Experimental and numerical simulation study on the dynamic fracture of coal by gas expansion

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Abstract
The high-pressure gas expansion-induced deformation and dynamic fracture of coal are important parts of coal and gas outburst. To better understand the law of this process, laboratory experiments and numerical simulation are used to study the law of damage. A cavity with different pressures of CH4 or N2 was destroyed by a jack to achieve the rapid expansion of the gas and coal fracture inside. The particle size distribution of the coal particles before and after the experiment was measured, and the breakage ratio and the newly added surface area were calculated. The experimental results indicate that during the gas expansion process, the breakage ratio of coal and the newly added surface area clearly increase with the increase in gas pressure. Finally, a numerical model based on peridynamic theory was developed to simulate crack generation and the propagation of coal induced by the expansion of gases at different pressures. The numerical simulation results show that the higher the initial gas pressure is, the higher the number of failure units. Moreover, only when the gas pressure is large enough will the coal crack in various directions at the same time.

KEYWORDS
coil, crack propagation, gas expansion, peridynamic

1 | INTRODUCTION

Coal and gas outburst is a phenomenon in which a large amount of coal and gas are suddenly ejected from the coalbed wall, causing casualties and economic loss. China is the country that is most threatened by coal and gas outburst in the world. In 2005-2017, there were 210 coal and gas outburst accidents in China in which more than three workers died, with 1686 total deaths.1 Almost all relevant experts agree that gas plays a key role in coal and gas outburst. Due to the complex interaction mechanism between coal and gas, the process of coal and gas outburst can only be described qualitatively. On one hand, gas adsorption on coal will result in coal matrix swelling deformation. On the other hand, the gas pressure gradient during the emission of high-pressure gas may cause tensile damage to the
coal. However, to prevent coal and gas outburst disasters, we should clarify the mechanism by which high-pressure gas expansion dynamically destroys coal.

The numerical simulation method was used to study the related parameters such as ground stress, gas pressure, and coal mechanical properties. The energy in coal and gas outburst is mainly derived from the deformation energy stored in the coal and the expansion energy of the CH₄ gas. Numerical simulations and theoretical calculations show that the most important energy for initiating coal and gas outburst is gas expansion energy. The process of high-pressure gas expansion and destruction of coal includes three stages of gas flow, coal deformation, and destruction. Xu et al. established the fluid-solid coupling model of RFPA²D-GasFlow and studied the stress concentration in the coal seam and the expansion and destruction of coal driven by gas pressure through numerical simulation. The results show that the gas pressure gradient has a large influence on the occurrence of coal and gas outburst. Xue et al. constructed a coupled simulator of gas-damaged coal through FLAC³D and COMET3 to simulate the deformation of the coal roadway and the distribution of gas pressure. Peng et al. experimentally studied the destruction of the coal matrix in coal seams and the formation mechanism of a high gas pressure zone in coal seams.

The destruction of coal also affects the adsorption of gas by coal mass and the seepage of gas in coal seams. Currently, hydraulic fracture and blasting-induced fracture expansion in coal masses have been widely applied to improve coal seam permeability and coalbed methane drainage. Furthermore, field tests using high-pressure CO₂ gas fracturing to increase the permeability of the coal seam have achieved good results. The mechanism of this technology is that during the conversion of liquid high-pressure CO₂ into a gaseous state, the CO₂ violently expands and destroys the structure of the coal, producing a large number of cracks. Therefore, the permeability of the coal seam is improved. Chen et al. studied the process of high-pressure CO₂ expansion to destroy coal by numerical simulation.

To describe the specific process of coal fracture by gas expansion more clearly, a bond-based peridynamic method is used to simulate this process. As a meshless particle simulation method, the peridynamic method was first proposed by Silling in 2000. After that, Silling elaborated on the mechanics and basic model of the method. The original application of peridynamic is based on the mechanics equations of elastic media to describe the motion of particles and the fracture process of materials. Now, it is also applicable to other field equations. Moreover, it has been widely used in the numerical simulation of crack growth and evolution in the process of Brazilian splitting, hydraulic fracturing, and material compression fracture. Chen and Bobaru introduced a peridynamic model for the evolution of damage in a pitting corrosion scenario. Rokkam developed peridynamic approach and applied it to simulation of the corrosion damage, crack propagation, and prediction.

To better understand the process of high-pressure gas expansion-induced coal fracture, in this article a new experimental system was built to study the law of fracture. The damage effect on coal during the expansion of different pressures of CH₄ and N₂ was analyzed. Additionally, a numerical simulation method based on peridynamics was used to study the generation and evolution of cracks in the fracture process. Conclusions from this work may help to reveal the outburst mechanisms, as well as the fracture characteristics, of coal induced by high-pressure gas, which may also be able to provide some implications for the improvement of coal seam permeability.

2 | EXPERIMENTAL METHODS

2.1 | Experiment system

To study the law of high-pressure gas expansion in destroying coal, a new experimental system was designed based on the characteristics of coal and gas outburst initiation. Figure 1 is the schematic diagram of the experimental system.

The experimental system consists of five parts: pressure chamber, gas relief device, coal-gas migration pipeline, gas injecting system, and vacuum pumping system.

1. Pressure chamber

The pressure chamber is made of a plexiglass cylinder, flange, and bolt, which can effectively seal 0-2 MPa of gas. It is used to place the experimental coal samples and rush into the high-pressure gas.

2) Gas relief device

FIGURE 1 Experiment system
This part is made up of steel balls, jacks, and tempered glass, which can be used to quickly relieve the gas pressure of the pressure chamber, resulting in a higher gas pressure gradient (Figure 2).

(3) Coal-gas migration pipeline

The coal-gas migration pipeline is a PVC pipe used to constrain gas-solid flow and avoid personal injury due to splashing of high-speed particles.

(4) Gas injecting system

The gas injecting system is composed of gas storage cylinders, gas pressure balance tanks, and pipes, which can accurately control the gas pressure injected into the pressure chamber.

(5) Vacuum pumping system

The vacuum pumping system is composed of a vacuum gauge and vacuum pump connected through the pipeline, which can extract air from the pressure chamber, coal pore, and pipeline before the experiment.

The coal sample used in the experiment was taken from the 1209 working face of Wanfeng Coal Mine, Xiaoyi, Shanxi Province (Figure 3). The working face has a length of 1.012 km, a tendency of 0.14 km, a dip angle of 4°-8°, a coal seam thickness of 1.03-1.95 m, and a bulk density of 1.48 g/cm³. The test results of the mechanical parameters of coal samples are as follows: the tensile strength is 0.31 MPa; the compressive strength is 3.74 MPa; the elastic modulus is 0.28 GPa; the stiffness coefficient (consistent coefficient) is 0.5; and Poisson’s ratio is 0.3. The coal piece taken out was chopped and sieved to obtain the experimental coal sample with a particle size of 3.35-10 mm.

2.2 Experimental procedure

The critical procedure of the experiment can be concluded in Figure 4. After the pressure chamber is assembled, 1000 ± 10 g of experimental coal sample is loaded. After completing the airtight test of the chamber, the gas pressure relief device is assembled and the coal-gas migration pipeline is laid. To avoid the interference of air in the chamber, the pressure chamber is vacuumed before injecting the experimental gas. Since the injected gas is adsorbed by the coal particles, the gas injection is completed only if the gas pressure in the chamber is the same as the preset pressure for one hour. The tempered glass of the sealed cavity is fractured by a jack to release the high-pressure gas. The high-pressure gas carries the fractured coal particles formed by the gas expansion and flows in the coal-gas migration pipeline. After the cessation of the coal and gas spray, the coal particles in the chamber and the pipe are collected. The fractured coal mass is divided into seven kinds of particle diameters: 3.35-10 mm, 2.36-3.35 mm, 1.18-2.36 mm, 1-1.18 mm, 0.5-1 mm, 0.25-0.5 mm, and 0-0.25 mm, which are recorded as \( r_0, r_1, r_2, r_3, r_4, r_5, \) and \( r_6 \), respectively.

3 EXPERIMENTAL RESULTS AND ANALYSES

We have completed a total of 16 groups of experiments of \( \text{N}_2 \) and \( \text{CH}_4 \) expansion, destroying coal with eight different gas pressures (0.60, 0.75, 0.90, 1.05, 1.20, 1.35, 1.50, 1.65, and 1.80 MPa). After the experiment, a large amount of fine coal particles was distributed in the migration pipeline. This result indicates that a large number of coal particles with a primary particle size of 3.35-10 mm are fractured into smaller coal particles or coal powder. These fine coal particles are ejected outward by gas, and the distribution in the pipeline presents the characteristics of sorting. Larger particles of coal land near the pressure chamber, while smaller particles are carried further.

The results of coal sieving after the experiment with \( \text{CH}_4 \) are shown in Figure 5. Among them, \( r_0 \) (3.35-10 mm) is the original particle size coal, and the others are called new particle size coal. It can be seen that the original particle size coal sample shows a decreasing trend with the increase in \( \text{CH}_4 \) pressure. For experiments with the same gas pressure, the smaller the particle size is, the lower the amount of new particle size coal. It can be seen that new particle size coal is mainly composed of two sizes of \( r_1 \) (2.36-3.35 mm) and \( r_2 \) (1.18-2.36 mm). The experiments with \( \text{N}_2 \) have similar results. This result is shown that during the gas expansion process, the coal is destroyed, and the degree of fracture increases with increasing pressure.

FIGURE 2  Schematic of gas relief device
To quantitatively analyze the degree of damage to coal under different pressures and different gas expansion, we define two indicators: the breakage ratio and the newly added surface area. The coal particles are treated as homogeneous spheres of the same radius, and the mass can be calculated as:

$$m_i = \frac{4}{3} \pi r_i^3 \rho_c N_i$$  \hspace{1cm} (1)

where $m_i$ is the mass of the $i$-th particle size coal sample, g; $r_i$ is the average radius of the $i$-th particle size coal sample, cm; $\rho_c$ is the density of coal particle, g/cm$^3$; and $N_i$ is the number of coal particles.

The surface area of the coal is:

$$S_i = 4\pi r_i^2 N_i$$  \hspace{1cm} (2)

Coupling Equations (1) and (2), the following could be obtained:

$$S_i = \frac{3m_i}{r_i \rho_c}$$  \hspace{1cm} (3)

The newly added surface area of the coal particles is the difference between the total surface area of the coal sample before and after the gas expansion fracture, which can be expressed as:
where \( m \) is the mass of the coal sample before gas expansion, g.

The ratio of the mass of the coal whose particle size is changed to the mass of the total coal sample is defined as the breakage ratio \( R_m \).

\[
R_m = 1 - \frac{m_0}{m} 
\]

The mass of coal of different particle sizes obtained by sieving, the coal particle breakage ratio, and the newly added surface area are shown in Table 1.

The mass of coal of original particle size is reduced from 1000 g to <700 g during the experiment (Table 1). At least 30% of the coal particles are severely damaged. It is worth mentioning that a large number of pulverized coal with a particle size of <0.25 mm was produced after the experiment. This result indicates that the expansion of

**FIGURE 4** Experiment flowchart of the high-pressure gas expansion and destruction of coal

**FIGURE 5** Coal particles of different particle sizes after experiments with CH\(_4\); (A) 0.60 Ma; (B) 0.75 Ma; (C) 0.90 MPa; (D) 1.05 Ma; (E) 1.20 Ma; (F) 1.35 Ma; (G) 1.50 Ma; (H) 1.65 Ma; and (I) 1.80 MPa
the high-pressure gas is the main cause of the destruction of the coal.

Regardless of whether N₂ or CH₄ is used in the experiment, the coal breakage ratio clearly increases with the increase in gas pressure (Figure 6). The breakage rate and gas pressure are fitted by a linear relationship, and the fitted curve is in good agreement with the experimental results. The difference between the intercept of the fitted line of the N₂ experiment group and CH₄ experiment group is small. However, the slope of the fitting line of the CH₄ experimental group was significantly larger than that of the N₂ experimental group. This result means that under the same gas pressure, the destruction of coal particles by CH₄ expansion is more serious than that of N₂ expansion. Moreover, this phenomenon is more pronounced as the gas pressure increases. This result indicates that the effect of coal on the adsorption damage of CH₄ is significant in the process of gas expansion and destruction of coal mass.

Similarly, the relationship between the newly added surface area and the gas pressure is also linearly fitted. The results are shown in Figure 7. There is a positive correlation between the newly added surface area of the coal sample and gas pressure. Moreover, the slope of the CH₄ experimental group was also significantly larger than that of the N₂ experimental group. Due to the adsorption damage effect of coal on CH₄, the newly added surface area of CH₄ expansion and destruction of coal under the same conditions is much greater than that of N₂ expansion.
4 NUMERICAL SIMULATION OF THE FRACTURE PROCESS

4.1 Dynamic fracture process of coal by gas expansion

Coal is a double-porous structure with interconnected microscopic pores and macroscopic fissures, providing ample storage space and flow channels for gas. For a gas-containing coal mass, free gas acts on the crack and pore walls and exerts tensile stress on the coal. As shown in Figure 8, the coal particles are loaded in a pressure chamber and injected with a preset pressure of gas. The gas penetrates and diffuses into the free space of the coal through cracks and pore structures. When the gas pressure $P_{in}$ of the pore and fracture is the same as the gas pressure $P_{out}$ of the pressure chamber, the gas seepage and diffusion reach a dynamic equilibrium. At this time, under the dual action of free gas and adsorption gas, the coal mass is slightly deformed, but macroscopic cracking does not occur. If the gas in the chamber is discharged rapidly, as the gas diffusion and seepage velocity inside the coal particle are much smaller than the pressure relief velocity of the pressure chamber, a pressure difference $\Delta P$ ($\Delta P = P_{in} - P_{out}$) between the inside and the outside of the coal particle is rapidly formed. In the process of pressure relief, the pressure difference of gas increases rapidly. When the strength of the coal is exceeded, the cracks propagate and penetrate under the action of free gas tension, resulting in macrofracture. When the pressure difference exceeds the strength of the coal, the crack expands and penetrates under the action of free gas tension, resulting in macroscopic cracking.

Therefore, the main influencing factors of coal fracture by gas expansion are as follows:

1. Coal particle fracture depends on the tensile stress of gas formed on the crack surface. When the gas pressure is high enough, the crack tip stress intensity factor exceeds the fracture toughness and causes crack propagation.
2. When the degree of pore development of coal particles is high and the strength is low, the resistance of crack propagation is small, and it will be easy to cause coal fracture under tensile stress. In addition, the higher the degree of internal crack development, the larger the free surface of free gas action and the greater the stress intensity factor at the crack tip.
3. The pressure chamber needs to be able to relieve pressure quickly. During the pressure relief process, the gas pressure difference $\Delta P$ depends on the gas discharge rate of the pressure chamber. Only sufficient relief speed can produce a pressure differential sufficient to break the coal.

4.2 Basic peridynamic theory

According to the theory of peridynamic proposed by Silling, the deformation or failure of an object is carried out by the interaction between its internal point $x_{(i)}$ and the adjacent material point $x_{(j)}$ (Figure 9). When the distance exceeds the local interaction region $Hx_{(i,j)}$, the effect of the material point on the interaction between $x_{(i)}$ and $x_{(j)}$ will not be considered.

A material point can interact with other material points within a certain range, and the accumulation of these interactions can cause the final macroscopic deformation of the object. In peridynamic theory, the equation of motion at a material point conforms to the form of Newton’s second law in the Lagrangian coordinate system.29
where $\rho(x)$ is the density of coal, $H$ is the local interaction horizon, which is determined by the influence radius, $b(x, t)$ is the body force density vector, and $f(u' - u, x' - x, t)$ is the force density vector and can be computed as

$$f(u' - u, x' - x, t) = \left[ c \cdot S(u' - u, x' - x) \right] \frac{y' - y}{|y' - y|} \mu(t, x' - x)$$

where $c$ is the material parameter, which can be defined as

$$c = \frac{9E}{\pi h \delta^3}$$

where $E$ is the elastic modulus, $\delta$ is the horizontal radius, and $h$ is the thickness for 2-D situation.

The elongation $S(u' - u, x' - x)$ can be expressed as:

$$S(u' - u, x' - x) = \frac{|y' - y| \cdot |x' - x|}{|x' - x|}$$

In particular, $\mu(t, x' - x)$ can be obtained by

$$\mu(t, x' - x) = \begin{cases} 1 & \text{if } s < s_0 \\ 0 & \text{otherwise} \end{cases}$$

where $s_0$ is the critical stretch for bond failure and can be computed as

$$s_0 = \sqrt{\frac{10G_0}{\pi c \delta^5}}, \quad G_0 = \frac{cs_0^2 \delta^5}{10}$$

where $G_0$ is a specific parameter that denotes the work required to break all the bonds in every unit fracture area.

### 4.3 Numerical model of fracture by gas expansion

The process of gas expansion and causing the deformation a coal is illustrated in Figure 10. As shown in Figure 10, the material point $i$ is the contact point of the coal particle with

**FIGURE 9** Interaction between different material points in peridynamic

**FIGURE 10** An illustration of the numerical model of gas expansion-induced deformation
the high-pressure gas. The velocity of \( x_i \) in the new position at \( t + \Delta t \) time, \( \mathbf{r}_i^{t+\Delta t} \), can be defined as:

\[
\mathbf{r}_i^{t+\Delta t} = \mathbf{u}_i^{t+\Delta t} - \mathbf{u}_i^t \tag{12}
\]

where \( \mathbf{u}_i^t \) is the displacement vector at time \( t \), and \( \mathbf{u}_i^{t+\Delta t} \) is the new displacement vector at time \( t + \Delta t \).

The gas pressure provides an external load, which does not directly appear in the equation of motion. In the case of peridynamic theory, the coal matrix points located in domain \( \Omega \) interact with the gas. Thus, the external force \( \mathbf{F} \) can be computed by volume integration of the force densities over domain \( \Omega \) as

\[
\mathbf{F} = \int_{\Omega} Pd\mathbf{V} \tag{13}
\]

in which \( P \) is gas pressure, acting on a material point in domain \( \Omega \). \( P \) is defined as:

\[
PV = nRT \tag{14}
\]

where \( V \) is the volume of the internal pores of the coal particles, which can be calculated by the position coordinates of the points at the boundary; \( R \) is the ideal gas constant; \( T \) is the temperature and is considered unchanged; and \( n \) is the amount of gas, which is determined by seepage and desorption of coal. Since the period of high-pressure gas expansion is extremely short, the influence of seepage on the amount of gas in this process is small, so the effect of seepage is not considered in the simulation. The relationship between the amount of adsorption and the pressure of the gas can be described by the Langmuir equation.

\[
q = \frac{k_1 q_m P}{1 + k_1 P} \tag{15}
\]

where \( q \) and \( q_m \) are the adsorption amount and the adsorption capacity, respectively, and \( k_1 \) is the Langmuir adsorption constant. The change in the amount of gas during expansion is equal to the change in the gas adsorption amount.

The isothermal adsorption experiment has been conducted for the coal samples. The coal adsorption amounts under different gas pressures are acquired. The experimental results show good fitting effect with the Langmuir equation (Equation 15). Through comparing the fitting parameters, the Langmuir adsorption constant \( k_1 \) and the adsorption capacity \( q_m \) are determined. After that, we substituted the newly determined Langmuir adsorption constant \( k_1 \) and the adsorption capacity \( q_m \) into our numerical model under no damage condition. The experimental-numerical comparison is shown as Figure 11. The numerical results show better agreement with the experimental results.

The specific parameters of the model are listed in Table 2. The crack propagation process can be described more accurately with an increased number of particles \( N \), but the computation time will be greatly expanded. Therefore, \( N \) is set to 7740 due to the particle size of the experimental coal mass and accuracy. The time step is determined by considering the spatial step size, as well as the total duration, of the gas expansion-induced deformation and fracture.

### Table 2

| Parameter                         | Value                     |
|-----------------------------------|---------------------------|
| Time step \( \Delta t \)          | \( 1.25 \times 10^{-7} \) s |
| Ideal gas constant \( R \)        | 8.314 J mol\(^{-1}\) K\(^{-1}\) |
| Particle numbers \( N \)          | 7740                      |
| True density \( \rho \)           | 1.48 g/cm\(^3\)           |
| Radius of the model \( r \)       | 5 mm                      |
| Temperature \( T \)               | 25°C                      |
| Adsorption capacity \( q_m \)     | 26 m\(^3\)/t              |
| Particle area \( \Delta V \)      | 19.625 mm\(^3\)          |
| Poisson’s ratio \( \nu \)         | 1/3                       |
| Horizon \( \delta \)              | 3.15 \( \Delta x \)       |
| Particle spacing \( \Delta x \)   | 0.05 mm                   |
| Elastic modulus \( E \)           | 0.28 GPa                  |
| Langmuir adsorption constant \( k_1 \) | 0.3 MPa\(^{-1}\)        |
| Initial crack length \( L \)      | 4 mm                      |
| Thickness of the particle \( h \) | 1 mm                      |
| Initial crack width \( D \)       | 0.4 mm                    |
The Fortran programming language is adopted for the established model implementation and numerical solution. The numerical solution process includes the establishment of the geometric model, initialization of the material parameters, setting of the initial and boundary conditions, integration to obtain the elongation rate, calculation of the interaction force, and integration to obtain the displacement and velocity and whether the bond between the material points is broken (Figure 12).

5 | SIMULATED RESULTS AND DISCUSSION

5.1 | Dynamic process of gas expansion-induced coal fracture

According to the size of the coal particles in the experiment, the geometric model established is shown in Figure 13.

The initial pressure was set to 1.8 MPa, and the other parameters are given in Table 2. Then, the numerical solution is performed according to the process shown in Figure 12, and the simulation result is shown in Figure 14.

As the simulation progresses to 2.5 μs, stress concentration begins to occur near the crack tip, and the unit near the tip is slightly damaged. The deformation and damage in 7.5, 10, and 12.5 μs show that as the loading time increases, the damage area near the crack tip expands along both sides of the x-axis, showing a “butterfly” distribution, and the number of fractured units increases gradually. In 15 μs, a slight damage zone begins to appear at both ends of the coal particle in the y-axis direction. Subsequently, up to 25 μs, the crack tip damage region extends to the surface of the coal particles in the x-axis direction, and the damage region in the y-axis direction gradually expands from both ends of the coal particles toward the center of the coal particles. From 25 to 75 μs, the damaged area extends to the center along the y-axis and penetrates with the crack. After 75 μs, the damage amount of the damaged area unit gradually increases. In 125 μs, the units near the crack tip are completely destroyed, and the coal is fractured along the x-axis direction.

FIGURE 12  Flowchart for the peridynamic model
5.2 Law of coal particle coal fracture under different pressures

Under the same geometric model conditions, the initial pressures of 0.6, 0.9, 1.2, and 1.5 MPa were also numerically simulated. The simulation results of 1000s are shown in Figure 15.

It can be seen from Figure 15 that the damage zone is distributed on both sides of the x-axis under the initial pressure of 0.6 and 0.9 MPa, while the damage areas are on both sides of the x-axis and y-axis when the initial pressure is 1.2, 1.5, and 1.8 MPa. Moreover, as the initial pressure increases, the displacement of the crack, the damage area, and the number of damage units increase, which indicates that the degree of damage of the coal particles is positively correlated with the initial pressure under the same conditions of the initial crack.

The numerical simulation results show that the number of damaged units increases with the increase in gas pressure (Figure 16(A)), which is consistent with the law that the newly added surface area increases with the increase in gas pressure. This is because the energy required to induce damage is larger under higher gas pressures, leading to larger damage areas and more damage units.

Figure 13 shows the geometric model of coal fracture, which provides a visual representation of the fracture zone under different pressures. The figures in Figure 14 illustrate the dynamic fracturing process under the initial pressure of 1.80 MPa, allowing for a clearer understanding of the fracture progression. Finally, Figure 15 presents the simulation results of coal deformation and fracture under different initial gas pressures, offering insights into the effects of various pressures on coal fracture behavior.
pressure during the experiment (Figure 16(B)). The numerical simulations and experiments show that the degree of coal fracture is positively correlated with gas pressure from both mesoscopic and macroscopic perspectives. The comparison between the numerical simulation and the experimental results shows that the laws obtained by the two research methods can complement and mutually verify each other.

6 | CONCLUSION

The aim of this paper was to investigate and analyze the dynamic fractures properties of coal under the expansion of gases at different pressures using laboratory experiments and a numerical simulation approach. The following main conclusions can be drawn based on the experimental and simulated results:

1. The coal mass in the high-pressure gas chamber will be destroyed into smaller coal particles after gas expansion. The amount of new particle size coal can reflect the extent of fracture.
2. During the gas expansion process, the breakage ratio of coal and newly added surface area clearly increase with the increase in gas pressure. Due to the stronger adsorption capacity, the degree of fracture to coal by CH4 expansion is higher than that of N2.
3. Based on the experimental and simulated results, the model based on the peridynamic theory can accurately simulate the crack propagation and penetration morphology at different initial pressures on the coal surface, which complements and verifies the experiment. The peridynamic model considering the desorption of coal fracture by gas expansion can provide a new technique for simulating the failure process and revealing the fracture mechanism of coal under high gas expansion conditions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

Data used in this article are available through email from the corresponding author.

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REFERENCES

1. State Administration of Safety Supervision and Administration of China. http://media.chinasafety.gov.cn:8090/iSystem/shigumain.jsp. January 20, 2018.
2. Xue S, Yuan L, Wang Y, Xie J. Numerical analyses of the major parameters affecting the initiation of outbursts of coal and gas. Rock Mech Rock Eng. 2014;47(4):1505-1510.
3. Xue S, Wang Y, Xie J, Wang G. A coupled approach to simulate initiation of outbursts of coal and gas—model development. Int J Coal Geol. 2011;86(2–3):222-230.
4. Yu B, Su C, Wang D. Study of the features of outburst caused by rock cross-cut coal uncovering and the law of gas dilatation energy release. Int J Min Sci Technol. 2015;25(3):453-458.
5. Valliappan S, Wohua Z. Role of gas energy during coal outbursts. Int J Numer Meth Eng. 1999;44(7):875-895.
6. Xu T, Tang CA, Yang TH, Zhu W, Liu J. Numerical investigation of coal and gas outbursts in underground collieries. Int J Rock Mech Min Sci. 2006;43(6):905-919.
7. Peng SJ, Xu J, Yang HW, Liu D. Experimental study on the influence mechanism of gas seepage on coal and gas outburst disaster. Saf Sci. 2012;50(4):816-821.
8. Fenghua A, Yu Y, Xiangjun C, Li Z, Li L. Expansion energy of coal gas for the initiation of coal and gas outbursts. Fuel. 2019;235:551-557.
9. Hu Y, Lu W, Wu X, Liu M, Li P. Numerical and experimental investigation of blasting damage control of a high rock slope in a deep valley. Eng Geol. 2018;237:12-20.
10. Wang T, Zhou W, Chen J, Xiao X, Li Y, Zhao X. Simulation of hydraulic fracturing using particle flow method and application in a coal mine. *Int J Coal Geol*. 2014;121(Complete):1-13.

11. Cao Y, Zhang J, Zhai H, Fu G, Tian L, Liu S. CO2 gas fracturing: a novel reservoir stimulation technology in low permeability gassy coal seams. *Fuel*. 2017;203:197-207.

12. Lu T, Wang Z, Yang H, Yuan P, Han Y, Sun X. Improvement of coal seam gas drainage by under-panel cross-strata stimulation using highly pressurized gas[J]. *Int J Rock Mech Min Sci*. 2015;77:300-312.

13. Chen H, Wang Z, Chen X, Chen X, Wang L. Increasing permeability of coal seams using the phase energy of liquid carbon dioxide. *J CO2 Utilization*. 2017;19:112-119.

14. Silling SA. Reformulation of elasticity theory for discontinuities and long-range forces. *J Mech Phys Solids*. 2000;48(1):175-209.

15. Silling SA, Askari E. A meshfree method based on the peridynamic model of solid mechanics. *Comp Struct*. 2005;83:1526-1535.

16. Silling SA, Epton M, Weckner O, Xu J, Askari E. Peridynamics states and constitutive modeling. *J Elasticity*. 2007;88:151-184.

17. Oterkus S, Madenci E, Oterkus E. Fully coupled poroelast peridynamic formulation for fluid-filled fractures. *Eng Geol*. 2017;225:19-28.

18. Han SW, Diyaroglu C, Oterkus S, et al. Peridynamic direct concentration approach by using ANSYS. 2016 IEEE 66th Electronic Components and Technology Conference (ECTC). IEEE. 2016.

19. Kilic B, Madenci E. Peridynamic theory for thermomechanical analysis. *IEEE Trans Adv Packag*. 2010;33(1):97-105.

20. De Meo D, Diyaroglu C, Zhu N, Oterkus E, Siddiq MA. Modelling of stress-corrosion cracking by using peridynamics. *Int J Hydrogen Energy*. 2016;41(15):6593-6609.

21. Bobaru F, Duangpanya M. A peridynamic formulation for transient heat conduction in bodies with evolving discontinuities. *J Comput Phys*. 2012;231(7):2764-2785.

22. Dihao A, Yuechao Z, Qifei W, et al. Experimental and numerical investigation of crack propagation and dynamic properties of rock in SHPB indirect tension test. *Int J Impact Eng*. 2019;126:135-146.

23. Nadimi S, Miscovic I, McLennan J. A 3D peridynamic simulation of hydraulic fracture process in a heterogeneous medium. *J Petrol Sci Eng*. 2016;145:444-452.

24. Ha YD, Lee J, Hong JW. Fracturing patterns of rock-like materials in compression captured with peridynamics. *Eng Fract Mech*. 2015;144:176-193.

25. Chen Z, Bobaru F. Peridynamic modeling of pitting corrosion damage. *J Mech Phys Solids*. 2015;78:352-381.

26. Rokkam S, Gunzburger M, Brothers M, Phan N, Goel K. A non-local peridynamics modeling approach for corrosion damage and crack propagation. *Theor Appl Fract Mech*. 2019;101:373-387.

27. Rokkam S, Desai T, Gunzburger M. Development of novel peridynamics framework for corrosion fatigue damage prediction, Technical Report, Phase I STTR Final Report, Distribution B (Limited to U.S. Government agencies), Navy Contract: N68335–13-C-0343. Lancaster, PA: Advanced Cooling Technologies Inc; 2014.

28. Rokkam S, Gunzburger M, Brothers M, Shanbhag S, Lees E. Development of novel peridynamics framework for corrosion fatigue damage prediction, Technical Report, Phase II STTR Base Final Report, Distribution B (Limited to U.S. Government agencies), Navy Contract: N68335–15-C-0032. Lancaster, PA: Advanced Cooling Technologies Inc; 2017.

29. Madenci E, Oterkus E. *Peridynamic Theory and Its Applications*. New York, NY: Springer; 2014.