$$\alpha = \frac{1}{L} \ln \frac{A_m}{A_i}$$

In the equation, $L$ is the distance from the transmitting transducer to the receiving transducer; $A_m$ is the first wave amplitude before the start of loading; and $A_i$ is the first wave amplitude during gas explosion.

![FIGURE 9 Crack development diagram](image)

Since the attenuation coefficient $\alpha$ can favorably reflect the internal damage of the coal and rock mass, we can analyze the empty hole effect on the secondary crack growth during the gas explosion process. The change curve of the attenuation coefficient $\alpha$ of the sample over time is shown in Figure 11.

The whole process of gas explosion can be roughly divided into two stages. The first stage (I) is the first time the fluctuation in the attenuation coefficient changes greatly. Accordingly, the damage mechanism analysis of the empty hole effect on the coal and rock mass can be performed here. The compression wave reaches the free surface and generates a reflected wave, which generates radial tensile stress, and causes large damage to the coal and rock mass. At 0.18 seconds, the attenuation coefficient reaches a maximum of 0.0042. It is proven that when the main crack channel is formed at this moment, the most severe damage changes in the coal and rock mass internally occur.

The second stage (II) occurs between 0.23 seconds and 0.8 seconds, during which gas explosion is completed, secondary cracks are generated due to the effect of gas wedges, and the propagation of secondary cracks caused damage to the coal rock again, which causes the attenuation coefficient to fluctuate. However, the secondary cracks develop more slowly than the main cracks during this period.

To explore the CO$_2$ presplitting blasting of empty holes in the coal and rock mass, and the effect of energy on crack propagation, ultrasonic instruments were used to collect the amplitude of the wave at the instant of blasting. Due to the different propagation speeds and fluctuation frequencies of sound waves in different media, amplitude-time diagram of the different groups of samples was used to analyze the internal damage of the samples at various times. Using the amplitude of the first wave, we calculated the attenuation coefficient $\alpha$, analyzed the crack propagation at different stages, and analyzed the effect of energy on crack propagation control under the empty hole effect; this further proves that the main formation of cracks is due to the superposition of compression waves and reflected waves.

4 | NUMERICAL SIMULATION

4.1 | Building a similar model

ANSYS/LS-DYNA is a full-featured nonlinear explicit analysis package that can handle all kinds of complex nonlinear problems. ANSYS/LS-DYNA is especially suitable for analyzing various dynamic nonlinear problems such as shocks and explosions. The Euler algorithm can overcome the computational difficulties caused by the severe distortion of the unit. To better study the empty hole effect on crack development under the effect of carbon dioxide gas explosion,
A three-dimensional model is provided in which two holes are set on each side of a carbon dioxide explosion hole. The advantages and the effect of voids on the permeability of the coal seams were studied.

Based on the model diagram shown in Figure 1, we built a corresponding numerical simulation model diagram. In order to facilitate the observation of crack development after gas explosion, the size of the numerical simulation was 200 times larger than that of the test. The size of this model is 14 m × 14 m × 28 m, and the explosion hole spacing is 3 m, which is divided into 279,992 units. The physical and mechanical parameters of the coal and rock mass were measured experimentally: E, G, and K are the elastic modulus, the shear modulus, and the bulk modulus of the coal and rock mass, respectively. The values are 3.20, 1.28, 2.10 GPa respectively, the density is 1200 kg/m³; and μ is the Poisson’s ratio of the coal and rock mass, where the value is 0.25. In the numerical simulation, due to the limitation of computer power, a finite volume numerical model must be used to replace the actual infinite coal seams. Therefore, the boundary effect of stress waves on the left and right boundaries must be prevented by using, borders to effectively address this issue.

4.2 Simulation results and analysis

4.2.1 Influence of the empty hole effect on the coal seam

To verify that the experimental empty hole effect on the coal seam was obtained, through the Equations (9), we obtained the propagation characteristics of the stress wave with the increase of the free surface, and the equations roughly restored the crack development under the action of the empty hole effect. Several time node diagrams with obvious steering action characteristics were intercepted by simulating the entire gas explosion process. The simulation results obtained the pressure clouds in the coal and rock mass at different times, which further verified the control of the empty hole effect on the coal and rock mass.

Figure 12A is a pressure cloud diagram showing the time from when CO₂ is introduced into the sample to 0.18 seconds. At this time, an air explosion occurs in the sample, and the pressure in the explosion hole reaches a peak of 6.296 × 10⁻⁴ MPa. A main crack will appear at the blast hole and extend to the periphery of the hole. At this time, the pressure in the hole also reaches a peak of 5.626 × 10⁻⁴ MPa. When the gas explosion occurs to 0.53 seconds, a clear connection channel is initially formed between the blast hole and the empty hole, and the control of the empty hole begins to take effect. As shown in Figure 12B, the inner space of the sample is empty at this time. The degree of fracture of the coal and rock mass at the hole is more significant than that at other parts. In the late stage of gas explosion at 1.1 seconds, we can see from Figure 12C that the internal pressure of the sample is gradually decreasing at this time, and the peak pressure in the blast hole reaches 9.603 × 10⁻⁵ MPa. At 1.5 seconds, the entire process of gas explosion of the sample is completed. As shown in Figure 12D, it can be clearly seen that a connected main crack is formed between the blast hole and the empty hole. Most of the cracks around the blast hole...
follow the movement in the direction of the holes, and the degree of fracture of the coal and rock mass at the holes is more severe.

As can be seen from Equation (5) \( E = \int_0^t \sigma (t) u(t) dt \), the change of \( E \) will change with the change of \( \sigma \). Based on this theory, we can observe the change of \( E \) in the process of air burst, so as to further verify that when the main crack channel is formed, the maximum stress and the maximum energy are located there. Energy and stress curves corresponding to different times obtained through the simulation are shown in Figure 13. During the period of 0-0.18 seconds, the total energy dissipation in the coal and rock mass is the largest, and the stress introduces a peak, which indicates that the energy and stress inside the coal and rock mass have a negative linear correlation between the blast hole and the empty hole, when the main crack channel is formed. The stress peak at 0.18 seconds also confirms the theoretical analysis, that is, when the compression wave reaches the free surface, a reflected wave will be generated. The superposition of the reflected wave and the compression wave creates a main crack channel between the blast hole and the empty hole. At this moment, the main stress at the crack is the largest.

Experimental and numerical simulation analyses of CO2 presplitting blasting of empty hole in the coal and rock mass can be used to deduce the empty hole effects on the crack propagation of the coal and rock mass, that is, when carbon dioxide is introduced into infinite coal and rock mass media, gas explosions occur. At that time, generate shock waves are generated in the coal and rock mass, and the intensity of the shock wave rapidly decays with the propagation distance, therefore, its damage characteristics to the coal rock mass will also change accordingly.\(^{39,40}\) The empty hole effect is applied to the CO2 blasting of the coal and rock mass: (a) The empty hole provides a free surface for the coal seam. After the gas explosion, the compression wave generated by the coal and rock mass meets the hole wall and generates a reflected tensile wave. The strength is greater than the tensile strength of the coal and rock mass, and it corresponds to the radial displacement of the coal and rock mass and the fracture of the coal and rock mass. (b) After a CO2 gas explosion in the coal seam, a compression wave is generated in the coal and rock mass. The compression wave strength is greater than its resistance. Under the action of explosive gas, the compressive strength of the coal and rock mass is displaced toward the empty hole, and a crack channel is formed between the blast hole and the empty hole.

5 | CONCLUSION

In this paper, a carbon dioxide gas explosion test is performed on a coal and rock sample containing voids, and a numerical model is established in conjunction with LS-DYNA to study the effect of empty holes on the crack development of coal and rock mass under the effect of carbon dioxide gas explosion. The results show the following:

1. After a gas explosion occurs, the peak pressure in the explosion chamber reaches \( 6.296 \times 10^{-4} \) MPa. Under this pressure peak condition, the main crack will fully develop along the direction of the empty hole and form an approximate straight line between the blast hole and the empty hole. The main crack channel provides good control for the development of coal seam cracks.

2. According to the strain change observed on the surface of the sample by using VIC-3D, and the attenuation coefficient \( \alpha \) calculated by using the amplitude collected by the ultrasonic wave, the internal stress and attenuation coefficient of the coal and rock mass reach their peak values when the main crack channel is formed; this indicates that the most severe damage occurred within the coal and rock mass at this time.

3. Numerical simulations show that the main crack channel is formed at 0.13 seconds and that the energy dissipation is at a maximum when the internal stress of the coal and rock mass reaches 0.18 seconds. During the time period of 0-0.18 seconds, there is a negative linear correlation between energy and stress. After 0.18 seconds, the energy and stress inside the coal and rock mass tend to be gentle.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT
The data used to support the findings of this study are available from the corresponding author upon request.

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