Research Article

Characteristics of Stress, Crack Evolution, and Energy Conversion of Gas-Containing Coal under Different Gas Pressures

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Received 5 February 2021; Revised 23 February 2021; Accepted 26 February 2021; Published 15 March 2021

Academic Editor: Guanglei Zhang

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In order to study the meso-mechanism of deformation, crack evolution, and energy conversion of gas-containing coal under loads, considering the gas pressure and adsorption expansion, the gas-solid coupling calculation program of MatDEM software was developed, and the triaxial compression process of gas-containing coal under different gas pressures was numerically simulated. The results show that the strength and stiffness of gas-containing coal decrease with the increase of gas pressure. During the loading process, the permeability of the coal sample decreases first and then increases, while the initial permeability, minimum permeability, and maximum permeability all decrease with the increase of gas pressure. There are far more shear cracks in coal samples than tension cracks, and the number of cracks increases simultaneously with the peak stress drop. With the increase of gas pressure, the macroscopic cracks in coal samples gradually change from large-angle shear cracks to multiple intersecting small-angle ones, and the coal sample gradually changes from brittle failure to ductile. There is an initial accumulation of elastic energy inside the gas-bearing coal, and the dissipated damping heat presents a stage change. As the loading stress level increases, the gas pressure gradually produces a degrading effect. The rockburst tendency of gas-bearing coal changes from weak to none with the increase of gas pressure, which is related to the evolution of the accumulated elastic energy and dissipated damping energy in the coal.

1. Introduction

China is the largest coal producer and consumer in the world, and coal accounts for nearly 70% of the country's total energy consumption. More than 50% of the mined coal seams in the country are high gas coal seams. Gas disasters are the mine disasters with the largest coal mine casualties and losses in China. Gas is the main cause of gas disasters such as coal and gas outbursts and gas explosions [1–3]. Gas-containing coal is a typical heterogeneous multiphase medium composed of coal solid particles, free gas, and adsorbed gas. The mechanical and nonmechanical effects of free gas and adsorbed gas make the mechanical properties

and permeability characteristics of gas-containing coals very different from those of ordinary coals [4, 5]. Therefore, studying the stress, deformation, crack evolution, and energy conversion of gas-containing coal with gas-solid coupling under gas pressures is very important for the understanding and prevention of gas disasters.

The influence of gas-solid coupling on the deformation and failure process of gas-containing coal can be divided into two aspects.

- (1) The effect of coal structure on gas flow in the mechanical process is as follows: the pore structure and volume of coal change under loads, which will

cause internal gas pressure fluctuations and gas permeability changes. He [6] found that the gas escape pressure decreases intermittently during the compression process and reaches the maximum at the peak stress. The permeability test found that the gas permeability gradually decreases during the initial compaction and elastic stage and starts to increase at the failure stage when a large number of cracks are generated and connected [7, 8]. Wei found [9] that the effective gas permeability of the raw coal sample decreases nonlinearly under the condition of constant effective stress with increasing water content

- (2) The influence of gas pressure on coal structure is as follows: gas seepage causes pore pressure disturbance, and the pore pressure acts on the pore structure to cause crack propagation and structural instability. Many different tests have shown that the strength of gas-containing coal samples decreases to varying degrees with the increase of gas pressure [7–9]. Liang and Wang [10] conducted triaxial compression tests on gas-containing coal and found that the brittleness of coal increases significantly with increasing gas pressure. The mechanical action of pore gas and the nonmechanical action of adsorbed gas simultaneously affect the deformation and strength characteristics of coal. For methane-based gas, the adsorption of methane on the pore structure surface will cause the adsorption structure surface to expand, resulting in adsorption expansion stress, which has a greater impact on the overall structure [11–16]

Numerical simulation is an effective method for studying the mechanical behavior of gas-containing coal under load. Most of the domestic and foreign solutions for gas-solid coupling numerical simulation of gas-containing gas are studied by the method of continuum mechanics [17–20]. Zhao and Kaunda [17] performed numerical simulations on gas-containing coal pillars under different gas pressures based on FLAC3D software and analyzed the strength of impact tendency under different sizes. Yang [18] proposed an improved anisotropic permeability model based on the theory of linear elastic pore mechanics, assuming that coal is a transversely isotropic fractured medium. Similarly, Tao et al. [19] analyzed the change of permeability according to the Klinkenberg effect of gas adsorption, which is in good agreement with the experiments. However, for coal and rock, which are essentially discontinuous materials, the discrete element method may be more suitable and accurate, and it is more convenient to know the mechanical response on the mesoscale. In this paper, considering the gas pressure and adsorption expansion, we developed a simulation method for the gas-solid coupling of porous media on the MatDEM software platform (<http://matdem.com>), and based on this, we studied the mechanical characteristics of gas-containing coal during triaxial compression including grain stress, pore pressure, macroscopic deformation and failure, crack evolution, and energy conversion.

2. Numerical Test Platform and Assumption

2.1. Numerical Test Platform. Gas-containing coal is a discontinuous structure composed of mineral particles and gas, and the particle flow software can be used to simulate this discontinuous feature. By setting the properties of the basic particles, the meso-material structure of the coal can be reflected essentially, and the overall mechanical properties of the coal can be obtained.

The MatDEM software platform uses the particle discrete element method and is developed by Liu Chun and his team at Nanjing University in China. MatDEM software has the function of self-training materials. It only needs to input 6 macromechanical parameters to automatically obtain the material's micromechanical parameters. Compared with general commercial discrete element software, such as PFC, which directly sets the bond strength between particles, it greatly saves the time to adjust model parameters. Using innovative GPU matrix calculation method and 3D contact algorithm, MatDEM realizes 15 million 3D element motion calculations per second (where in 2D is 40 million elements), and the number and calculation speed of calculation element are more than 30 times that of some commercial software (3 million 3D elements, and 10 million 2D elements). It has been successfully applied in slope instability [21], hob breaking rock [22, 23], rock compaction failure [24], etc. The advantage of MatDEM in modelling the gas-solid coupling problems is that the number of simulation units is more, the calculation is faster, and it can reach the level of one million units in the 2D case, providing calculation support for future engineering-scale simulations. Therefore, we choose this software platform to study the gas-solid coupling of gas-containing coal in this paper.

2.2. Assumption. The gas-solid coupling effect of coal is a very complex issue. Considering the two most important mechanical effects of gas on the pore structure during the gas-solid coupling process, that is, the mechanical effect of pore pressure on the structure and the adsorption and expansion of the pore structure surface. The basic assumptions are as follows:

- (1) Ignore the gas exchange process in the adsorption and desorption process, and only consider the gas permeation behavior caused by the pore pressure difference
- (2) The temperature and viscosity of the gas migration process remain unchanged, that is, isothermal adsorption and percolation
- (3) The gas permeability of adjacent pores follows the cubic law
- (4) The simulation test conditions are quasistatic

In fact, gas exchange mainly affects the mechanical properties of coal through the process of adsorption and desorption, and the structural expansion and contraction caused by this process have been realized by changing the particle diameter in real-time in the simulation. However, considering gas

FIGURE 1: Numerical model of gas-containing coal sample and triangulation network.

TABLE 1: Microscopic parameters for numerical simulation.

Average normal stiffness/MPa	20.0460
Average tangential stiffness/MPa	7.1590
Average breaking force/N	11.8780
Average shear resistance/N	37.6636

exchange in the process of gas percolation requires a more complicated dual-medium permeation model. The gas adsorption will cause the supersaturated gas inside the pores to be absorbed, and the gas desorption will fill the expansion space caused by the destruction of the pore structure, both of which will reduce the gas pressure difference between adjacent pores and inhibit gas penetration and diffusion.

3. Gas-Solid Coupling Process

3.1. Pore Structure and Initial Aperture of Pore Throat. The numerical model of gas-containing coal consists of round particles and interparticle pores. Through the Delaunay triangulation method, the particles are divided into triangular networks, and the gas storage area of the pores is composed of blank areas formed naturally after the accumulation of round particles. Therefore, the area of each pore area (two-dimensional) can be calculated from the coordinates and radius of the particles. The seepage channel is considered as the gap between the particles, and the length of the channel is simply the average of the diameters of the two particles. The seepage direction is perpendicular to the connecting direction of the two particles. The model and the triangular network are shown in Figure 1. The average radius of coal samples is 0.3 mm, with a total of 14,726 particles. 27945 pores are formed by the triangular splitting. After the model is stacked, the length and width are 97 mm and 51 mm, respectively. According to the laboratory test [8], the macro-

scopic elastic modulus, compressive strength, Poisson's ratio, density, and internal friction coefficient are 9.53 GPa, 63.9 MPa, 0.15, 1650 kg·m⁻³, and 0.35 in order. The microscopic parameters of the model are calculated by the macro-micro conversion formula [25], which is listed in equations (1)–(6), as shown in Table 1.

$$K_n = \frac{\sqrt{2}Ed}{4(1-2\nu)}, \quad (1)$$

$$K_s = \frac{\sqrt{2}(1-5\nu)Ed}{4(1+\nu)(1-2\nu)}, \quad (2)$$

$$X_b = \frac{3K_n + K_s}{6\sqrt{2}K_n(K_n + K_s)} \cdot T_u \cdot d^2, \quad (3)$$

$$F_{S_0} = \frac{1 - \sqrt{2}\mu_p}{6} \cdot C_u \cdot d^2, \quad (4)$$

$$\mu_p = \frac{2\sqrt{2} + \sqrt{2}I}{2 + 2I}, \quad (5)$$

$$I = \left[(1 + \mu_i^2)^{1/2} + \mu_i \right]^2, \quad (6)$$

where K_n is the interelement normal stiffness, K_s is the shear stiffness, X_b is the breaking displacement, F_{S_0} is the shear resistance, μ_p is the coefficient of friction, E is the Young's modulus, ν is the Poisson's ratio, T_u is the tensile strength, C_u is the compressive strength, and μ_i is the coefficient of intrinsic friction.

At the contact point between particles, it is assumed that there is an initial aperture a_0 . The initial aperture setting allows fluid flow in the fluid channel formed by the two particles even when they are tightly compacted, thereby simulating the initial matrix permeability of the material. The aperture of the channel depends on the contact force between

FIGURE 2: Change curve of gas compressibility factor [27].

the particles. When the normal contact force between the particles is the compression force, the pore aperture is

$$a = \frac{a_0 F_0}{F + F_0}, \quad (7)$$

where F is the compression force between two particles, and F_0 is the compression force when the pore aperture is reduced to half of the initial size.

When two cemented particles are stretched, or the cementation is broken to form a connected domain, the pore aperture is:

$$a = a_0 + \alpha(d - R_1 - R_2), \quad (8)$$

where d is the distance between two particles, R_1 and R_2 are the radii of the two particles, respectively, and α is a dimensionless coefficient. The value of α is 1.

3.2. Gas Pressure Calculation. There is free gas in coal pores, which is a state of free motion and has the characteristics of conventional gas, so the gas state equation is generally used to describe its physical characteristics. However, when the ideal gas state equation is applied to CH₄ and other gases, there will be deviations. It is generally described by Van der Waal's equation [26]. In practical applications, the gas compression factor Z is often introduced, namely,

$$p = \frac{nZRT}{V}, \quad (9)$$

where p is the gas pressure, Pa; V is the gas volume, m³; n is the total amount of gas, mol; T is the gas temperature, K; R is the ideal gas constant, about 8.31441 J/(mol·K); Z is the compressibility factor, its value changes with temperature and pressure, as shown in Figure 2 [27].

3.3. The Mechanical Effect of Gas Pressure on Pore Structure. As mentioned above, the mechanical effect of gas pressure on coal is mainly manifested and that pore pressure promotes pore deformation and destruction and volume expansion of coal particles due to gas adsorption. The former is achieved

FIGURE 3: Schematic diagram of adsorption expansion.

by applying body force in the direction of the particle line to the particles forming the pores, and the latter is achieved by changing the diameter. Aiming at the adsorption expansion of coal, Wu [28] obtained the expansion linear strain formula of the coal sample under constraints based on the pore structure model, surface physical chemistry, and elastic mechanics theory, which is

$$\varepsilon_s = \frac{2a_m \rho RT(1 - 2\nu) \ln(1 + b_m p)}{EV_m}, \quad (10)$$

where a_m is the limit adsorption capacity under the reference pressure, about 19.95 m³/t; b_m is the adsorption equilibrium constant of coal, about 1.081 MPa⁻¹; ρ is the apparent density of coal, t/m³; V_m is the molar volume, $V_m = 22.4 \times 10^{-3}$ m³/mol.

The arc of the particle as the adsorption surface is shown in Figure 3, due to the adsorption expansion, the overall diameter of the particle increases and the pore volume decreases. Therefore, the change in particle diameter due to pressure change is

$$dr = \frac{r_i \theta_i}{2\pi} \varepsilon_s = \frac{r_i \theta_i a_m \rho RT(1 - 2\nu) \ln(1 + b_m p)}{\pi EV_m}, \quad (11)$$

where r_i and θ_i are the particle radius and the central angles of the arc of the pore, respectively.

FIGURE 4: Effective stress-strain curves under different gas pressure with confining pressure of 10 MPa.

4. Numerical Simulation Results and Analysis

The numerical model of gas-containing coal is shown in Figure 1, and the conventional triaxial compression numerical simulation is performed. The confining pressure is 10 MPa, and the gas pressure is 0 MPa, 1 MPa, 2 MPa, 3 MPa, 4 MPa, and 5 MPa, respectively. The stress and strain, the number of tensile cracks and shear cracks, elastic energy, and damping heat dissipation are simultaneously monitored, and the deformation and failure mechanism of gas-containing coal during the loading process is analyzed from both macroscopic and microscopic aspects.

4.1. Stress-Strain Curves. The stress-strain curve reflects the deformation and strength characteristics of the gas-containing coal during the whole process of deformation and failure. Figure 4 shows the effective stress-strain curves of the gas-containing coal samples under different gas pressures at a confining pressure of 10 MPa. When the gas pressure is 0 MPa, the effective stress is the axial stress. When the gas pressure is not 0, the effective stress is equal to the measured stress minus the initial pore stress after adsorption expansion equilibrium. The gas-containing coal sample went through five deformation stages from the initial hydrostatic pressure state to failure: compaction stage, elastic deformation stage, crack propagation stage, postpeak failure stage, and residual stage. (1) Compaction stage: this stage cannot be represented in a typical discrete element simulation, but it exists in laboratory experiments. The pores in the coal sample are compacted, and some cracks are closed, resulting in a nonlinear deformation of the coal sample at the initial stage of loading. However, during the triaxial compression test, the confining pressure caused some of the primary defects in the coal sample to be compacted and closed before the

axial compression load, resulting in the compaction stage of the stress-strain curve of the coal sample being less obvious. The higher the gas pressure, the smaller the effective confining pressure of the coal sample, the more primary defects in the coal sample at the initial stage of axial compression, and the more obvious the compaction stage of the stress-strain curve of the gas-containing coal sample. (2) Elastic deformation stage: the stress-strain relationship conforms to Hooke's law. In this stage, the original defects of the coal sample are compacted, new cracks are not produced in large numbers, and the deformation of the coal sample is mainly reversible elastic deformation. (3) Crack propagation stage: the stress-strain curve of gas-containing coal presents obvious nonlinearity, the slope of the curve gradually decreases, and the stiffness of the coal sample decreases significantly. At this stage, a large number of microcracks in the coal sample are dense and confluent, forming larger macrocracks. (4) Postpeak failure stage: due to the stress drop of the coal sample, the deviator stress-axial strain curve of the gas-containing coal is curved downward and shows a nonlinear change. The slope of the curve is negative. At this stage, the microcracks in the coal sample merge and form the connected macroscopic crack surface, the effective bearing area of the coal sample gradually decreases with the crack propagation, and the bearing capacity of the coal sample decreases accordingly. (5) Residual stage: after the stress drops to a certain level, it remains basically unchanged, while the strain continues to increase. This is because under the action of confining pressure, the friction between the crack surfaces provides a stable residual bearing capacity for the coal sample, but the shear slip of the crack surface causes the coal sample to continue to deform.

The peak strength quantitatively characterizes the maximum bearing capacity of gas-containing coal. Figure 5 shows the variation of the peak strength of the coal sample with the

FIGURE 5: Variation of peak strength of coal sample with gas pressure.

gas pressure. It can be seen that as the gas pressure increases, the peak strength of the coal sample gradually decreases, roughly index relationship. Both pore gas pressure and adsorbed gas have a weakening effect on the carrying capacity of coal samples. The pore gas pressure acting on the inside of the coal sample particles weakens the confining pressure to close the coal sample cracks, promotes the crack propagation, and reduces the ability to resist damage. The adsorbed gas on the surface of coal particles weakens the cohesive force of the internal structure of the coal sample, making it easier to generate internal cracks in the coal sample. However, since the change of the adsorbed gas under unit gas pressure decreases with the increase of gas pressure, the change of peak strength of coal sample under unit gas pressure also decreases with the increase of gas pressure, so the attenuation range of peak strength of coal sample gradually decreases with the increasing gas pressure. Since the particles in the discrete element method are randomly generated by a random function, the models obtained under different random parameters are completely different in detail. Figure 5 shows the average results of multiple models, which are in good agreement with the experimental results [8].

The elastic modulus quantitatively characterizes the deformation properties of gas-containing coal. Figure 6 shows the normalized elastic modulus of a coal sample as a function of gas pressure. It can be seen that as the gas pressure increases, the elastic modulus decays exponentially. When the gas pressure is small, the elastic modulus has a larger change range, and when the gas pressure is higher than 2 MPa, the change range is reduced. This is because the adsorbed gas on the surface of coal particles weakens the bonding force between coal particles and reduces their ability to resist deformation. The experimental studies of many scholars have shown that the higher the gas pressure, the

FIGURE 6: Variation of normalized elastic modulus of coal sample with gas pressure.

smaller the change in the amount of adsorbed gas caused by the change in unit gas pressure. Therefore, as the gas pressure increases, the change in elastic modulus caused by the change in unit gas pressure becomes smaller. In the numerical simulation, the spring stiffness between discrete particles does not change, so the elastic modulus is basically unchanged in the elastic phase. The decrease in elastic modulus is mainly caused by the stress drop associated with local structural instability, so the numerical simulation value is higher than the experimental value.

4.2. Permeability. Figure 7 shows the change of permeability during loading under different gas pressures. It can be seen

(a) 1 MPa

(b) 2 MPa

FIGURE 7: Continued.

(c) 3 MPa

(d) 4 MPa

FIGURE 7: Continued.

FIGURE 7: Changes of stress and permeability with strain under different gas pressure.

that the permeability of gas-containing coal decreases first and then increases during the deformation and failure process. During the compaction and elastic deformation stages of coal sample deformation, the primary cracks and pores of the coal sample are gradually closed, and the newly generated cracks do not form effective macroscopic cracks that penetrate the entire model, and matrix infiltration dominates. As the axial load increases, the effective stress and axial strain of the coal sample gradually increase. The initiation and propagation of cracks in the coal sample provide a new channel for gas flow. The change trend of coal sample permeability gradually changes from decreasing to increasing. The effective deviator stress corresponding to the starting point of coal sample permeability increase is generally about 90% of the peak deviator stress, and the axial strain is about 85% of the peak axial strain. During the crack propagation stage of the coal sample, with the increase of the deviator stress and axial strain of the coal sample, the propagation and convergence of the cracks gradually increase the permeability of the coal sample. Because no macroscopic cracks are formed in the coal sample at this stage, the permeability increases slowly, and the permeability of the coal sample at the peak point of deviator stress is lower than the initial permeability, that is, the permeability at the zero point. In the postpeak failure stage, the formation of macroscopic cracks in the coal sample prompts the coal sample's permeability to increase rapidly and quickly exceeds the initial permeability. In the residual stage, the shear slip and propagation of the cracks in the coal sample continue to increase the permeability with the increase of axial strain. However, since no new macroscopic cracks are formed, the rate of increase in permeability is lower than the postpeak failure stage. It can be seen that the evolution of permeability in the process of deformation and

failure of gas-containing coal has obvious stage characteristics and correspond to the five stages of deformation and failure. The evolution characteristics of permeability in each stage are closely related to the law of crack change. The crack propagation in a coal sample not only determines the macroscopic stress-strain characteristics but also determines its permeability evolution characteristics.

In addition, the initial permeability, minimum permeability, and maximum permeability of coal samples all decrease with the increase of gas pressure, and the greater the gas pressure, the smaller the permeability attenuation caused by the increase of unit gas pressure. This is because the volume expansion of solid particles caused by gas adsorption occupies the space of cracks and pores under stress constraints, the gas flow channel is blocked, and the permeability is also reduced. The volume expansion of coal solid particles is directly proportional to the adsorbed gas content, and the higher the gas pressure, the smaller the change in the adsorbed gas volume caused by the change in unit gas pressure. Therefore, the higher the gas pressure, the smaller the increase in volume expansion of solid particles caused by the change of unit gas pressure, and the corresponding permeability attenuation amplitude also decreases.

4.3. Particle Stress and Pore Pressure. The temporal and spatial distribution and evolution of the particle stress and pore stress in the coal sample can be calculated, which is not available in laboratory tests. To save space, a sample with a gas pressure of 5 MPa is shown here. Figure 8 shows the axial particle stress distribution of gas-containing coal samples under different stress levels. Before the peak stress, as the load increases, the high-stress area of the internal particles is transferred downward from the top of the model and is

FIGURE 8: Axial stress distribution of particles under different stress levels in gas-containing coal.

FIGURE 9: Pore pressure distribution under different stress levels in gas-containing coal.

accompanied by local failure of the upper right part. After the peak stress, macroscopic connected cracks are generated, and high-stress particles are concentrated in the unstabilized overall structure. The particles near the crack also concentrated a large supporting stress, maintaining the stability of the current load state.

Figure 9 shows the pore pressure distribution of gas-containing coal under different stress levels. Since the gas pressure at the upper end is kept constant during the loading process, the internal gas mass is conserved, and the pores between the particles become larger during the deformation and failure process, and the gas pressure calculated by equation (9) will decrease. The particle adsorption pressure is the average value of the surrounding pore pressure, which will also reduce the particle diameter and the expansion stress, resulting in a greater degradation effect.

4.4. Cracks. Figure 10 shows the distribution and evolution of cracks in coal samples under different gas pressures. From a

macropoint of view, the failure of coal samples under different gas pressures is mainly caused by two macroscopic cracks intersecting on the left side of the model. With the increase of gas pressure, the crack intersection point moves to the middle part of the sample, and the macrocracks in the upper half of the crack bifurcate, and the structural damage becomes more serious. The reason may be that the loading mode is the displacement control of the upper pressure plate, the stress is transmitted from top to bottom, and the upper end is damaged first. Although the number of balances is sufficient to simulate the quasistatic process, in order to dissipate the internal energy of the model as soon as possible, the empirical damping [25] used makes the compaction and mechanical effects of the upper part more significant. Therefore, the higher the gas pressure, the earlier the main cracks that cause instability in the upper part initiate and expand. It can also be seen that with the increase of gas pressure, the macroscopic cracks in the coal sample change from large-angle shear cracks to multiple intersecting small-angle

FIGURE 10: Distribution and evolution of cracks in gas-containing coal under different gas pressures.

shear cracks, and the failure mode gradually changes from brittle shear to ductile shear. This may be because the adsorbed gas in the coal sample reduces the cohesive force between coal particles, softens the coal sample to a certain extent, and weakens the brittleness of the coal sample.

It can also be seen from Figure 10 that under the same stress level, the higher the gas pressure, the more the number

of cracks. We counted the number of cracks in the coal sample during the entire loading process. Taking into account the different mechanisms of crack generation, the numbers of tensile cracks, shear cracks, and total cracks were counted, as shown in Figure 11. It can be seen that the change of the number of cracks in the deformation and failure process of coal samples under different gas pressures has a similar law,

FIGURE 11: Continued.

(d) 3 MPa

(e) 4 MPa

(f) 5 MPa

FIGURE 11: Changes of the number of cracks in gas-containing coal during deformation and failure.

which can be roughly divided into the following four stages: slow growth stage, rapid growth stage, violent growth stage, and steady stage. (1) Slow growth stage: this stage corresponds to the compaction stage and the elastic deformation stage of the coal sample. As the load increases, microcracks in the coal sample initiate and slowly expand, the total number of cracks rises slowly, and appears to be disorderly and random in space (see Figure 10), and most of them are shear cracks, while tension cracks are almost absent. (2) Rapid growth stage: this stage corresponds to the crack growth stage. The microcracks in the coal sample are gradually dense and merge to form larger cracks. As the axial strain increases, the total number of cracks rises rapidly. Shear cracks account for the majority, but tensile cracks increase significantly. The predominant gathering area of cracks gradually formed in space (see Figure 10). (3) Violent growth stage: corresponds to the postpeak failure stage from the peak point. The cracks propagate rapidly and converge to form a connected main crack, and a large amount of energy is released instantly, causing violent cracking activities. Near the peak point, the crack number curve rises approximately vertically. (4) Steady stage: corresponding to the residual stage of the coal sample deformation. At this stage, the cracks in the coal sample slip and propagate, and almost no new cracks are formed.

Gas affects the crack evolution properties of coal samples. With the increase of gas pressure, the slow growth stage of cracks is shorter, and the increase in the number of cracks in the violent growth stage is smaller. It can also be seen from Figure 10 that the coal sample under the gas pressure of 0 MPa has very few cracks before 60% of the peak stress, while the coal sample under the gas pressure of 5 MPa has a considerable number of microcracks in the initial stage of loading. This is because the gas has a weakening effect on the coal sample, so that the coal sample starts to initiate and propagate cracks at a lower stress level. When the gas pressure is 0 MPa, the increase in the number of cracks in the violent growth stage accounts for more than 70% of the final total number of cracks, while it is only about 50% when the gas pressure is 5 MPa. This indicates that with the increase of gas pressure, the severity of the damage of gas-containing coal samples gradually weakened, and the brittle failure gradually changed to ductile failure.

4.5. Energy. The energy in the discrete element model mainly includes mechanical energy and thermal energy. Mechanical energy includes kinetic energy, gravitational potential energy, and elastic potential energy, which transform into each other in various forms and are transformed into heat energy under the action of friction, fracture, and damping. The total heat in the model is the sum of damping heat, fracture heat, and friction heat.

The cementation between particles can be regarded as a set of orthogonal springs, which are normal spring and tangential spring, corresponding to normal stiffness and tangential stiffness. Through the tangential stiffness, normal stiffness, fracture displacement, and other parameters between particles, energy changes such as elastic energy, dissipation damping heat, and fracture heat can be calculated. The elastic energy of the system is the elastic energy stored

FIGURE 12: Changes of the elastic energy during deformation and failure under different gas pressures.

by all springs. The kinetic energy of the system is the sum of the kinetic energy of all particles. For a tangential spring, the maximum static friction force limits its deformation, and the friction heat is calculated by the static friction force and the relative shear displacement of the particles. The fracture heat is the heat directly converted by the elastic potential energy of the spring between particles, assuming that the spring stops vibrating immediately after breaking. The damping heat is equal to the product of the damping force on the particle and the moving distance, which is the heat generated by damping which weakens the elastic wave and dissipates the kinetic energy in the particle system [29].

Figure 12 shows the changes in the elastic energy of gas-containing coal during deformation and failure under different gas pressures. The pore structure expands in volume after adsorbing gas, resulting in expansion stress. The internal particles are squeezed and stretched due to the cementation, resulting in initial elastic deformation and accumulating initial elastic energy. The maximum accumulated elastic energy at the peak stress decreases with the increase of gas pressure. When the sample is unstable, the elastic energy is released largely, and the residual elastic energy is basically unchanged under the action of confining pressure after the peak point.

Figure 13 shows the change of the dissipated damping heat during deformation and failure under different gas pressures. Dissipated damping heat, as the cumulative sum of dissipated energy, has four distinct stages in the process of deformation and failure. First, when the strain is less than 0.003, the dissipated damping heat is basically the same under different gas pressures, and it grows approximately linearly, that is, the overall energy dissipation of the system is mainly stress wave dissipation. In stage II, the greater the gas pressure, the more damping heat is dissipated, indicating

FIGURE 13: Changes of dissipated damping heat in the process of deformation and failure under different gas pressures.

FIGURE 14: Change of fracture heat and instantaneous kinetic energy of gas-containing coal.

that a certain amount of instantaneous kinetic energy generated inside the bond is dissipated after the bond fractures, and the gas pressure gradually produces a degrading effect, as shown in Figure 14. Stage III is the stage of macroscopic instability and destruction, a large number of bonds are broken, and the dissipation energy rises sharply; stage IV is the residual stage after the peak, and the energy dissipation gradually tends to be stable.

4.6. Rockburst Tendency. According to the National Standard of the People's Republic of China "Method for Measuring the

Classification Index of Rockburst Tendency of Coal GB/T 25217.2-2010," the impact energy index of coal can be used as the evaluation standard. The impact energy index K_E is obtained from the whole stress-strain curve of the rock and is defined as the ratio of the area under the stress-strain curve before and after the peak point, that is, the ratio of the energy stored by the rock before the peak strength to the energy required for failure after the peak.

$$K_E = \frac{A_e}{A_x}, \quad (12)$$

FIGURE 15: Changes of the rockburst tendency and energy of coal samples with different gas pressures.

where A_e is the energy stored by the rock before the peak strength, and A_x is the energy required for failure after the peak point. When K_E is between 1.5 and 2, the coal sample has a weak rockburst tendency, and when it is less than 1.5, there is no rockburst tendency.

Figure 15 shows the rockburst tendency and energy accumulation and release of coal samples under different gas pressures. It can be found that the cumulative elastic energy before the peak point decreases approximately linearly with the increase of gas pressure, while the dissipated damping energy increases in the failure stage after the peak point relatively large, which causes the overall rockburst tendency of coal to change from weak to none. Liu et al. [4] conducted uniaxial compression tests on gas-containing coal under different gas pressures and evaluated their rockburst tendency according to 4 different indexes, including dynamic failure time, elastic energy index, impact energy index, and uniaxial compressive strength. All test results have reached the same conclusion. Xue et al. [30, 31] studied the influence of gas pressure on coal and rock bursting tendency based on the energy method and found that the impact energy index, effective impact energy index, and residual energy index all decrease with the increase of gas pressure. The change of rockburst tendency can also be confirmed by the abovementioned crack evolution law. In the coal seam which has typical dynamic hazards, there is a critical value of gas pressure. When the gas pressure is higher than the critical value, gas outburst is the main disaster. When the gas pressure is lower than the critical value, the rockburst is the main disaster [30].

5. Conclusions

Through the fluid-solid coupling simulation of gas-containing coal, considering gas pressure and adsorption expansion, from the perspectives of macromechanical behavior, permeability, microcrack evolution, energy accumulation and release, the

deformation, and failure mechanism of gas-containing coal under different gas pressures is analyzed. The main conclusions are as follows.

- (1) In the discrete element method, the adsorption and expansion of gas-containing coal can be effectively simulated by increasing the particle diameter. Based on the MatDEM software, a gas-solid coupling simulation method for porous media has been developed
- (2) The compressive strength and elastic modulus of gas-containing coal decrease with the increase of gas pressure. The pore gas pressure acting on the inside of the coal sample particles weakens the confining pressure to close the coal sample cracks, promotes the crack propagation, and reduces the ability to resist damage. The adsorbed gas on the surface of coal particles weakens the bonding force between coal particles and reduces their ability to resist deformation
- (3) During the process of deformation and failure of gas-containing coal, the permeability of coal samples first decreases and then increases. The initial permeability, minimum permeability, and maximum permeability of coal samples all decrease with the increase of gas pressure, and the greater the gas pressure, the smaller the decrease in permeability caused by the increase in unit gas pressure
- (4) With the increase of gas pressure, the macroscopic cracks in the coal sample gradually changed from large-angle shear cracks to multiple intersecting small-angle shear cracks. The number of cracks at the same stress level increases, and the increase in the number of cracks during the violent growth stage becomes small. The coal sample gradually changed from brittle failure to ductile failure

- (5) The cumulative elastic energy before the peak strength decreases approximately linearly with the increase of gas pressure, while the increase of dissipated damping energy is relatively large, and the overall rockburst tendency of coal samples changes from weak to no

Data Availability

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

Conflicts of Interest

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

Acknowledgments

The authors are supported by the National Natural Science Foundation of China (Grant Nos. 51934007 and 42030810), and the Fundamental Research Funds for the Central Universities (Grant No. 2017QNA31).

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