Experimental Study on High-Pressure Air Blasting Fracture for Coal and Rock Mass

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Abstract
In order to research on the issue of high-pressure gas blasting fracture deeply, a high-pressure gas blasting cracking experimental system was established; the effects of gas pressure and gas volume on the morphology of crack growth were studied; the p-t curve of pressure in the blasting process with time was obtained; and the mechanism of high-pressure gas blasting cracking was analyzed in this paper. The conclusion has shown that the stage of effect of high-pressure gas blasting on the test block includes three stages: the gas jet impact stage, the crack initiation and development stage, and the perforation fracture stage. In the design of gas pressure of 5 MPa, the experimental block only produces one longitudinal main crack. As the gas pressure increases to 7.5 MPa and 10 MPa, besides forming one longitudinal main crack, a transverse main crack is formed with further expanded 4-6 secondary cracks. In the same design of gas pressure regardless of volume size, each pressure variation stage has the same length, and the experimental block of the cracking pressure is basically the same. With the higher design pressure, the cracking pressure and the fracture pressure are higher. In the same design of gas pressure, with the larger gas volume, the fracture pressure required for the experimental block is smaller.

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In order to research on the issue of high-pressure gas blasting fracture deeply, a high-pressure gas blasting cracking experimental system was established; the effects of gas pressure and gas volume on the morphology of crack growth were studied; the $p-t$ curve of pressure in the blasting process with time was obtained; and the mechanism of high-pressure gas blasting cracking was analyzed in this paper. The conclusion has shown that the stage of effect of high-pressure gas blasting on the test block includes three stages: the gas jet impact stage, the crack initiation and development stage, and the perforation fracture stage. In the design of gas pressure of 5 MPa, the experimental block only produces one longitudinal main crack. As the gas pressure increases to 7.5 MPa and 10 MPa, besides forming one longitudinal main crack, a transverse main crack is formed with further expanded 4–6 secondary cracks. In the same design of gas pressure regardless of volume size, each pressure variation stage has the same length, and the experimental block of the cracking pressure is basically the same. With the higher design pressure, the cracking pressure and the fracture pressure are higher. In the same design of gas pressure, with the larger gas volume, the fracture pressure required for the experimental block is smaller.

1. Introduction

The permeability in high-gas coal seam is widely low, only $10^{-4} \sim 10^{-3}$ mD, due to sedimentary environment and geological changes, which is unfavorable for gas drainage [1]. For single coal seam mining or the first mining seam (protect seam) in the coal seam group, the hydraulic permeability improvement and the deep-hole precracking blasting were mainly put into practice to increase permeability. The hydraulic permeability improvement method included hydrofracture, hydraulic punching, hydraulic cutting, hydraulic drilling, and high-pressure pulsed water jet [2–6]. Abundant theories and experimental researches were carried out to gain lots of achievement.

Recently, the high-pressure gas blasting fracture is developed as a nonexplosive blasting method. The two main stages of stress wave and high-pressure gas action during blasting are identified in the process of rock fracture caused by explosive blasting, which are helpful to crack propagation and rock breakage. The effect of stress wave is to produce initial crack, and high-pressure gas will lead to crack propagation [7–9]. The blasting mechanism of explosive and high-pressure gas is mainly different from the peak pressure and duration of stress wave [10]. Nevertheless, the mechanical response caused by the two blasting modes can be divided into two stages: dynamic loading stage leading to the comminution zone and crack cavity and quasi-static loading stage leading to the increase and expansion of existing cracks [11]. The high-pressure air was compressed by a compressor or physical change (liquid-gas conversion). A high-pressure blasting cartridge was installed into a coal seam, and the high-pressure air released instantaneously and expanded to
work on surrounding medium controlled by a manual or electric operating mechanism [12–14]. This high-pressure blasting fracture method was used to improve block crushing rate and manage jam in section coal bin or coal bunker [15, 16]. Considering high performance in safety and fracture, this method was applied to improve permeability in high gas burst in the coal seam, and the superior result was achieved. In order to research on the issue of high-pressure gas blasting fracture deeply, a high-pressure gas blasting cracking experimental system was established; the effects of gas pressure and gas volume on the morphology of crack growth were studied; the \( p-t \) curve of pressure in the blasting process with time was obtained; and the mechanism of high-pressure gas blasting cracking was analyzed in this paper.

2. Experimental Method and Project

2.1. Experimental System. Supported by State Key Laboratory of Coal Resources and Safe Mining (SKLCRSM16X03), the high-pressure gas blasting cracking experimental system was established, as shown in Figure 1. The system comprised 5 parts, including gas supply system, storage system, control system, blasting system, and test system. The gas supply system is used to supply high-pressure air, constituted by nitrogen cylinders, air compressor, and gas booster pump; nitrogen was treated as raw material for safety consideration. The storage system includes couple of high-pressure vessel, and the main equipment in the control system is a pneumatic high-pressure shut-off ball valve to control air path. The blasting system was made up by experimental block and protect chamber, and the test system is used to examine the air pressure changes by the process of blasting.

Most of the coal seams in China influenced by geological tectonic movement are considered to have developed into complex and soft structures. The internal structure of the coal body is very complex and anisotropic, which will have an indeterminate effect on the blasting test results. So the repeatability of the experiment was confirmed by using a fixed proportion of the similar simulation material instead of the coal sample in situ. The experimental block was made up by cement, sand, and plaster which were mixed according to a certain ratio as the requirement of strength based on the mechanical parameters (Table 1) of 12# coal seam in Dalong Coal Mine located in the Tiefacoalfield, as shown in Figure 2. The size of the cubic block is 150 mm \( \times \) 150 mm \( \times \) 150 mm. The procedure of preparation includes similar material mixing, casting, melding, and maintenance. The whole process was carried out in the laboratory environment to reduce the influence of temperature and humidity on physical and mechanical performance.

The release tube (Figure 3), made by special steel, was designed for the blasting experiment, and triplex rows releasing holes were manufactured in its front end along designed direction and angle, which lead to high-pressure nitrogen release when control valves switched on. The release tube was set into the center of the sample when casting concrete block. For better effect of contact between tube and concrete, lath thread was welded on the outer surface of the release tube, and SHZ planting-bar anchorage glue was applied to stick the release tube and concrete block.

2.2. Test Program. Three pressure levels and three vessels were designed to conduct the blasting fracture experiment and overlapped to form 9 group tests totally. The 1L, 2L, and 3L vessels were adopted and 5 MPa, 7.5 MPa, and 10 MPa high-pressure air was applied, which are shown in Table 2.

The experimental sample was put into a protective chamber, and the high-pressure air pipeline was connected with the test system. The designed air was injected into a constant volume high-pressure vessel. The launching control system was started, and the blasting fracture experiment was carried out after the gas circuit was checked.

The images of concrete blocks and its fractures were captured after 9 group blasting tests. The crack propagation patterns of sample, failure characteristics, and effects of gas pressure and gas volume on the morphology of crack growth were studied according to comparison and analyses transversely and longitudinally.

3. Experimental Results and Analyses

3.1. The Influence of Pressure on Crack Growth. The complete elastoplastic constitutive equation is shown as follows [17]:

\[
D = \frac{1}{2G} \sigma - \frac{3v}{E} \sigma_h I + \frac{1}{2} (1 - f) \varepsilon_p \cdot \left( \frac{3S}{\sigma_e} + f \sinh \frac{\theta I}{\gamma^2} + f \theta \sinh \frac{\theta}{\gamma} \right),
\]

with

\[
\theta = \frac{3\sigma_h}{2\sigma_e},
\]

\[
\gamma = \frac{\tau}{\sigma_e},
\]

\[
\sigma_h = \frac{1}{3} I,
\]

\[
\tau^2 = \frac{3}{2} S : S,
\]

\[
S = \sigma - \sigma_h I,
\]

\[
\varepsilon_p = \begin{cases} 0, & \text{for } \sigma_e < \sigma_y, \\ \sigma_y \left( \frac{\sigma_e}{\sigma_y} \right)^{1/n} - \sigma_e E \sigma_y / E, & \text{for } \sigma_e \geq \sigma_y, \end{cases}
\]

where \( E, G, \) and \( v \) are the usual elastic constants, \( \sigma \) denotes the Jaumann stress rate, and the superposed dot represents differentiation with respect to time, \( \sigma_e \) is the effective stress, \( f \) is the void volume fraction (porosity), \( \tau \) is the Mises stress, \( S \) is the stress deviator, \( I \) is the second-order unit tensor, \( \sigma \) is the stress tensor, \( \sigma_e \) is the macroscopic hydrostatic stress, \( n \) is the strain hardening index, and \( \sigma_y \) is the yield stress.
The quasi-static expansion of the elemental spherical cell can be deduced from the study by Durban and Baruch [18–21] on expansion of a thick-walled sphere. The cavity expansion theory is the basic theory generally adopted in the impact load of geotechnical materials. Its characteristic region is shown in Figure 4 [17]. When the pressure is enough to cause spherical cavity expansion, the void in the concrete around the cavity will be gradually compacted to produce a compaction zone. The compression wave generated by the elastic spherical surface will spread around at the elastic volume wave velocity, and the compression wave will form the elastic zone or the elastoplastic zone [18]. While the compression wave propagates, the circumferential tensile stress will be generated. Since the tensile strength of concrete is far lower than its compressive strength, cracks will be generated around the compaction zone, forming the cracking zone.

Figure 5 shows the results on crack growth of the sample in 1 L vessel with different designed gas pressures. In the design of gas pressure of 5 MPa, there was a main longitudinal fracture throughout its surface and the sample cracked along drilling hole. A longitudinal crack was formed, and the sample was separated into half without any secondary fracture surface. There was no transverse main crack and secondary crack observed in the side view. When the designed air pressure reached at 7.5 MPa, it is obvious to observe two cross main cracks in the surface of the block along longitudinally and transversely. Meantime, two secondary cracks were produced connected with the transverse main crack in the left view surface, which separated concrete into 4 pieces. When the designed pressure improved to 10 MPa, two main cracks were generated and extended to left side and back side. In this case, secondary cracks were developed, and pieces of the block were smashed.

Table 1: The physico-mechanical parameters of the concrete specimen.

| Parameters                        | Value  | Unit    |
|-----------------------------------|--------|---------|
| Young’s modulus, E                | 0.8    | GPa     |
| Poisson’s ratio, μ                | 0.23   |         |
| Mass density, ρ                   | 1500   | kg/m³   |
| Uniaxial compressive strength    | 4.14   | MPa     |
| Uniaxial tensile strength        | 0.68   | MPa     |
With the increment of designed air pressure, the block started to form transverse main cracks, and these cracks made turn and bifurcated with secondary cracks production in the process of extension. The damage of the block turned from throughout crack to destroy partly. The degree of fragmentation and the number of secondary cracks increase obviously in this procedure. The crack fracture zone extends further, and the fracture interface is curved and rough. When the gas volume is 2L and 3L, the same experimental results and variations occur during the pressurization process.

3.2. The Influence of Volume on Crack Growth. Figure 6 shows the results on crack growth of sample in 10 MPa designed air pressure with different designed gas vessels. When the vessel was 1L, a longitudinal crack was formed, and the sample was separated into half with many secondary fractures in the view of back side. The transverse crack was also formed to bifurcate with secondary crack generation in the front view and left side view. However, no crack was seen in right side view, which means that the transverse crack could arrive to right side to form through crack.

When the vessel was 2L, the similar longitudinal crack was formed. But a horizontal transverse crack was produced in the left side view and a small crack was observed in the right side view, which illustrated that the main transverse crack make turn in the process of extension, and the irregular crack surface was created.

When the air vessel reached 3L, the horizontal transverse crack was generated through whole block with obvious throughout longitudinal main crack and secondary crack, which form cross arrangement.

In the aforementioned conclusion, with the same air pressure, the vessel has a large influence on the crack growth.
The transverse main crack changed from nonthrough crack to through crack, and the steering angle turned smaller with increasing of the vessel. It is illustrated that dilatation energy of air increased with the air vessel increasing, and the working time was extended to crack the concrete block.

When the air pressure is 5 MPa, there was only one longitudinal crack generated without any transverse crack. But the transverse crack was generated when the air pressure is 7.5 MPa, which means that the minimax transverse crack generation air pressure is between 5 MPa and 7.5 MPa.

3.3. Parameter Analyses on Crack Characteristics. The characterization parameters of crack in each test group have been studied statistically, mainly including number of main cracks, number of secondary cracks, and degree of crushing, as shown in Table 3.

The breakage of the block in the function of air pressure usually happened in the drilling hole area, and the cracks were centered of the drilling hole to extend throughout block. The irregular crack surface shows obviously tendon fracture character. In this test, the longitudinal main crack was made in the surface of the block. With the increasing of air pressure, the transverse main crack started to form and lead the production of secondary crack. The longitudinal main crack had priority due to nontriaxial experimental condition. In the influence of density, the block was free horizontally, and the crack would tend to develop along transverse direction. In the same designed gas vessel, the larger the gas pressure, the more the blocks of crushing. In the same designed gas pressure, the number of main cracks changed little with the increasing of the gas vessel, but the number of transverse crack increased, or the secondary crack decreased.

With the increasing length of the transverse main crack, the secondary crack would be restrained resulting in that active stress wave arrived at end firstly, and then, the reflection stress wave meets the propagation crack, and the quasi-static stress field around the borehole will be superimposed with the dynamic stress field formed by the reflection wave. The superposition process increases the stress intensity factor at the crack tip, thus promoting the propagation of the main crack and weakening the propagation of cracks in other directions.

3.4. Characteristics of Cracking Gas Pressure Variation in the Process of High-Pressure Air Blasting Fracture. Figures 7 and 8 show the pressure-time curve (p-t curve) in different designed air pressures and gas vessels. Table 4 summarises time of each stage, initial crack pressure, and fracture pressure in release tube.

There are three stages in the process of test observed from Figures 6 and 7, which are gas rapid increasing stage,
slow increasing stage, and drop stage. Corresponding to the high-pressure gas on the test block, there are also three stages: jet impaction stage, initial fracture stage, and failure stage.

As shown in Table 4, the rapid increasing stage has the same duration, no matter how large the vessel is. These samples with 5 MPa, 7.5 MPa, and 10 MPa designed air pressure correspond to 47 ms, 65 ms, and 78 ms at the rapid increasing stage and 104–109 ms, 100–106 ms, and 250–256 ms at the slow increasing stage. It is observed that the rapid increasing stage and slow increasing stage would experience longer with higher designed air pressure, which illustrates that the working duration would increase with higher air pressure.

These samples with 5 MPa, 7.5 MPa, and 10 MPa designed air pressure correspond to 2.3–2.5 MPa, 3.5 MPa, and 4.4–4.5 MPa initial fracture pressure, no matter how large the vessel is. It is observed that the initial fracture pressure would increase with higher designed pressure. However, the similar initial fracture pressure happened with different vessels.

These samples with 5 MPa, 7.5 MPa, and 10 MPa designed air pressure correspond to 3.5–3.8 MPa, 4.5–5.1 MPa, and 6.6–7.4 MPa failure stress, no matter how large the vessel is. It is observed that higher designed air pressure leads higher failure stress which was affected by the vessel with same designed air pressure. The 10 MPa designed air pressure was taken as an example; the 1 L, 2 L, and 3 L
designed vessel has 7.4 MPa, 6.9 MPa, and 6.6 MPa failure stress, which means that larger failure stress was required with the larger designed vessel. It is illustrated that relatively gas pressure could break throughout block with larger gas flow.

The shock wave pulverizes the medium around the hole and attenuates into a stress wave during the formation of the pulverized zone. The stress wave radially compresses and shatters the medium outside the zone and reaches the dynamic cracking strength, thus causing the crack initiation and propagation. After the action of the compression stress wave, the reflection stress wave at the prefabricated crack causes the explosion crack to continue to expand, which plays an important role in the crack extension. The quasi-static energy of expansion produced by high-pressure gas blasting is the main energy of rock fragmentation. Stress wave propagates well in hard rock with high-wave impedance, and its velocity is high. Rock failure mainly depends on stress wave action. For soft rock with low-wave impedance, the propagation performance of the stress wave is poor, and the velocity of wave is low. The failure of the rock mainly depends on the expansion pressure of high-pressure gas. For rocks with medium-wave impedance, stress wave and detonation gas also play an important role.

3.5. Cracking Mechanism Analysis of High-Pressure Gas Blasting. High-pressure air released from releasing hole and
Figure 8: $p$-$t$ curve of high-pressure nitrogen fracturing under different design gas volume conditions: (a) $V = 1\text{ L}$, (b) $V = 2\text{ L}$, and (c) $V = 3\text{ L}$.

Table 4: The length of each stage and the experimental block cracking pressure and breaking pressure.

| Volume of container (L) | Vessel pressure (MPa) | Fast rising stage of pressure (ms) | Cracking pressure (MPa) | Slowly rising stage of pressure (ms) | Breaking pressure (MPa) | Pressure drop stage (ms) | Remarks                  |
|-------------------------|-----------------------|-----------------------------------|------------------------|-------------------------------------|------------------------|------------------------|--------------------------|
| 1                       | 5                     | 47                                | 2.5                    | 104                                 | 3.8                    | 83                     |                          |
|                         | 7.5                   | 65                                | 3.5                    | 100                                 | 5.1                    | 303                    |                          |
|                         | 10                    | 78                                | 4.5                    | 250                                 | 7.4                    | 374                    |                          |
|                         | 5                     | 47                                | 2.5                    | 107                                 | 3.5                    | 82                     |                          |
| 2                       | 7.5                   | 65                                | 3.5                    | 104                                 | 5.1                    | 301                    | Gas pressure drops below 1 MPa |
|                         | 10                    | 78                                | 4.5                    | 251                                 | 6.9                    | 371                    |                          |
|                         | 5                     | 47                                | 2.3                    | 109                                 | 3.3                    | 80                     |                          |
| 3                       | 7.5                   | 65                                | 3.5                    | 106                                 | 4.5                    | 300                    |                          |
|                         | 10                    | 78                                | 4.4                    | 256                                 | 6.6                    | 370                    |                          |
supplied aerodynamic force and thrust which broke the block. The function of high-pressure air for the block could be divided into two processes: jet impaction function and quasi-static expansion. There are three stages in the process of test observed from the $p$-$t$ curve, which are gas jet impaction stage, initial fracture stage, and failure stage.

In the gas jet impaction stage, air pressure increased rapidly to initial fracture pressure. The high-pressure air supplied jet impact energy with part dilatation energy, so the obvious crack could not be observed in the block. However, stress wave was evoked and broadcasted. When the air pressure improved to initial fracture pressure, the crack started to generate and reach the crack stage with air pressure increase. In this stage, the air pressure kept increasing to peak value to fracture. Before meeting the reflected wave, the initial crack spread in the function of high-pressure gas quasi-static state. When meeting the reflected wave, the superposition of quasi-static stress field and dynamic stress field caused further propagation until throughout fracture was formed to break the block. In the failure stage, the air pressure drops from peak values to 1 MPa within a few hundred milliseconds because cracks extend from the inside of the specimen to the surface.

4. Conclusions

(1) In the low design of gas pressure, the experimental block only produces one longitudinal main crack. As the gas pressure increases air pressure and vessel, besides forming one longitudinal main crack, a transverse main crack is formed with further expanded 4–6 secondary cracks. In the same designed gas vessel, the larger the gas pressure, the more the blocks of crushing. In the same designed gas pressure, the number of main cracks changed little with the increasing of the gas vessel, but the number of transverse crack increased, or the secondary crack decreased.

(2) The whole of the crack process has the same duration, no matter how large the vessel is. The rapid increasing stage and slow increasing stage would experience longer with higher designed air pressure. The similar initial fracture pressure happened with different vessels. The initial fracture pressure would increase with higher designed pressure. Higher designed air pressure leads higher failure stress which was affected by the vessel with same designed air pressure. Relatively, gas pressure could break throughout block with larger gas flow.

(3) There are three stages in the process of test, which are gas rapid increasing stage, slow increasing stage, and drop stage. Corresponding to the high-pressure gas on the test block, there are also three stages: jet impaction stage, initial fracture stage, and failure stage.

Data Availability

All relevant data are available from FigShare at https://figshare.com/s/f0e1e4358b40bf2e01571.

Conflicts of Interest

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

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