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Experimental Study on Coal and Gas Outburst Risk under Different Water Content Rates in Strong Outburst Coal Seams

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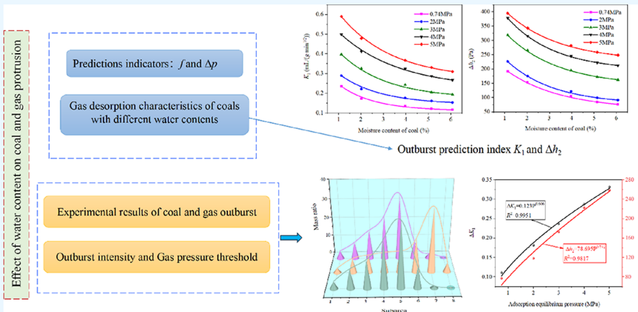
Cite This: *ACS Omega* 2024, 9, 1485−1496

ABSTRACT: To investigate the alleviation potency of coal seam water infusion on coal and gas outburst, this paper focuses on the Qidong coal mine outburst coal seam, where outburst accidents have occurred many times, and obtains the impact of water content on outburst prediction parameters by studying the features of outburst parameters and gas desorption law under different water content rates. How water content affects outburst was also researched through the use of a self-made outburst simulation test system, and the relationship between water content and outburst intensity and critical gas pressure was studied. It can be concluded that with the rise of water content, the initial velocity of gas diffusion, the gas desorption index of drilling cuttings, and the adsorption constant *a* decrease, but the firmness coefficient (*f*) increase, and these indicators are exponentially related to the water content. Meanwhile, as the water content raises, the outburst pressure threshold increases, the outburst intensity gradually decreases, and the less likely outburst occurs. Under 0.5 MPa pressure, as the water content arose from 2.02 to 5.14%, the outburst intensity was significantly weakened, while no outburst occurred as the water content reached to 10.25%. Fitting analysis of the influence curve of outburst parameters and comparing the vital values of outburst prediction indexes finally determined that the water content rate of 5.14% could be used as a key index for water injection measures for coal and gas outburst prevention coal seam in Qidong coal mine no. 9. This research offers a guiding significance for the outburst prevention measures of water infusion in outburst coal seams and gives a feasible scheme for the safe mining of outburst coal mines.



1. INTRODUCTION

Coal and gas outburst is a complicated dynamic disaster of coal mining, which will instantly eject a large quantity of coal and gas into the mining room such as the roadway and mining face. The coal throw out in the course of the outburst has high kinetic power, which will cause equipment damage and casualties. The gushing gas has the risk of suffocation and explosion, which enlarges the disaster effect.[1−3] Since the first outburst disaster in the world, over 400,000 outbursts have occurred around the world, and 22 countries and regions have experienced outbursts. The outburst accidents have developed into one of the severest dynamic disasters in coal mining.[4,5] The past decade has seen nearly 60 gas outburst accidents throughout China, killing over 300 people.[6] This shows that outburst is yet a primary disaster in China's coal mine production that needs to be addressed.

The reason why coal and gas burst out has always been a research hotspot for scholars at home and abroad.[7−9] At present, there is a universal acknowledgment that outburst is related to ground stress, gas pressure, coal's own structure and nature, coal seam structure, and other factors.[10−12] Moisture is one of the key elements affecting gas infiltration and gas extraction. Water injection measures in protruding coal seams are helpful to prevent and control outburst and manage gas.[13,14] On one side, moisture can promote the enlargement of coal seam fracture channels and improve the permeability of coal seams, which facilitates gas extraction. On the other side, moisture can repel the gas in the coal seam, reduce the gas desorption rate and desorption volume of coal, and reduce the outburst.[15] Outburst prediction is required before coal seam mining so as to effectively prohibit the outburst.[16] In China, predictions usually include indicators such as drill cuttings weight index (S), drill cuttings gas desorption index (K_1) and (Δh_2), initial velocity of gas diffusion (Δp), Protodyakonov's coefficient, and gas pressure.[17−19] Coal moisture is a key element affecting the important value of the outburst prediction parameters and outburst risk level. It has been confirmed that as the water of coal adds, the risk level of

Received: October 10, 2023
Revised: November 29, 2023
Accepted: December 7, 2023
Published: December 27, 2023

https://doi.org/10.1021/acsomega.3c07896
ACS Omega 2024, 9, 1485−1496

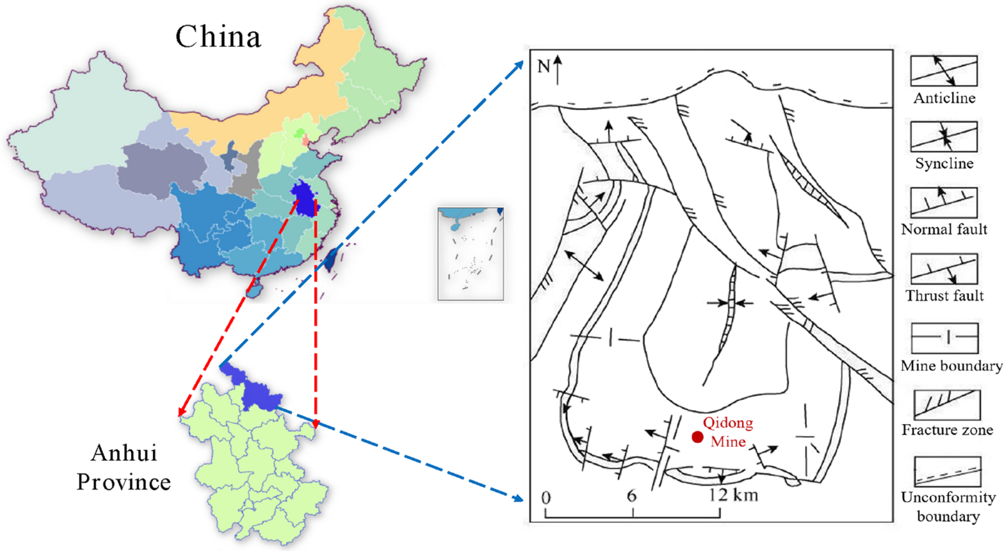


Figure 1. Geological structure of the Qidong coal mine in Huaibei mining area.

outburst will decrease, and the relative outburst intensity will also decline.[15,20−22] This is due to the fact that coal is more able to take in water molecules than methane molecules is, so water injection in coal seams can effectively prevent outburst.[23,24] The coal seam wetting by moisture can alter the mechanical features of coal, soften the coal body, and greatly decrease the permeability of coal seam. The moisture in the pores and fissures of the coal seam certainly hinders gas migration, and the gas emission rate of the coal seam is greatly reduced. In other words, the growth of water content decreases the rate of gas desorption and the initial velocity of gas diffusion, thus decreasing the gas desorption.[25,26] Moreover, moisture can enhance the capability of plastic deformation of a coal body and reduce the energy of crushing media. The more moisture of coal, the more difficult it is to be crushed and the lower the possibility of outburst.[27]

Previous studies have shown that water injection in coal seams unloads pressure and discharging gas on the coal body in the macroscopic level,[28] which plays the role of hydraulic loosening. It also has the effect of sealing the gas adsorbed in coal pores in the microscopic level, which plays the role of inhibiting gas desorption.[29] The content of water has different effects on its macro- and micro effects. Therefore, it is necessary to conduct sufficient laboratory studies on the gas desorption effect after water injection in coal bodies to determine how outburst water content rates influence the gas desorption amount and desorption speed. At present, most scholars have studied the process and energy change of outburst with different outburst water content rates, focusing on exploring the mechanism and law of outburst occurrence.[8,22,30] However, relatively few studies have been conducted on the possibility of outburst with diverse outburst water content rates and the key indicators of gas outburst prevention and control under water injection measures. In addition, the course of water injection measures at the site showed that too much moisture would increase the difficulty for gas to be desorbed and extracted, which is not helpful to prevent and control the outburst. However, too little moisture also hardly meets the standard of needed outburst prevention. Thus, it is especially vital to select a specific water content index for outburst coal seams in water injection steps, while there is no uniform measure yet. Thus, if the key value of water content under water injection measures needs to be determined, it is highly significant to study various outburst prediction parameters, desorption law after gas adsorption equilibrium, and outburst law of coal bodies with diverse outburst water content rates.

This paper selects the outburst coal seam of a representative outburst mine in a certain area as the research object. First, the outburst risk parameters (f) and (Δp) of coal under diverse water contents are measured, and the outburst prediction indexes K_1 and (Δh_2) are obtained from the desorption experiments of coal under different water contents. Then, combined with the outburst characteristics obtained from the outburst simulation test under distinct water contents and finally by comparing with the important value of outburst prediction index, the important water content index for outburst prevention and control under water injection measures is summarized, which provides theory and technique for the water injection outburst prevention measures in this coal mine. Through the study of outburst risk under diverse water contents, the effect of moisture on outburst and its related laws are obtained, which is beneficial to better predict and prevent the outburst and also provides guiding significance for the mining safety of other outburst coal mines.

2. MATERIALS AND METHODS

2.1. Coal Sample Preparation. The test coal sample was chosen from the no. 9 coal seam of the Qidong coal mine. The Qidong coal mine is located in Huaibei Coalfield, Anhui Province, China (Figure 1). The outburst intensity and frequency will increase as the coal seam tends to be deeper. The coal seam in the dangerous outburst area is very likely to have outbursts, among which many are related to geological structure and most occurred in the working surface between the stone door uncovered coal surface and coal seam excavation surface. Such a coal seam is high likely to burst out as 25 accidents have taken place there. The coal specimen were sealed and preserved after sampling on site to prevent oxidation. The elementary parameters of the coal can be measured by the WS automatic industrial analyzer, and the results are shown in Table 1.

Table 1. Industrial Analysis Results of Coal Samples

samples	industrial analysis			
	M_{ad}/%	A_{ad}/%	V_{ad}/%	FC_{ad}/%
1	3.67	16.32	10.39	69.62
2	3.59	16.45	10.42	69.54
3	3.65	16.14	10.47	69.74
average	3.64	16.30	10.43	69.63

The aim of this paper is to probe into the risk of coal outburst under various water contents, so coal specimen with diverse water contents has to be in store. The production steps are as follows: (1) According to different experimental requirements, the coal samples were crushed and screened according to the corresponding particle size. (2) The samples were fully dried in the vacuum drying oven and then soaked in distilled moisture for 7 days to make the coal samples fully absorb moisture and reach saturation. (3) Coal samples with various water contents were made in accordance with different drying periods and sealed in sealed bags. Among them, the water contents of coal samples employed in the outburst parameter determination experiment and desorption test were 1.13, 2.02, 3.97, 5.14, and 6.07%; the water contents of coal samples used in the outburst test were 2.02, 5.14, and 10.25%. The diagram of the test equipment and procedures is manifested in Figure 2.

2.2. Gas Outburst Parameter Determination of Coal With Diverse Water Content Rate. *2.2.1. Protodyakonov's Coefficient.* Protodyakonov's coefficient of coal samples is also called the firmness coefficient (hereinafter referred to as *f*). The *f* value is formed by the falling hammer measure in accordance with the national standard GB/T 23561.12−2010 of the People's Republic of China. The *f* value of coal samples with diverse water contents was measured 3 times, and the arithmetic even value was chosen as the firmness coefficient.

2.2.2. Adsorption Constant (a). Coal is a complex heterogeneous porous medium, which has a great deal of pores and fissures. The adsorption, desorption, and seepage of gas are directly influenced by the pore features of coal. At constant temperature, the relation between pressure and adsorption capacity follows the Langmuir equation.[31] In this experiment, a high pressure volumetric method gas adsorption device (refer to Figure 1) was used for the determination of Langmuir adsorption constants to study the rule of the impact of water content of coal specimen on the *a* values of adsorption constants of coal. A total of 50 g of each coal sample with diverse water contents of 0.2−0.25 mm particle size were selected for the experiment.

2.2.3. Initial Velocity of Gas Diffusion (Δp). The measurement method for the initial velocity of gas diffusion is to place a 3.5 g coal sample with a particle size of 0.25−0.5 mm under a gas equilibrium pressure of 0.1 MPa and adsorb it to saturation. The amount of gas diffused into a fixed space within 10 to 60 s is measured using the Δp to represent. The WT-1 gas diffusion initial velocity tester was employed to test coal samples.

2.3. Gas Desorption Experiment of Coal with Different Water Contents. The adsorption and desorption of gas by coal are some of the key elements affecting coal outburst. About 90% of coal seam gas is in the adsorption state, and moisture significantly affects the desorption and transformation of coal seam gas. Thus, it is vitally important to probe the gas desorption features of coal under diverse water contents to prevent outburst. The isothermal desorption device (refer to Figure 1) was employed to perform gas desorption experiments on five kinds of coal specimens with various water contents at the similar adsorption equilibrium pressure and temperature, and the adsorption equilibrium pressure was selected as 0.74, 2, 3, 4, and 5 MPa in turn.

2.4. Coal and Gas Outburst Analogical Simulating Test under Diverse Water Content Rate. *2.4.1. Experimental System.* On the basis of in-depth understanding of the characteristics of domestic and foreign outburst simulation equipment, an outburst simulation test platform was made and built to meet the outburst similarity theory,[32] as revealed in Figure 3. It primarily consists of three parts: outburst cavity,

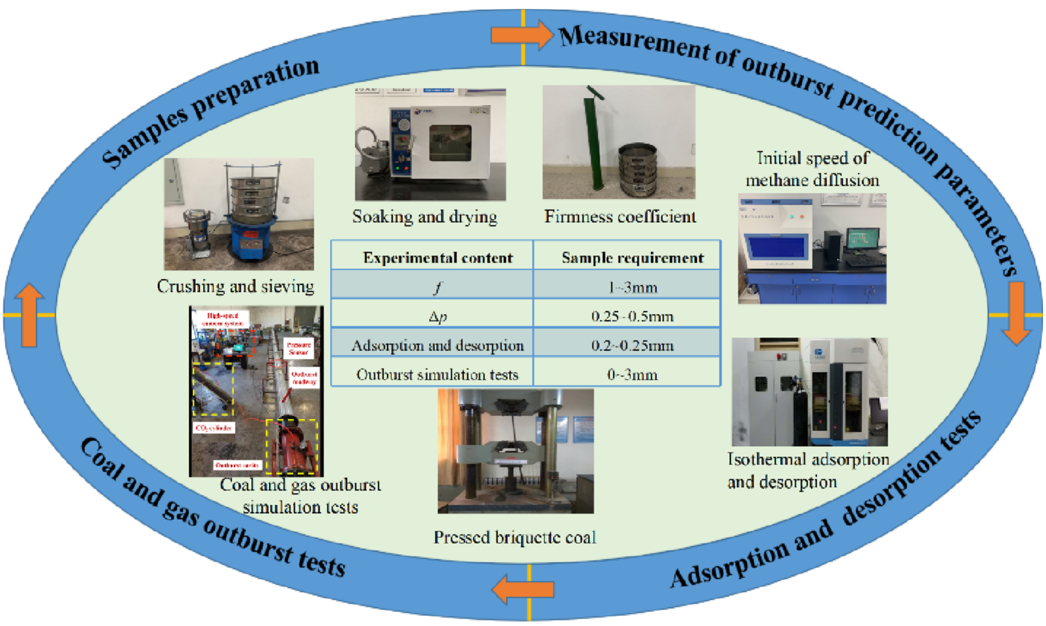


Figure 2. Experimental equipment and flowchart.

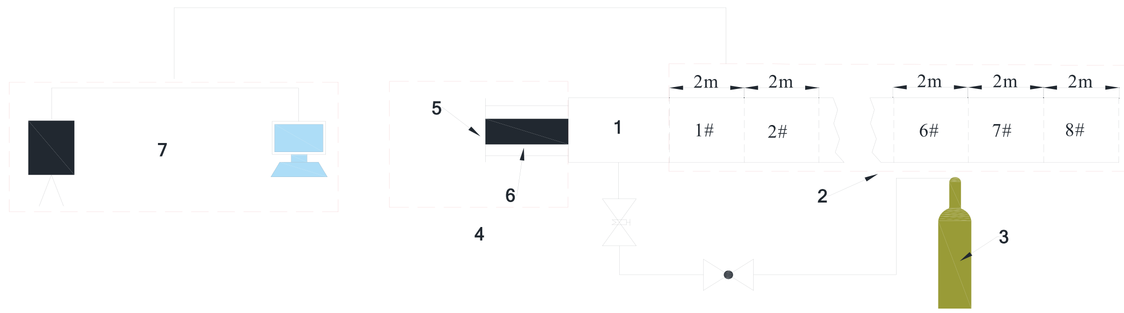


Figure 3. Coal and gas outburst simulation test system. (1) Outburst cavity; (2) simulated roadway; (3) gas cylinders; (4) stress loading device; (5) reaction frame; (6) lifting jack; (7) high-speed system.

outburst roadway, and a high-speed camera system. The platform can realize outburst tests under various gas pressure and water content conditions. The outburst roadway is made of visual materials, which can study the migration and distribution of outburst coal powder and the outburst intensity in the process of outburst. Among them, the outburst cavity is made of high strength steel, and the maximum pressure is 5 MPa. The internal diameter of the cavity is 200 mm, the length is 500 mm, and the wall thickness is 10 mm. The outburst port is located in front of the cavity, and the diameter of the outburst port is 40 mm. There are three reserved holes in the chamber, which can be used as pressure gauge interface, inflation port, and exhaust port. The simulated roadway is made of a transparent hard tube from plexiglass material. Each section of the roadway is 2 m long, the inner diameter and wall thickness are the same as the cavity, and the pressure is 1.5 MPa. The roadways are connected to each other by flanges with rubber gaskets for sealing. The model of the high-speed camera is the Y7 series of IDT company, with a resolution of 2 million and a minimum exposure time of 200 ns. The experimental test protocol is shown in Table 2. The test conditions are the same, except that the coal water content and gas pressure are different.

Table 2. Coal and Gas Outburst Test Scheme

test number	moisture content rate (%)	gas pressure (MPa)	ambient temperature (°C)
1	2.02	0.3	25
2	2.02	0.4	25
3	2.02	0.5	25
4	5.14	0.4	25
5	5.14	0.5	25
6	10.25	0.5	25

2.4.2. Test Method. To ensure the security of the experiment, the gas employed in the experiment is CO_2, and its adsorption behavior is similar to that of CH_4 on the coal surface. The experimental steps are shows below:

1. Outburst cavity filling coal sample. The prepared coal samples were filled into the cavity after compacting with the hydraulic loading system of the rock mechanics experiment system in the ratio of 0−0.5 mm:0.5 mm to ∼1 mm:1−3 mm, and the axial pressure was set to 2 MPa to simulate the ground stress and seal the cavity.
2. Detect air tightness. Filling 0.1 MPa helium into the outburst cavity, and the pressure representation number remains unchanged after 1 h, indicating that the cavity has good air tightness.
3. Simulation roadway connection. Connect the outburst cavity to the simulated roadway, and the simulated roadway to the simulated roadway.
4. Inflation of the cavity. Inject CO_2 gas into the cavity for 24 h continuously from the inlet pipe to make the gas pressure in the room reach the test pressure and close the valve after the coal sample realizes the adsorption balance.
5. Outburst activation. Open the pressure relief device to initiate outburst fast. Record the entire outburst process with a high-speed camera while opening the outburst port.

6 Test data collection. Collect the coal powder in the roadway after the test and weigh coal powder in various areas of the roadway.

3. RESULTS AND ANALYSIS

3.1. Gas Outburst Parameter Features with Different Water Content Rate. *3.1.1. Results of Protodyakonov's Coefficient (f).* Figure 4 shows that the f value rises as the

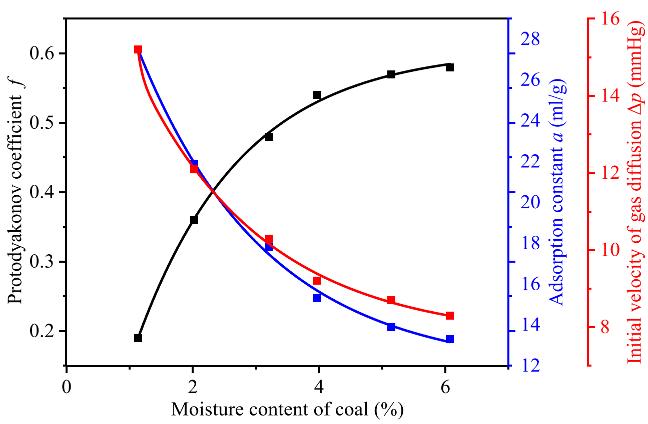


Figure 4. Variation law of the gas outburst parameters with different water content rates.

water content increases, but the growth rate will come to decline and eventually tend to be stable. It is mostly because of that when the water increases, the plastic deformation of the coal body will be enhanced, and the deformation of the body will increase greatly in the course of crashing the coal body, which can absorb more energy, while the energy employed to crush the body is reduced. When the water content coal is higher, the energy essential to crush the body is greater, and the harder coal is to be crushed, the less likely coal and gas will burst out.[33]

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ACS Omega 2024, 9, 1485−1496

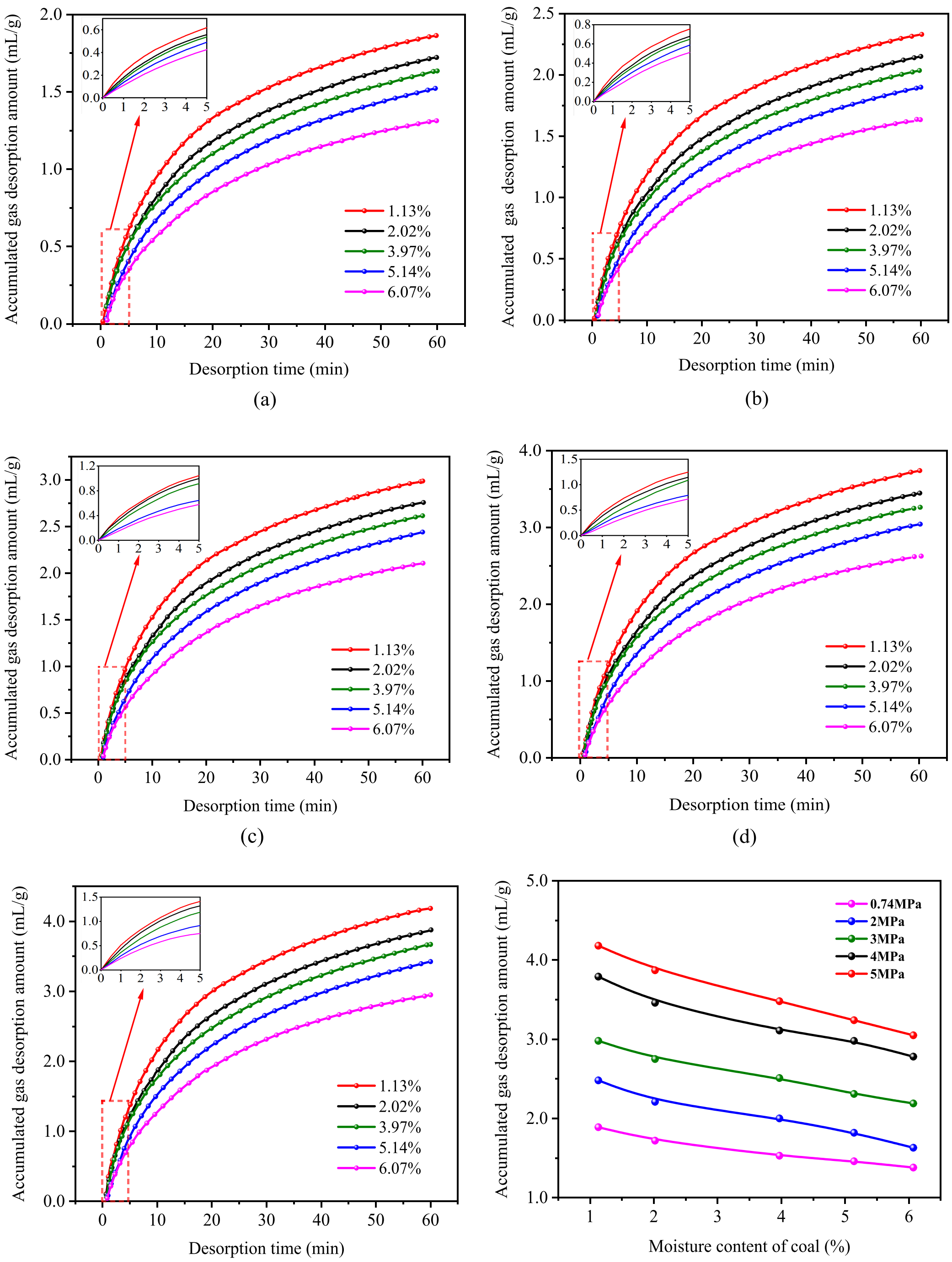

Figure 5. Desorption curves of coal samples with various water contents rate under various adsorption equilibrium pressures of (a) 0.74, (b) 2, (c) 3, (d) 4, and (e) 5 MPa, and (f) accumulated gas desorption amount.

3.1.2. Results of Adsorption Constant (a). Figure 4 shows that the adsorption constant (a) of coal declines with the growth of water content, and the attenuation rate gradually decreases, which conforms to the changing law of (Δp). It is because of that as water molecules enter the coal body, part of the free moisture is combined with the internal pores and fracture surfaces of the coal body, and methane is extremely insoluble in moisture, so water molecules will have a competition with methane molecules for adsorption. Moisture molecules will take up the adsorption room in the internal pores and fractures of the coal body, and the effective field of coal adsorbing methane will be lessened accordingly as the adsorption capacity of coal for water molecules is more than that of methane molecules. Consequently, with the growth of water content, the limit adsorption capacity of coal for methane will decrease,[30] which is consistent with the findings of others.[34,35]

3.1.3. Results of Initial Velocity of Gas Diffusion. The rate and capacity of gas release in coal seams can be used to examine the emission and transfer of coal seam gas, and play a predictive role in gas outburst.[17−19] It is a general belief that when the initial velocity of gas release tends to be higher, the

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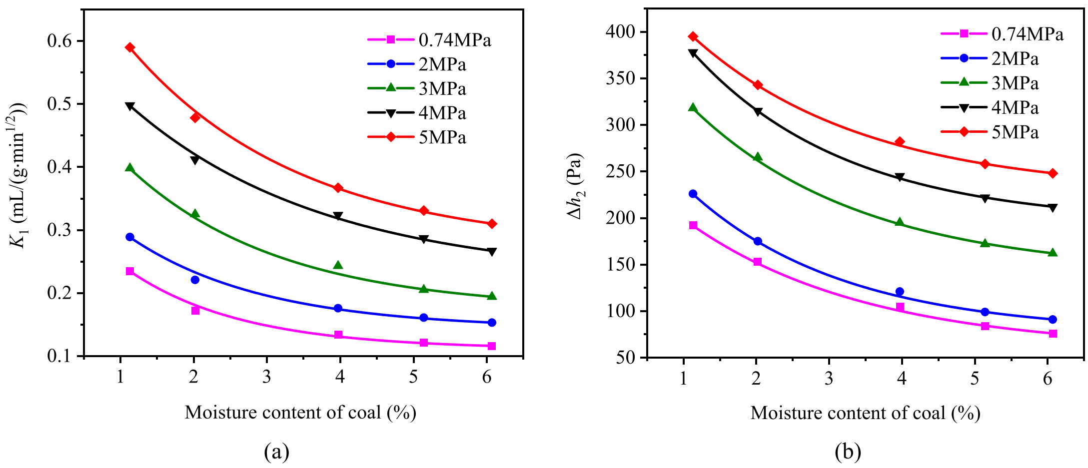

Figure 6. Transformation of gas desorption index of drilling cuttings with water content (a) K_1 and (b) Δh_2.

Table 3. Coal and Gas Outburst Test Results

test number	moisture content (%)	gas pressure (MPa)	outburst or nonoutburst (Y/N)	coal briquette mass (kg)	outburst coal powder mass (kg)	relative outburst intensity (%)
1	2.02	0.3	N	15.126	0	0
2	2.02	0.4	Y	15.079	4.161	27.6
3	2.02	0.5	Y	15.375	5.365	34.9
4	5.14	0.4	N	15.849	0	0
5	5.14	0.5	Y	15.761	3.987	25.3
6	10.25	0.5	N	16.248	0	0

coal seam is to more likely to have outburst.[36] Figure 4 indicates that Δp falls with the growth of water content, and its rate declines and to be flat. This indicates that moisture has an prohibitive impact on the emission of gas. This is mainly because when moisture enters the pores and fissures inside the coal body, moisture occupies the internal space of the coal body, which will cause the gas release channel to be blocked. Consequently, the channels of gas release remaining in the coal body will fall and the speed of gas release will slow down, so Δp will be greatly reduced.

3.2. Gas Desorption Characteristics with Different Water Content Rates. *3.2.1. Effect of Different Water Contents on Gas Desorption Characteristics of Coal.* The changing curve of gas desorption with different water content rates at different times is drawn in the same figure, as shown in Figure 5a−e.

The experimental outcomes indicate that (1) with the similar adsorption equilibrium pressure, when the initial desorption rate of the low water content coal specimen was larger, the gas desorption amount per unit time would be larger. The initial desorption speed would decline as the water content rate increased. In addition, with the rise of desorption time, the desorption rate of coal specimen decreased from fast to slow, and the desorption amount per unit time also decreased gradually. (2) Under different adsorption equilibrium pressure circumstances, the amount reached the maximum, as the water content rate was 1.13%. With 5 MPa of adsorption equilibrium pressure, the cumulative desorption amount reached the maximum 4.18 mL/g. The cumulative gas desorption number reduced with the rise of the water content, which suggests that moisture has an obvious prohibitive impact on gas desorption.

The relation between the cumulative gas desorption within 1 h and the water content can be seen in Figure 5f. As has been shown that the cumulative gas desorption within 1 h gradually decreased as the water content rises. The rate of desorption tended to decline and the desorption capacity tended to decrease as the water content kept increasing. When the moisture content is the same, the desorption amount increases with the increase of adsorption equilibrium pressure. The change of desorption amount with water content under different adsorption equilibrium pressure is basically the same.

3.2.2. Gas Desorption Index of Drilling Cuttings with Different Water Content Rates. The gas desorption index of drilling cuttings (K_1) and (Δh_2) are important indexes to make a prediction about the risk of coal seam outburst, which comprehensively shows the coal seam gas content and the gas desorption rate at the first stage of pressure relief.[17−19] K_1 represents the gas desorption quantity in the first minute, and Δh_2 reflects the pressure difference generated by gas desorption in the first 4 to 5 min.[37] The effect of diverse water contents on K_1 and Δh_2 can be obtained according to the desorption experimental data in Section 3.2.1, which is shown in Figure 6. As the water content is the same, K_1 and Δh_2 arise with the growth of the adsorption equilibrium pressure. As the adsorption equilibrium pressure is similar, K_1 and Δh_2 decrease with the rise of water, and the rate of decrease gradually falls with the rise of water content. From its trend, as the water goes over a certain number, K_1 and Δh_2 will not change significantly.

3.3. Coal and Gas Outburst Features with Diverse Water Content Rates. *3.3.1. Experimental Results of Coal and Gas Outburst.* The experimental results under various water contents and different gas pressures are classified into two kinds: outburst and nonoutburst. The results can be seen in Table 3, where the outburst strength related is the rate of outburst coal quantity to loaded coal quantity.

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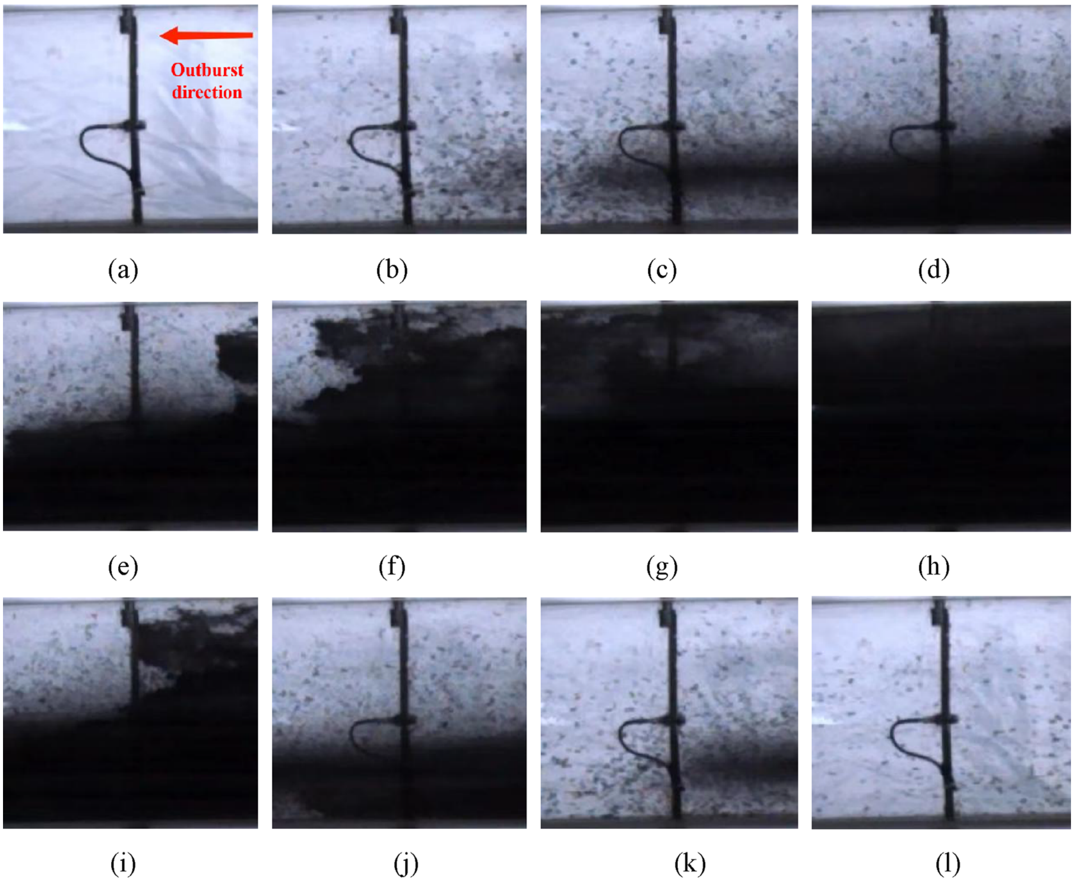

Figure 7. Course of coal and gas outburst in simulation tests. (a) Stage I: outburst preparation; (b–d) stage II: outburst initiation; (e–h) stage III: outburst development; (i–l) stage IV: outburst termination.

The experimental results suggest that the changes of gas pressure and water content have a great impact on the occurrence and intensity change of outburst. When the water content is the same, the outburst intensity rises with the growth of gas pressure. As the gas pressure is the same, the outburst intensity decreases with the growth of water content. Table 3 shows that there is a gas pressure threshold during outburst,[38] and the water content affects pressure threshold significantly. With the rise of water, the critical gas pressure rises, and the outburst strength declines. When the water content rate was 2.02%, outburst occurred at 0.4 and 0.5 MPa gas pressure, while at 5.14% water content, outburst occurred only at 0.5 MPa pressure. Outburst did not occur as the water content was 10.25% and gas pressure was 0.5 MPa.

3.3.2. Characteristics of Coal and Gas Outburst Process. The development course of the outburst is extremely short, and the state of the coal body changes continuously with the changes in space and time. The process can be classified into four phases: preparation, initiation, development, and termination.[38] The camera is placed at a distance of 1 m from the outburst mouth. Figure 7 shows four typical stages of the whole process. In the starting phase, the coal body is crushed and tossed out under gas pressure and ground stress, and the outburst cavity realizes rapid pressure relief. In the outburst development phase, the two-phase flow of gas-bearing pulverized coal fully develops in the tunnel space and the gas-bearing coal rapidly fills the roadway space and continues to proceed under the expansion effect of high-pressure gas. In the outburst termination phase, because of the continuous release of gas in the outburst cavity, the gas expansion impact will continuously decay, the outburst power will gradually disappear, the pulverized coal will no longer be thrown, and the pulverized coal will sink to the bottom of the roadway under the action of gravity.

3.3.3. Spatial Distribution of Outburst Pulverized Coal. *3.3.3.1. Distribution Features of Outburst Pulverized Coal.* Due to the continuous release of gas in the outburst cavity, the high-pressure gas expansion decreases, the pulverized coal-gas two-phase flow force gradually disappears, the coal powder is no longer thrown out, and the fine-grained coal dust finally settles slowly to the bottom of the roadway under the action of gravity. At this time, observe the distribution pattern of coal powder completely settled at the bottom of the roadway. Figure 8 shows the transverse and longitudinal spread of coal powder in the roadway. The transverse distribution of coal powder is characterized by a wavy pattern; the longitudinal distribution of coal powder is characterized by the fine particle size coal dust cover above and the coarse particle size coal powder below.[39] This is because the fine particle size coal powder has a lighter mass and is suspended and settled in the tunnel for a longer time.

The area of the experimental simulation roadway is divided, and the distance from the outburst mouth is divided into one area every 2 m and increased to the eighth area in turn. The coal powder after the outburst is weighed, and the mass proportion of the three groups of coal powder is shown in Figure 9.

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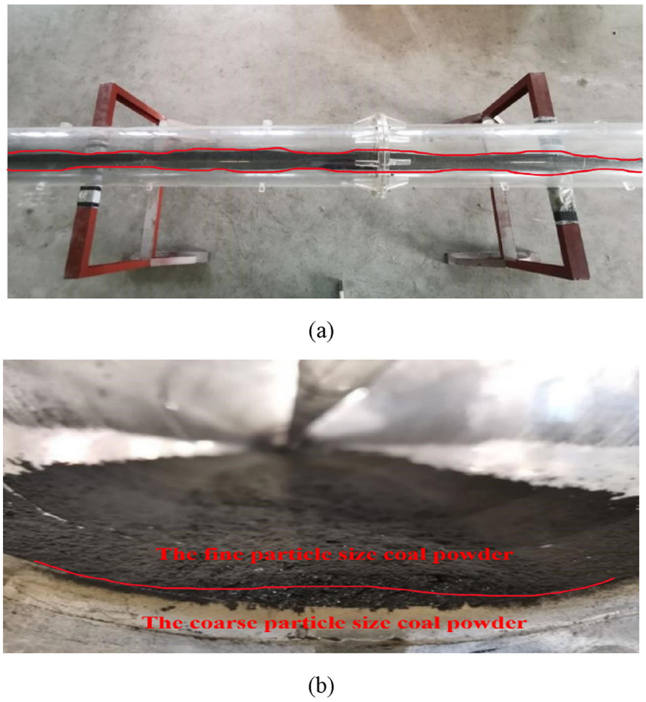

Figure 8. (a) Transverse distribution of coal powder. (b) Longitudinal distribution of coal powder.

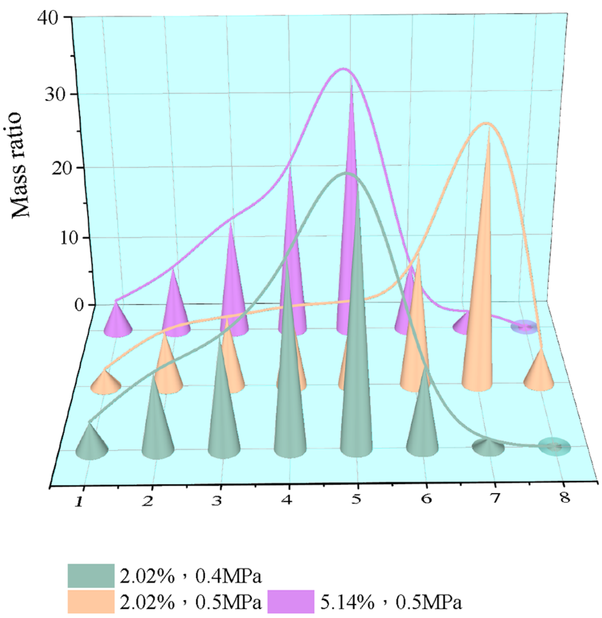

Figure 9. Proportion of outburst coal powder in each region.

Figure 9 shows that the spread of pulverized coal after the outburst presents a normal distribution. The pulverized coal after outburst is mainly distributed in zones 3, 4, and 5 and less in zones 1 and 2. This phenomenon indicates that in the preliminary and medial stages of the outburst, sufficient energy in the room to break through a great deal of coal and throw them out far can be seen. With the consistent advance of the outburst, energy consumption is significant, with only a small portion of coal being crushed and tossed out over a limited area. Lastly, the outbreak ended. Comparing tests 2 and 3, it was found that the pulverized coal migration distance rises from zone 7 to zone 8 when the gas pressure ratio increases from 0.4 to 0.5 MPa. Comparing tests 3 and 5, it was found that as the water content increased from 2.02 to 5.14%, the ratio of pulverized coal in the first five regions increased significantly, and the farthest outburst distance was shortened by 2.51 m. Therefore, the water hugely affects the spread of outburst pulverized coal and the farthest outburst distance. With the growth of water, the cohesion between coal particles rises, and the density of unit coal particles increases after the coal powder absorbs moisture,[40] so the coal powder thrown becomes more compact.

3.3.3.2. Particle Size Spread Features of Outburst Pulverized Coal. The particle size of coal powder was classified into three categories of fine, medium, and coarse according to 0−0.5, 0.5−1, and 1−3 mm, and the particle size of coal powder distributed in each roadway after protruding was sieved in turn to obtain the particle size spread in each area and plotted in Figure 10, among which (a), (b), and (c) represent tests 2, 3, and 5, respectively.

Figure 10 shows that the three groups of outburst simulation experiments under diverse conditions show a similar particle size spread of outburst pulverized coal in the roadway. As the distance from the outburst mouth increases, the mass ratio of fine particle size pulverized coal decreases continuously, the mass proportion of medium particle size pulverized coal rises first and then declines, and the mass proportion of coarse particle size pulverized coal increases continuously.

Compared with experiments 2 and 3, as the water content is the same, the farthest area of coal powder migration increases with the growth of the gas pressure. In comparison with experiments 3 and 5, when the gas pressure is the same and the water content increases from 2.02 to 5.14%, the farthest area for coarse coal particle migration decreases from zone 8 to zone 7, the farthest area for medium coal particle migration decreases from zone 7 to zone 6, and the farthest area for fine coal particle migration decreases from zone 6 to zone 5. It is obvious that the coarse particle size has the farthest migration distance among the three particle sizes, followed by the medium particle size coal particles, and the fine particle size coal particles are the closest. The more the water, the closer the coal powder migration is. This phenomenon is associated with the intensity of the coal body. The higher the water content, the higher the intensity, and the smaller the work done by the coal powder, the closer the coal powder migration distance will be.

4. DISCUSSION

4.1. Energy Conversion Study of Coal and Gas Outburst Process. The outburst process follows the energy conservation theorem,[41] that is, the flexible strain energy W_e, the gas expansion energy W_p and the inner energy ΔU of coal are transformed into the crushing work W_1, the tossing work W_2 and the gas flow field loss energy ΔE, as in eq 1:

$$W_e + W_p + \Delta U = W_1 + W_2 + \Delta E \quad (1)$$

In the course of energy release and dissipation of outburst, the energy consumed by friction heat and vibration generated by the outburst coal body hitting the roadway wall is relatively small. In order to facilitate the study, it can be ignored.[42] eq 1 can be rewritten as

$$W_e + W_p = W_1 + W_2 \quad (2)$$

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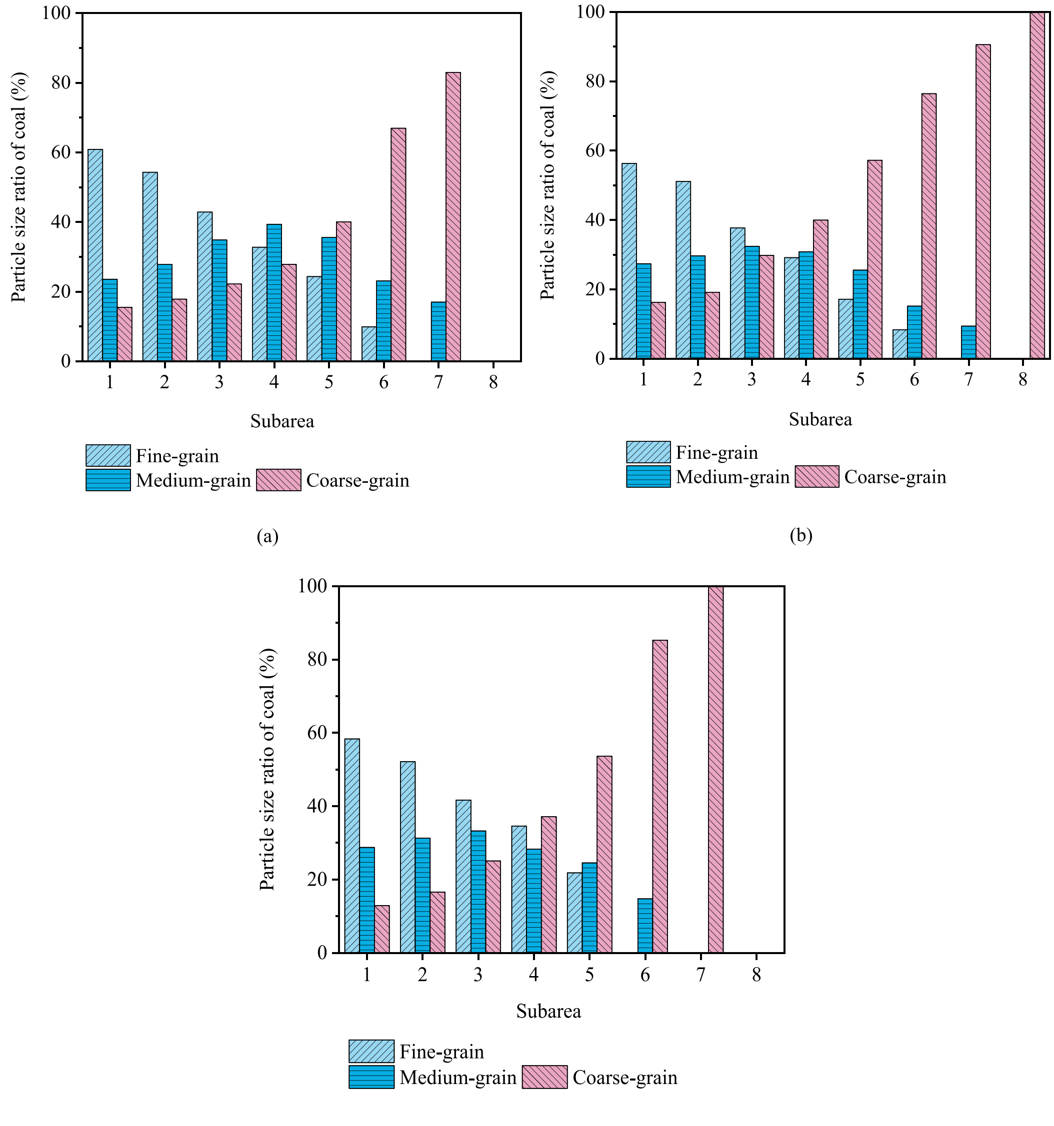

Figure 10. Distribution features of pulverized coal with diverse particle sizes (a) 2.02%, 2 MPa, (b) 2.02%, 0.5 MPa, and (c) 5.14%, 0.5 MPa.

The flexible energy per unit volume of coal rock mass in the three-dimensional stress state can be described by eq 3:

$$W_e = \frac{1}{2E}[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)] \quad (3)$$

where W_e is the flexible energy per unit volume of coal rock, MJ/m^3; σ_1, σ_2, andσ_3 are the primary stress in three directions, MPa; μ is Poisson's ratio of coal; and E is the modulus of elasticity of coal.

The gas expansion energy can be described by eq 4:

$$W_p = \frac{p_0 V_0}{\gamma - 1}\left[\left(\frac{p_{gas}}{p_0}\right)^{\gamma-1/\gamma} - 1\right] \quad (4)$$

where p_{gas} and p_0 are the experimental gas pressure and atmospheric pressure, atmospheric pressure is taken as 0.1 MPa; V_0 is the gas volume engaged in the outburst process; and γ is the multiparty index, taken as 1.13.

The crush of coal can be described by eq 5:

$$W_1 = \alpha\frac{6}{\rho}\left(\frac{1}{d} - \frac{1}{D}\right) \quad (5)$$

where α is the energy needed to generate a unit of newly added surface area, J/m^2; ρ is the obvious density of coal after crushing, kg/m^3; D is the even diameter of the coal before crushing, m; and d is the calculated diameter of the coal after crushing, m.

The throwing work of coal can be described by eq 6:

$$W_2 = \frac{1}{2}mv^2 \quad (6)$$

where m is the mass of the thrown coal, t; and v is the throwing speed of the crushed coal, m/s.

Based on the above calculation process, the energy changes in the outburst process were calculated, which can be seen in Table 4.

From Table 4, comparing tests 2 and 3, as the gas pressure rose from 0.4 to 0.5 MPa, the total energy of the outburst process increased from 1176.1 to 1897.1 J. Comparing tests 3 and 5, it is clear that the energy of the outburst process

Table 4. Energy Calculation Results of the Outburst Process

test number	We (J)	Wp (J)	W_1(J)	W_2 (J)	total energy(J)
2	397.2	783.4	602.5	573.6	1176.1
3	653.6	1243.5	1183.4	713.7	1897.1
5	354.9	678.1	679.4	353.6	1033.0

decreases by 864.1 J as the water content rises from 2.02 to 5.14%. This shows that enhancing the water content of the coal can decrease the energy of the outburst process. This is because when the coal sample is injected with moisture, the flexibility and intensity of the coal decrease, the plasticity rises, the energy needed for the outburst inoculation improves, and the energy converted to the outburst excitation decreases.

4.2. Impact of Different Water Content Rates on Coal and Gas Outburst. The test results of gas outburst parameters indicate that the gradual rise of the water content rate leads to the decline of initial velocity of gas diffusion (Δp), gas desorption index of drilling cuttings (K_1 or Δh_2) and cumulative gas desorption and the increase of consistent coefficient (f), all of which are exponentially related to the water content rate. The variation patterns of the parameters above suggest that the growth of coal moisture can lower the possibility of outburst accident. In light of the variation law of each parameter containing water, the rise of the f value of the coal will not be obvious as the water content rate goes beyond a certain value. At the same time, the adsorption constants a, Δp, K_1, and Δh_2 of coal do not change significantly.

The test outcome suggests that the occurrence and the intensity of outburst are directly related to water content of coal. The water content of the coal specimen will be higher; the critical gas pressure will be greater when there is an outburst; and the specimen will be less prone to burst out. The gas, which is adsorbed on the face of the coal body and inside the original pores, is reduced, leading to a reduction in the gas content of the coal body. On the basis of the ideal gas equation of state,[43] when the volume of adsorbed gas declines, it leads to growth in the key gas pressure as outburst occurs.[44] From the fierce adsorption theory, when the water of coal grows, more adsorbed gas desorbs into the free state, resulting in an outburst less likely to occur. Outburst may not occur as the water content rate reaches a critical value.

In the light of fracture mechanics, the minimum pressure values required for coal bodies with various water content rates to break are calculated, which can be seen in Figure 11. With the same water content, the minimum gas pressure required to damage the coal body rises with the growth of fracture toughness. With the same fracture toughness, when the water content is higher, the minimum gas pressure required for destruction to occur will be higher. When the fracture toughness changes in the range of 0.01−0.10 MPa·m$^{1/2}$, the minimum pressure value of 0.32−0.45 MPa is required for the destruction of coal with water content of 2.02%, and the minimum pressure value of 0.51−0.72 MPa is required for the destruction of coal with a water content rate of 5.14%, which is consistent with the outburst test results in Section 3.3.1. The destruction of coal with a water content rate greater than 5.14% requires a higher gas pressure value.

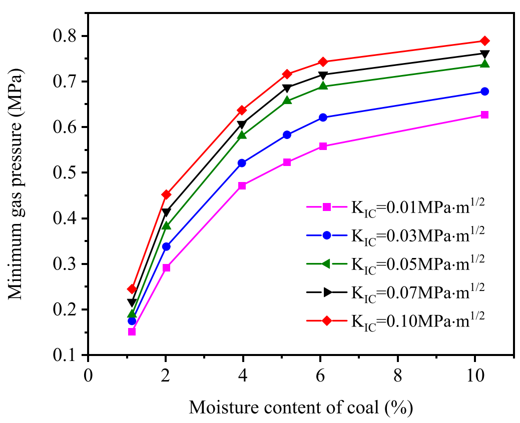

Figure 11. Minimum gas pressure value required for destruction of coal with diverse water content.

4.3. Key Indexes of Coal and Gas Outburst Prevention under Water Injection Measures. For outburst coal seams, water injection is a valid way to prevent outburst. However, the effect of antioutburst is not proportional to the amount of moisture injected;, excessive moisture will make it hard for gas to be desorbed and extracted, which does not help to prevent and control protrusion. However, too little moisture does not meet the standards required for outburst prevention. Table 5 is the key value of the outburst risk index in the "Rules to Prevent Coal and Gas Outburst". From the above experimental results, the change of water content in coal seam hugely affects the value of outburst prediction index. If the parameters can be controlled within the key value of outburst risk index before coal mining, the occurrence of outburst accidents will be effectively reduced.

Table 5. Key Value of Coal Seam Outburst Risk Index

decision index	original coal seam gas pressure P (MPa)	f	Δp (mmHg)	K_1 [mL · (g · min$^{0.5}$)$^{-1}$]	Δh_2 (Pa)
risk of outburst	≥0.74	≤0.5	≥10	≥0.4	≥160

Based on the results of the previous basic parameter experiments and desorption experiments, the gas outburst parameters of the no. 9 coal seam in the Qidong coal mine were obtained with different water content rates. Figure 4 shows that when the water content rate is more than 5.14%, the Δp value is less than 10 and the f value is greater than 0.5. Figure 6 shows that when the water content is more than 5.14%, the K_1 value is less than 0.4 and the Δh_2 value is less than 160. Figure 12 shows the fitting curve of the K_1 value and Δh_2 value with the change of equilibrium pressure under 5.14% water content. When the equilibrium pressure is 0.74, the K_1 value is 0.118, which is far less than the key value of 0.4 mL · (g · min$^{0.5}$)$^{-1}$, and the Δh_2 value is 87 Pa, far from the key value of 160 Pa. The test also indicates when the water content is more than 5.14%, the outburst is difficult to occur, and the risk of outburst will be obviously cut down. In summary, inference suggests that the water content rate of coal body should be more than 5.14% under the water injection antioutburst measures of no. 9 coal seam in the Qidong coal mine. Therefore, 5.14% coal water content can be employed as the key index of water injection antioutburst measures in no. 9 coal seam of the Qidong coal mine.

5. CONCLUSIONS

In conclusion, the characteristics of outburst parameters and the gas desorption law of the no. 9 coal seam in the Qidong coal mine with diverse water contents were studied, and the

https://doi.org/10.1021/acsomega.3c07896
ACS Omega 2024, 9, 1485−1496

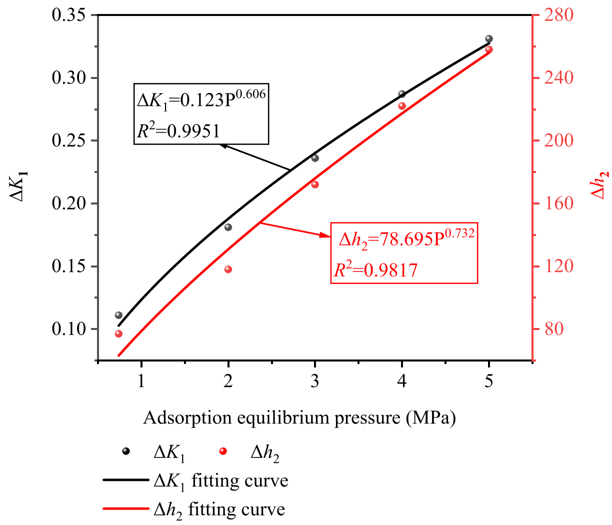

Figure 12. Fitting curve of adsorption equilibrium pressure effect on the K_1 and Δh_2 of coal with 5.19% water content.

relationship between water content and outburst parameters was gained. The effect of water content on outburst was studied by an outburst simulation test system, and the relation between water content and outburst intensity and key gas pressure was analyzed. The primary conclusions are below:

1. With the gradual growth of water content rate, the initial velocity of gas diffusion (Δp), the gas desorption index of drilling cuttings (K_1), and the adsorption constant a decline, while the hardness coefficient (f) increase. All of these indicators are exponentially related to water content. A conclusion can be made that enhancing the water content of coal is helpful to lower the possibility of outburst.
2. The appearance of outbursts and the magnitude of outburst intensity are directly related to the water content rate of the coal. With the growth of water content rate, the distance of outburst coal powder, the quantity of outburst coal, and the relative outburst intensity all show a declining trend. With the similar gas pressure (0.4 MPa), the outburst changed from occurrence to nonoccurrence as the water content rose from 2.02 to 5.14%. When the gas pressure threshold is added, the outburst strength and the amount of pulverized coal thrown declined, and the energy in the outburst process decreased by 864.1 J.
3. As the water content rate augments to a certain value, the outburst may not occur. As the water content is more than 5.14%: $f > 0.5$, $\Delta p<10$, $K_1<0.4$ mL · (g · min$^{0.5}$)$^{-1}$, $\Delta h_2<160$ Pa, the outburst risk is greatly reduced. In summary, 5.14% water content can be employed as a key indicator of water injection measures for preventing coal and gas outburst in no. 9 coal seam of the Qidong coal mine.

■ ASSOCIATED CONTENT

Data Availability Statement

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

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Funding

National Key Research and Development Program of China (No. 2018YFC0808101); National Natural Science Foundation of China (No. 51874008; No. 51474010; No. 51504009).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors are grateful for financial support from National Key Research and Development Program of China (no. 2018YFC0808101) and the support from the National Natural Science Foundation of China (no. 51874008; no. 51474010; no. 51504009). The authors also appreciate the editor and the anonymous reviewers for their careful reviews of this paper.

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