Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 1085296, 9 pages
https://doi.org/10.1155/2019/1085296

Research Article

Experimental Investigation on the Release Rule of the Gas Expansion Potential of Loaded Water-Filled Soft Coal

Hengjie Qin[1] **Jianping Wei**[2] **Donghao Li**[3] **and Sen Li**[1]

[1]*School of Architectural and Environmental Engineering, Zhengzhou University of Light Industry, Zhengzhou, Henan 450000, China*
[2]*School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*
[3]*School of Science, Henan University of Technology, Zhengzhou, Henan 450000, China*

Correspondence should be addressed to Jianping Wei; hpuwjp@163.com

Received 18 July 2019; Accepted 9 October 2019; Published 16 December 2019

Academic Editor: Fazal M. Mahomed

The aim of this study was to explore the evolution and release rule of internal energy storage in the process of coal and gas outburst and to further reveal the mechanism of coal and gas outburst from the perspective of energy. In this paper, the experiment of gas expansion energy release of coal samples under different adsorption pressures and with different moisture contents was carried out with the self-developed experimental device for release of gas-bearing coal expansion energy under load, and the energy of the whole outburst process was divided into three parts: the total expansion energy of gas, the energy consumed by destroying and throwing out coal body and the energy released inefficiently. On the basis of reasonable assumption, the energy evolution calculation model of each part was constructed with mathematical method. By analyzing the changes and distribution rules of three parts of energy under different experimental conditions, this paper explored the controlling effects of gas pressure, water content, and other variables on the energy evolution rules in the process of coal and gas outburst. Experimental and theoretical studies showed that in the gas-dominated coal and gas outburst process, the destruction of coal body was in the form of stratification; under each experimental condition, there existed a critical gas pressure value for the occurrence of coal and gas outburst, and there was a sudden change of energy evolution near this value; the existence of water made the critical pressure and the minimum energy consumption of coal and gas outburst increase obviously; under the experimental conditions, there was a linear relationship between the critical gas pressure and water content and a positive exponential relationship between the minimum energy consumption and water content.

1. Introduction

Coal and gas outburst is one of the frequent accidents in mine production. On one hand, it is difficult to control, with great harm, and in recent years, with the increase of mining depth, the outburst problem is more prominent; on the other hand, after more than 150 years of field practice and more than 50 years of laboratory simulation studies, there are still unresolved problems concerning the mechanism of coal and gas outburst to be solved [1, 2].

The mechanism of coal and gas outburst is complicated and there is no consensus conclusion, which is the root cause of frequent outburst accidents and difficulty to effectively control. Nonlinear release of energy storage in coal body is the most direct manifestation of coal and gas outburst [3–6]. Existing studies show that the elastic energy and gas expansion potential accumulated in gas-bearing coal bodies in the original state are the main energy sources for the occurrence of coal and gas outburst, however, coal and gas outburst generally occur in the coal seam with low strength and serious damage, so the gas expansion potential is much larger than the elastic energy of the coal body, and there is an order of magnitude difference between the two [7–9]. Airey [10] found through experiments that there was a peak energy in the early release of the gas expansion potential; that is, the initial gas expansion energy could play a very important role in the occurrence of coal and gas outburst. Barker-Read and Radchenko [11] found through experiments that the gas expansion potential was the main energy contributor to the gas outburst, but gas expansion potential of the slowly released gas could be released inefficiently and made no contribution to the occurrence of the outburst. It can be seen that the evolution and release law of gas expansion potential have a dominant control effect on the occurrence or not of outburst and the occurrence intensity of gas-containing coal after pressure relief. Based on this, regarding the quantitative description of gas expansion energy, Liu et al. [12, 13] conducted thermodynamic analysis on the process of coal and gas outburst and deduced the theoretical formula of gas expansion energy release. Li et al. [14] constructed a mathematical model of coal and gas outburst intensity based on certain assumptions. Wang et al. [15, 16] constructed a physical model of outburst in the process of mining from the perspective of energy and analyzed the role of gas content and other factors in outburst.

When coal and gas outburst is analyzed as a thermodynamic process, the temperature variation characteristic in the process is an inevitable problem. Some researchers [17–19] showed that the outburst process was short and the thermal conductivity of coal and gas was low, so the whole process could be regarded as an adiabatic process. However, other scholars [14, 20] believed that the gas in coal was evenly distributed and in full contact, and even if the outburst time was short, there was sufficient heat exchange between the two; therefore, the gas outburst process could be regarded as a variable process with almost constant temperature. The authors argued that if the coal rock mass and its internal gas were taken as a whole research system, considering the limited contact area between the whole system and the outside world and the extremely short time of outburst, the outburst could be considered as an adiabatic process, and the outburst energy mainly came from the deformation energy of coal and rock mass and the internal energy of the whole system; however, if only the internal gas in coal body was taken as the research object, because the mass of coal body in gas-containing coal body per unit volume was much larger than its internal gas mass, in the case of limited temperature drop [21], the release of gas internal energy cannot support the occurrence of coal and gas outburst, and the energy of coal and gas outburst mainly came from the matrix of coal skeleton, and gas was only the medium of its internal energy and external work. Therefore, taking gas as an independent object for thermodynamic analysis, coal and gas outburst can be considered as a constant temperature process.

Obviously, the study on the evolution and release of gas expansion energy of gas-containing coal after pressure relief is helpful to further reveal the internal mechanism of coal and gas outburst. Based on this, this paper conducted experiments on the release of gas expansion energy under different conditions, and divided the energy in the whole process of coal and gas outburst into three parts: the total gas expansion energy, the energy consumed by destroying and throwing out the coal body, and the energy released inefficiently. On the basis of reasonable assumption, the calculation model of each part of energy evolution was constructed with the mathematical method. By analyzing the change and distribution of three parts of energy under different experimental conditions, in this paper, the controlling effect of gas pressure, water content, and other variables on the energy evolution rule in the process of coal and gas outburst was explored.

2. Mathematical Derivation of Energy Calculation

2.1. Derivation of the Gas Expansion Potential. Based on the temperature measurement during the outburst experiment, the temperature change was not significant. Moreover, considering the complexity of the variable index in the varied process, within the scope of engineering practice, viewing the energy conversion of the gas outburst process as a constant temperature process not only facilitates calculation but also improves the standard of safety protection (the gas expansion potential that is calculated based on the constant temperature process is greater than the energy that is released during the actual evolution). The expansion potential of stored gas in coal is deducted based on the above analysis.

The amount of gas per unit of material varies from the pressure P_1 to P_2, and then, the work of expansion is as follows:

$$W_n = \frac{1}{n} P_1 V_1 \int_{V_1}^{V_2} \frac{1}{V} \mathrm{d}V = RT \ln\left(\frac{P_1}{P_2}\right), \quad (1)$$

where W_n is the expansion energy per mole of gas, V is the real-time volume, R is the thermodynamic constant, 8.314 J/mol^{-1}·K^{-1}; and T is the absolute temperature, K.

2.1.1. Calculation of the Expansion Work of Free Gas in the Unit Volume of Coal due to Pressure Relief. According to the ideal gas state equation,

$$n = \frac{P_1 \varphi}{RT_1}, \quad (2)$$

where φ is the coal porosity.

Substitute formula (2) in formula (1) and then in the unit volume of coal; the free gas varies from pressure P_1 to P_2, and the expansion work is as follows:

$$W_{yl} = P_1 \varphi \ln\left(\frac{P_1}{P_2}\right). \quad (3)$$

2.1.2. Calculation of the Work of Gas Expansion in Adsorbed Gas in the Unit Volume Coal. The desorbed gas converts from the adsorption state into a free state and participates in external expansion work, but desorbed gas under high pressure does more work than desorbed gas under low pressure, so the total amount of adsorbed gas cannot be used to calculate the work amount.

To facilitate the calculation, assume that the amount of gas adsorption (n) and pore pressure (P) have the following relationship:

$$n = \frac{abcPP_n}{(1 + bP)RT}, \tag{4}$$

where a and b are adsorption constants in the Langmuir model, in respective units of m^3/t and Pa^{-1}; c is the mass of combustibles per unit volume of coal, kg/m^3; and P_n is the standard atmospheric pressure, 0.1013 MPa.

In the gas desorption process, the gas pressure slightly drops dP, and then the molar amount of desorbed gas is calculated as follows:

$$\mathrm{d}n = \frac{abcP_n}{(bP + 1)^2 RT}\mathrm{d}P. \tag{5}$$

By combining formulas (5) and (1), we can determine that in the process of gas pressure reduction from P to P_2, the work amount of desorbed gas in the unit volume of coal under a slight drop of dP in the pore pressure is

$$W_{\mathrm{d}n} = \mathrm{d}nW_a = \frac{abcP_n}{(bP + 1)^2}\ln\left(\frac{P}{P_2}\right)\mathrm{d}P. \tag{6}$$

At this moment, the pore pressure per unit volume of coal is reduced from P_1 to P_2, and then the work amount of desorbed free gas is

$$\begin{aligned} W_{xf} &= abcP_n\int_{P_2}^{P_1}\frac{1}{(bP + 1)^2}\ln\left(\frac{P}{P_2}\right)\mathrm{d}P \\ &= acP_n\left(\frac{bP_1}{bP_1 + 1}\ln\left(\frac{P_1}{P_2}\right) + \ln\left(\frac{bP_2 + 1}{bP_1 + 1}\right)\right). \end{aligned} \tag{7}$$

Therefore, the volume of expansion energy during the process when gas in the unit volume of coal is reduced from the original gas pressure P_1 to P_2 is

$$\begin{aligned} W' = W_{yl} + W_{xf} &= acP_n\left(\frac{bP_1}{bP_1 + 1}\ln\left(\frac{P_1}{P_2}\right) + \ln\left(\frac{bP_2 + 1}{bP_1 + 1}\right)\right) \\ &+ P_1\varphi\ln\left(\frac{P_1}{P_2}\right). \end{aligned} \tag{8}$$

Under the experimental conditions, the gas expansion potential of stored coal is

$$\begin{aligned} W_p = V\cdot\Bigg[&acP_n\left(\frac{bP_1}{bP_1 + 1}\ln\left(\frac{P_1}{P_2}\right) + \ln\left(\frac{bP_2 + 1}{bP_1 + 1}\right)\right) \\ &+ P_1\varphi\ln\left(\frac{P_1}{P_2}\right)\Bigg], \end{aligned} \tag{9}$$

where V is the volume of the experimental coal sample, m^3.

2.2. Calculation of Expansion Energy Consumption

Energy consumption in piston propelling: when loaded gas-filled coal releases pressure in a direction, the internal high-pressure gas will flow under the action of the pressure gradient, then expand, do work, and release energy. To conduct experimental monitoring of the size of released energy, a piston device that is capable of moving back and forth was designed in the relief opening of the coal sampling mill. The release of the expansion potential will promote movement of the piston. By calculating the size of the energy consumption during the movement of piston, the work capacity of expansion can be measured. Piston energy consumption can be calculated by the following formula:

$$W_f = \int_0^x f(x)\mathrm{d}x, \tag{10}$$

where W_f is the piston energy consumption; x is the piston sliding displacement, m; and $f(x)$ is fitting function of dynamic friction resistance of piston versus different sliding displacement.

Energy consumption in coal destruction and ejection: a molded coal sample of pulverized coal was used in this experiment. Considering the mechanical property of molded coal, its extremely low elastic strength and poor reservoir capacity of elastic energy, in the experimental analysis, we can ignore the reservoir of elastic energy by regarding the energy consumed in the destruction-ejection of pulverized coal and the propelling of a piston comes from the gas expansion potential. Then, energy for destruction and the ejection of coal can be calculated by the difference between equations (9) and (10).

$$W_s = W_p - W_f. \tag{11}$$

3. Experiment on the Release of the Gas Expansion Potential

To study the energy release law of gas expansion potential under different conditions, the following experimental study was carried out in this paper.

3.1. Introduction to the Experimental Equipment. In this experiment, the experimental equipment that was self-developed by the research group for the simulation of loaded gas-filled coal outburst was used. The equipment is composed of five working systems, namely, the coal sample chamber (Φ100 mm × L200 mm), the axial stress loading system, the gas supply device, the outburst energy monitoring device, and the data acquisition system. Schematic diagram of the experimental device are shown in Figure 1,

The top of the cylindrical coal sample chamber (10) is provided with a hydraulic cylinder that is capable of providing a maximum axial pressure of 150 MPa. The coal sample chamber is opened in the horizontal direction and is connected by a flange to a cylindrical piston cylinder (20) and a horizontally movable piston rod (21). In the experimental process, the piston head contacted with coal and withstood the horizontal stress response of the coal sample

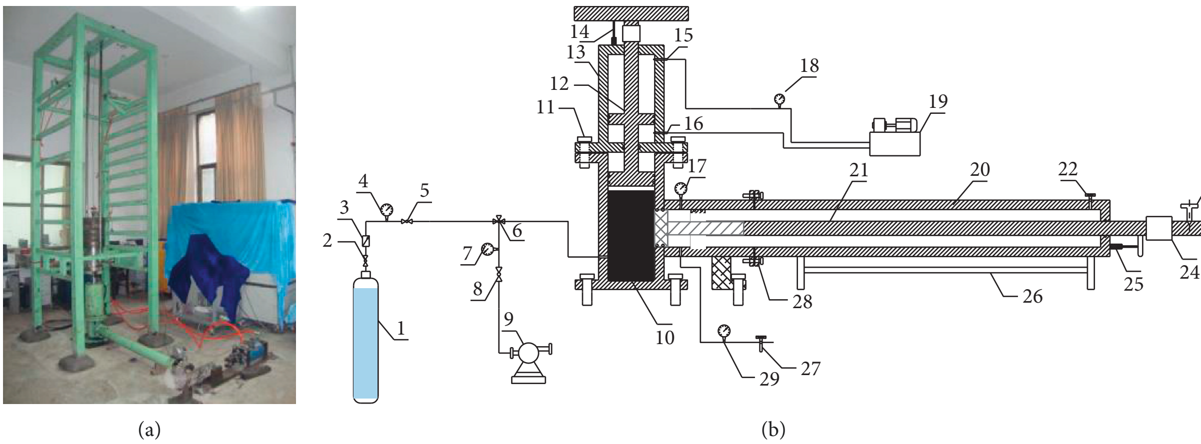

Figure 1: Gas expansion energy of gas containing the coal body release research device. (a) Physical map. (b) Schematic diagram.

in the compression molding. A high-precision stress sensor (24) is mounted on the right side of the piston rod to master the stress size of the coal body in the direction. Movement of the piston in the horizontal direction is controlled by the fixed pin (23), which is controlled by the scalable cylinder. After the coal sample is pressed and molded, a certain external load is given. The gas supply system (1) is used to supply gas to the coal sample. After the adsorption equilibrium, a fixed pin is operated so that coal body suddenly relieves in the horizontal cylinder direction and the internal gas potential is released, which promotes the movement of a piston rod (21) and overcomes friction work. The piston movement size and regularity are recorded by a guyed displacement sensor (25).

The experimental process is shown in Figure 2 below.

3.2. Preparation of Coal Samples and the Experimental Program. To study the effect of moisture and adsorption pressure on the release rule of the expansion potential more purposefully, the sieved pulverized coal was configured to the coal sample with different moisture contents. The molding pressure of molded coal was controlled at 50 MPa, followed by continuous loading of 30 min. The coal sample with different moisture contents was subjected to an expansion potential release experiment under pore pressure, in order to ensure the full absorption of CO_2 in the coal sample. Enable sufficient adsorption of over 12 hours, when readings of pressure gauges 4 and 17 are equal and remain stable for more than 1 hour; it is considered that adsorption equilibrium has been reached. The specific experimental program is shown in Table 1.

4. Experimental Results of the Release of the Gas Expansion Potential

4.1. Determination Result of the Energy Consumption of a Horizontal Piston. According to the experimental procedure, the static and dynamic friction force is measured when the horizontal piston moves to different positions. The values are shown in Table 2.

Through curve fitting of the dynamic friction data, the optimal fitting function $f(x)$ can be obtained, as shown in Figure 3.

Through data fitting, we can obtain

$$f(x) = 0.2331e^{1.2649x}. \tag{12}$$

Substitute $f(x)$ in formula (13); the friction work consumed during the piston movement to a location can be obtained and calculated:

$$W_f = 0.18465e^{1.2649x}. \tag{13}$$

In the formula, x is the piston displacement in meters and W_f is the piston friction energy consumption in kJ.

4.2. Experimental Results and Data of the Gas Expansion Energy. According to the experimental scheme, gas expansion energy release experiments were carried out in four moisture contents. Table 3 shows experimental data under different experimental conditions. “No” means No gas outburst, “Yes” means Gas outburst.

Limited by space, the coal sample with 4.5% moisture content was only provided here. With the increase in adsorption pressure, experimental coal samples experienced the following destruction process after pressure relief in a horizontal direction, as shown in Figure 4.

5. Analysis and Discussion of the Experimental Results

5.1. Analysis of the Law of Expansion Energy Release under Different Adsorption Pressures. As seen from Figure 4, for different adsorption pressures, loaded gas-filled coal is subjected to varying degrees of damage in the process of expansion energy release, and with the increase in adsorption pressure, the coal destruction scope increases. Under the experimental condition, when the adsorption pressure was less than 0.708 MPa (absolute pressure), coal suffered from local damage corresponding to the adsorption pressure in the vicinity of relief opening, which did not lead to overall instability or the outburst of coal. When the

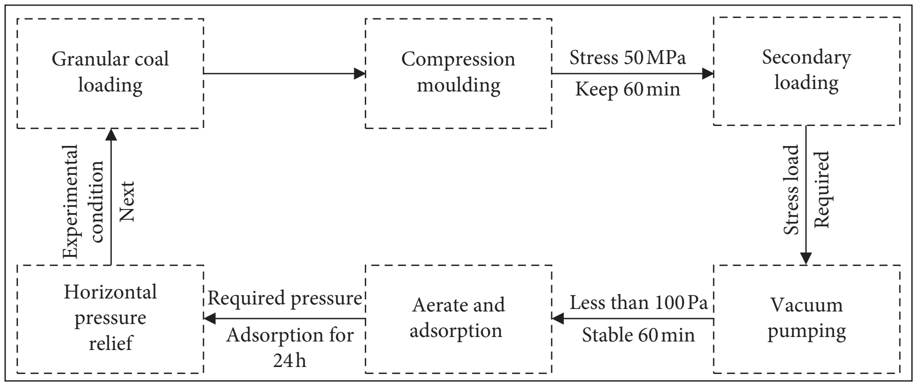

Figure 2: Experimental flowchart.

Table 1: Characteristics of coal sample and experimental scheme.

Characteristics of coal sample	Adsorption volume constant (m^3/kg)	Adsorption pressure constant (Pa^{-1})	Coal location	Coalification degree	Particle size/mesh	Quality of coal (g)
	0.036656	$1.12E-06$	9th Hemei (China)	Anthracite	40~80	1400
Experimental scheme	Forming pressure (MPa)	Repression time (min)	Moisture content (%)			
			4.5	4.8	5.4	5.4
	50	30	Different adsorption equilibrium pressure			

Table 2: Calculation of the friction resistance of the piston in different positions.

Position (m)	0.52	0.53	0.56	0.62	0.65	0.66	0.71	0.73	0.75	0.75	0.76
Air pressure (MPa)	0.11	0.12	0.11	0.13	0.14	0.13	0.14	0.14	0.14	0.15	0.16
Static friction (kN)	0.56	0.59	0.56	0.66	0.68	0.65	0.71	0.71	0.73	0.77	0.80
Dynamic friction (kN)	0.45	0.47	0.45	0.53	0.55	0.52	0.57	0.57	0.58	0.62	0.64

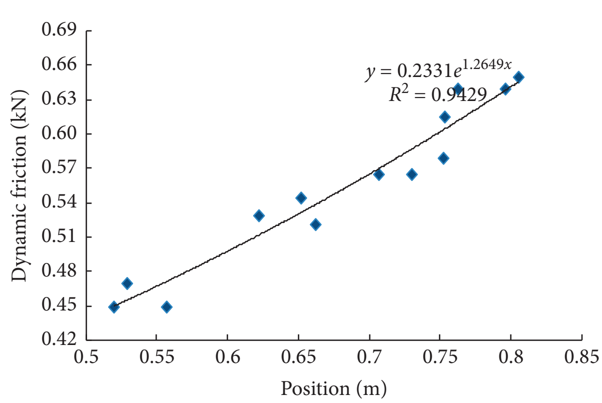

Figure 3: Data fitting of dynamic friction.

adsorption pressure reached 0.728 MPa, after sudden pressure relief, coal had outburst power. Furthermore, it can be seen from Figure 3 that the outburst begins from the spallation damage of coal in the outburst, with gas as the dominant inducement.

To investigate the release law of gas expansion potential under different adsorption pressure conditions, data under the condition of 4.5% moisture content were processed and analyzed. The storage expansion potential in the original state can be calculated by using formula (9), energy consumption of the horizontal cylinder piston can be calculated by formula (13), and the difference between the two can be considered as work in the coal destruction and ejection. Figures 5 and 6 are the piston energy consumption and destruction and the coal energy consumption data analysis diagram in the coal destruction-ejection under different pressure conditions, respectively.

As seen from the above data, when other experimental conditions remain unchanged, the gas adsorption pressure in coal gradually increased, there exists a sudden jump in the energy consumption of the piston movement and coal destruction. With gas as the working medium, the suddenly released energy further damages and throws coal and promotes the movement of the horizontal piston.

Figure 5 shows the energy consumption and energy dissipation ratio of the piston movement under different adsorption pressure conditions. Data show that

(1) Before the outburst, energy consumption in the displacement of the horizontal piston shows a good linear correlation with the adsorption pressure size

(2) When the adsorption pressure reaches a certain threshold (0.728 MPa), an outburst occurs after the pressure relief; energy consumption in the displacement of the horizontal piston does not increase with the increase in adsorption pressure, but suddenly drops at the outburst threshold

(3) After an outburst occurs, expansion energy release experiment continues under greater gas adsorption pressure, and then the piston movement shows a

Table 3: Experimental data of the expansion energy release experiment under the conditions of different water contents and adsorption pressures.

Moisture (%)											
4.50	Adsorption (MPa)	0.609	0.642	0.662	0.694	0.708	0.728	0.755	0.783	0.842	0.892
	Piston (m)	0.69	0.77	0.82	0.84	0.86	0.57	0.74	0.80	0.97	1.05
	Conclusion	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Coal output (kg)	—	—	—	—	—	0.35	0.46	0.467	0.474	0.481
4.80	Adsorption (MPa)	0.632	0.692	0.745	0.76	0.762	0.789	0.813	0.852	0.886	0.902
	Piston (m)	0.66	0.77	0.83	0.83	0.84	0.48	0.57	0.69	0.79	0.81
	Conclusion	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Coal output (kg)	—	—	—	—	—	0.26	0.35	0.38	0.421	0.452
5.10	Adsorption (MPa)	0.694	0.756	0.785	0.806	0.815	0.822	0.838	0.856	0.876	0.899
	Piston (m)	0.71	0.80	0.80	0.81	0.77	0.27	0.37	0.37	0.47	0.53
	Conclusion	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Coal output (kg)	—	—	—	—	—	0.28	0.32	0.35	0.39	0.385
5.40	Adsorption (MPa)	0.725	0.753	0.796	0.823	0.856	0.884	0.895	0.923	0.933	0.949
	Piston (m)	0.74	0.79	0.82	0.82	0.79	0.23	0.32	0.42	0.47	0.55
	Conclusion	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Coal output (kg)	—	—	—	—	—	0.22	0.28	0.36	0.38	0.39

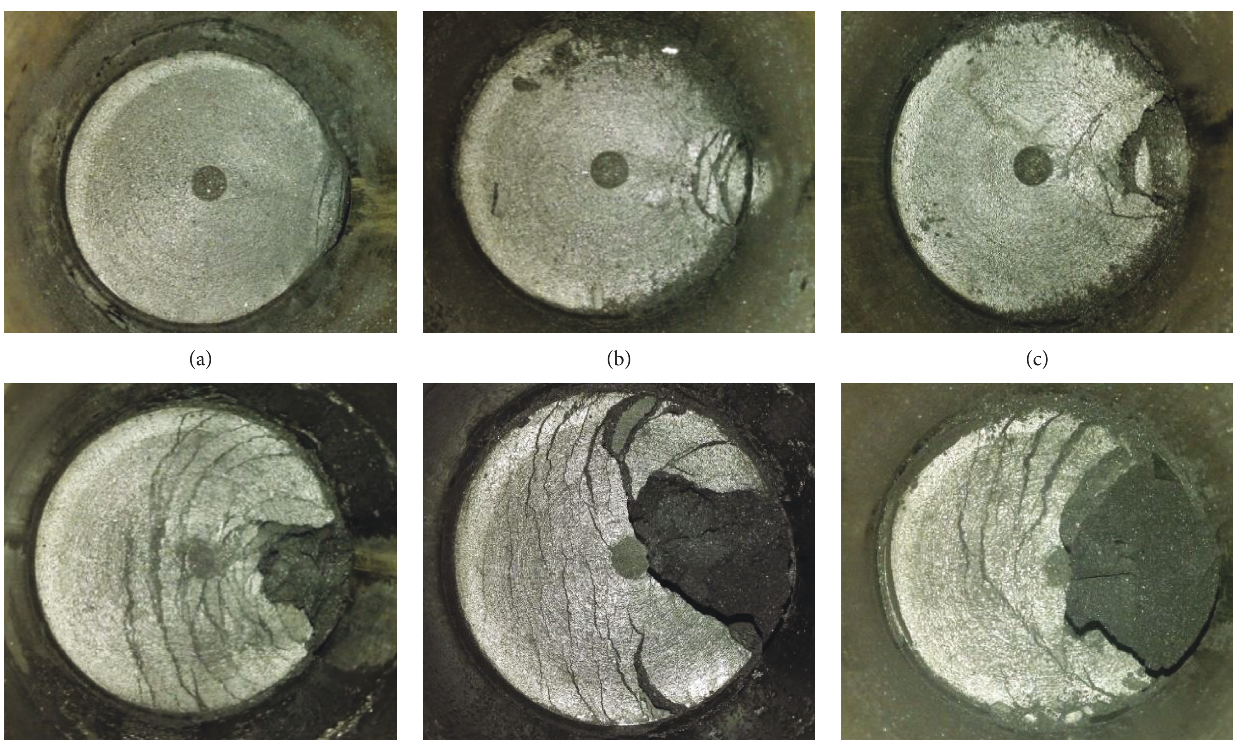

Figure 4: Coal sample failure process under different adsorption pressures after the test. (a) $p = 0.609$ MPa. (b) $p = 0.642$ MPa. (c) $p = 0.694$ MPa. (d) $p = 0.728$ MPa. (e) $p = 0.783$ MPa. (f) $p = 0.892$ MPa.

significant positive correlation with an increase in the adsorption pressure, and the increase rate of piston energy consumption is larger than that before the outburst.

(4) Before the outburst, the friction energy dissipation ratio slowly decreases with the increase in adsorption pressure, with the decrease rate gradually increasing. When the adsorption pressure reaches the outburst threshold, the outburst causes the piston energy dissipation ratio to drop sharply from 76.5% at 0.708 MPa to 50.05% at 0.728 MPa. Continue with the expansion energy release experiment under greater adsorption pressure, then piston friction energy dissipation rises slightly, but basically stabilizes at a level of approximately 65%.

Figure 6 shows energy consumption and the energy dissipation ratio of coal destruction and ejection under different pressure conditions. Data show that

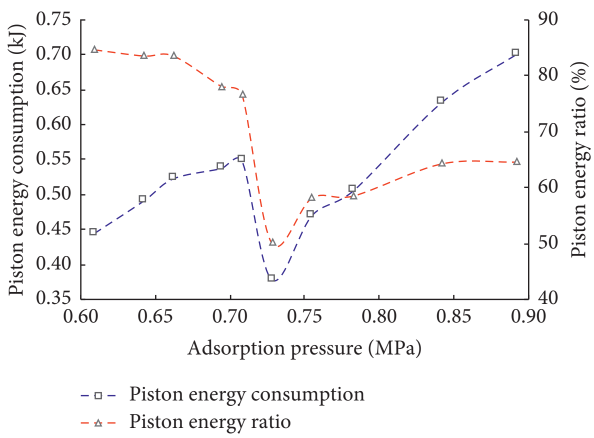

FIGURE 5: Energy dissipation analysis of the horizontal piston under different adsorption pressures after the test.

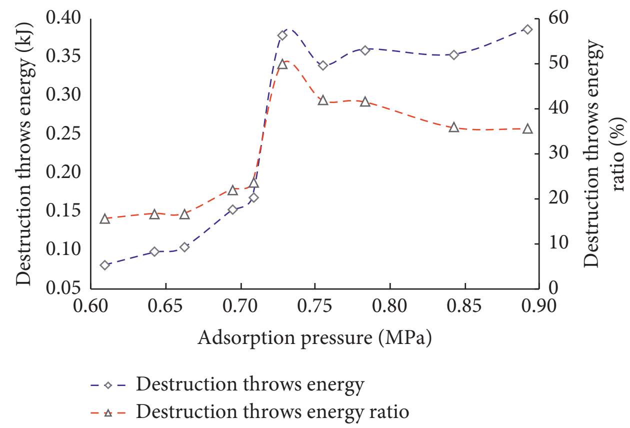

FIGURE 6: Energy dissipation analysis of failure and throwing the coal body under different adsorption pressures after the test.

(1) There was an obvious sudden jump in the energy consumed in coal destruction and ejection throughout the whole experiment.

(2) Before the outburst, energy consumption and the energy dissipation ratio of the part increased with the adsorption pressure increase, and the increase rate of the high-pressure stage was higher than that of the low-pressure stage, which indicated that before the outburst, the gas expansion potential release caused a certain degree of damage to coal, and consumed energy. Moreover, the bigger the adsorption energy is, the greater the damage there is to coal after sudden pressure relief, and the more energy consumption there is.

(3) After the outburst occurred, the energy dissipation ratio significantly decreased with the adsorption pressure increase because the increase is limited in the energy consumed in coal destruction and ejection after outburst, so that there is more released expansion potential to propel the piston movement.

5.2. Analysis of the Law in Effect of the Moisture Content on Expansion Energy Release. In the underground coal reservoir environment, water is one of the important components of coal. There has been extensive previous research on the water factor, and such research found that the existence of water greatly affects the adsorption [22–24] and seepage [25, 26] characteristics of coal. In this paper, an experimental study on gas expansion energy release under different moisture content conditions of coal samples was carried out. The following shows energy consumption in the destruction and ejection of four groups of coal samples with different moisture contents under different adsorption pressure conditions.

Figure 7 shows that existence of water causes an obvious increase in the critical pressure of coal outburst and the minimum energy consumption required for outburst. That is, under the same adsorption pressure condition, water hinders the outburst occurrence, which is coincident with the conclusions of previous studies [27, 28]. As seen in Figure 8, in data fitting, a good linear relationship is found between the critical pressure of outburst and the coal water

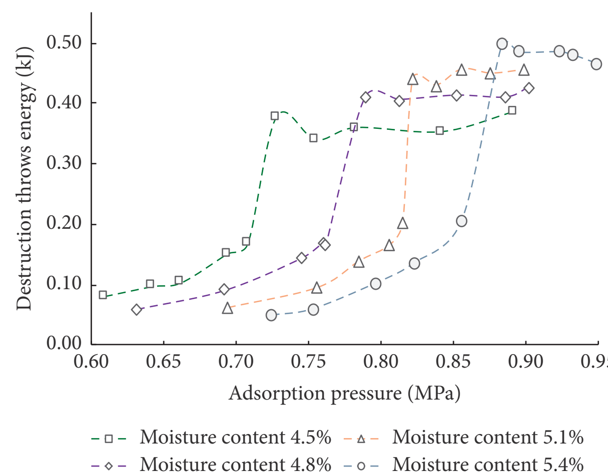

FIGURE 7: Energy dissipation analysis of the failure and throw of coal body under different adsorption pressures and water contents after testing.

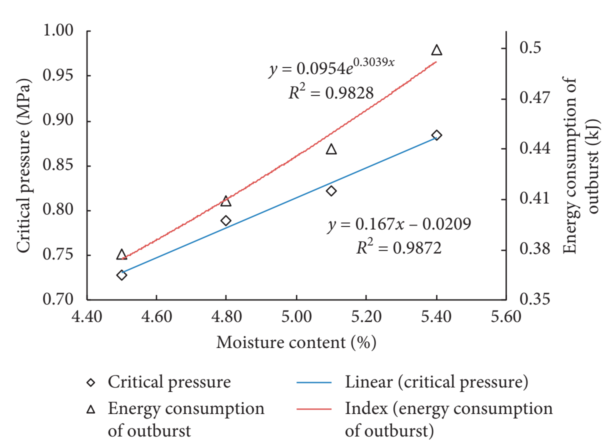

FIGURE 8: Outburst pressure and minimum outburst energy dissipation under different water contents after testing.

ratio, while the relationship between the minimum energy consumption (energy consumption in coal destruction and ejection) required for the outburst corresponding to the outburst critical point and the moisture content has a degree of fitting with an exponential function.

Almost all coal reservoirs contain water, and water in the coal is generally divided into free water, hygroscopic water, and bound water according to the existence state [29]. Under the experimental conditions, water hinders the outburst occurrence mainly by reducing the adsorption capacity of coal and changing the mechanical properties of coal.

(1) The presence of water mainly affects its adsorption of gas in the following ways, and literature 24 has made an in-depth study on this aspect, so it will not be repeated here.

(2) In addition, under experimental conditions, the presence of water makes the cementation force larger between the coal particles in the process of molded coal pressing, and the water content can reduce the coal accumulation of elastic energy and enhance its plastic deformation ability. Hence, in the process of expansion energy release, coal is subjected to more plastic deformation under the action of a gas pressure gradient, which reduces energy accumulation and delays the occurrence of overall coal instability.

Thus, through action from these two aspects, water hinders the outburst occurrence.

In terms of energy evolution, moisture reduces the coal adsorption of gas, thereby reducing the total expansion potential reservoir of the coal before the pressure relief. In the low adsorption pressure stage, the flow pressure gradient is unable to overcome the tensile strength of coal, the expansion potential releases slowly, and most of the released energy propels the piston movement. With the increase in adsorption pressure, coal after the pressure relief is subjected to tensile damage corresponding to the pressure under the action of a pressure gradient. The higher the moisture content is, the stronger the cementation of the molded coal sample is. Furthermore, the plastic deformation ability of the coal sample increased, resulting in the increased energy consumption required for the corresponding destruction of coal. Therefore, higher gas adsorption pressure is needed to achieve complete instability of coal and the destruction of outburst. As shown in Figure 8, the higher the moisture content of the coal sample is, the higher the critical pressure of the outburst and the minimal energy consumption is. When the gas adsorption pressure is greater than the critical pressure of the coal outburst, the energy consumption in coal destruction and ejection slightly increases with an increase in the adsorption pressure, but its energy dissipation ratio slightly lowers, and the same trend is observed between coal samples with different moisture contents.

6. Conclusions

(1) In the gas-dominated outburst, the outburst occurrence starts from the spallation damage of coal. In the process of gas flow, under action of the pressure gradient, coal is torn and damaged. When certain pressure conditions are met, spallation damage approaches the inner coal, causing overall instability of coal, quick desorption of absorbed gas, and the occurrence of outburst.

(2) Under different experimental conditions, there is a critical pressure value for the outburst, and there is a nonlinear mutation phenomenon near the value in the energy evolution. Before the critical pressure, energy consumption and the energy dissipation ratio of coal destruction increased with the increase in the adsorption pressure. When critical pressure was reached, an outburst occurred; energy consumption and the energy dissipation ratio of coal destruction and ejection suddenly increased, demonstrating obvious nonlinear characteristics. The experimental results after critical pressure of the outburst was reached showed that with the increase in adsorption pressure, the energy consumption in coal destruction and ejection tended to be stable after a slight increase, but the energy dissipation ratio had a decreasing trend.

(3) The existence of water causes the critical pressure of a coal outburst and the minimum energy consumption required to increase significantly. The critical pressure is linearly related to the moisture content under experimental conditions, and there is a positive exponential relationship between the minimum energy consumption of an outburst and the moisture content.

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 no conflicts of interest.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (51574112 and 51804278), Henan Science and Technology Research Project (192102310252), and "Innovation Team Development Plan" of the Ministry of Education of China (IRT_16R22) the State Key Laboratory Cultivation Base for Gas Geology and Gas Control (Henan Polytechnic University).

References

[1] V. Hudecek, "Analysis of safety precautions for coal and gas outburst-hazardous strata," *Journal of Mining Science*, vol. 44, no. 5, pp. 464–472, 2008.

[2] J. Sobczyk, "The influence of sorption processes on gas stresses leading to the coal and gas outburst in the laboratory conditions," *Fuel*, vol. 90, no. 3, pp. 1018–1023, 2011.

[3] J. Litwiniszyn, "A model for the initiation of coal-gas outbursts," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 22, no. 1, pp. 39–46, 1985.

[4] L. Paterson, "A model for outbursts in coal," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 23, no. 4, pp. 327–332, 1986.

[5] I. Gray, "The mechanism of and energy release associated with outbursts," in *Proceedings of the Occurrence, Prediction and Control of Outbursts in Coal Mines*, pp. 111–125, Australasian Institute of Mining and Metallurgy, Melbourne, Australia, 1980.

[6] Z. Zheng, "Analysis of mechanism of coal and gas outburst in order of magnitude and dimension," in *Collected Works of Zheng Zhemin*, Science Press, Beijing, China, 2004.

[7] S. Valliappan and Z. Wohua, "Role of gas energy during coal outbursts," *International Journal for Numerical Methods in Engineering*, vol. 44, no. 7, pp. 875–895, 2015.

[8] H. Qin, J. Wei, and S. Li, "Analysis of the coal seam spalling-failure mechanism based on the seepage instability theory," *PLoS One*, vol. 14, no. 7, Article ID e0219735, 2019.

[9] F. Du and K. Wang, "Unstable failure of gas-bearing coal-rock combination bodies: insights from physical experiments and numerical simulations," *Process Safety and Environmental Protection*, vol. 129, pp. 264–279, 2019.

[10] E. M. Airey, "Gas emission from broken coal. An experimental and theoretical investigation," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 5, no. 6, pp. 475–494, 1968.

[11] G. R. Barker-Read and S. A. Radchenko, "Gas emission from coal and associated strata: interpretation of quantity sorption-kinetic characteristics," *Mining Science and Technology*, vol. 8, no. 3, pp. 263–284, 1989.

[12] M. Liu and A. Yan, "Thermodynamic process analysis of coal and gas outburst," *Journal of Jiaozuo Institute of Technology (Natural Science Edition)*, vol. 20, no. 1, pp. 1–7, 2001.

[13] M. Liu, A. Yan, and W. Ding, "Study on thermodynamic process of coal and gas outburst," *Journal of China Coal Society*, vol. 28, no. 1, pp. 50–54, 2003.

[14] C. Li, B. Xie, and J. Cao, "The energy evaluation model of coal and gas outburst intensity," *Journal of China Coal Society*, vol. 37, no. 9, pp. 1547–1552, 2012.

[15] G. Wang, W. Cheng, and J. Xie, "Analysis of the gas content in the coal and gas outburst," *Journal of China Coal Society*, vol. 36, no. 3, pp. 429–434, 2011.

[16] G. Wang, M. Wu, and W. Cheng, "Analysis of energy conditions for coal and gas outburst and factors influencing outburst intensity," *Rock and Soil Mechanics*, vol. 36, no. 10, pp. 2974–2982, 2015.

[17] G. Wen, "Study on energy of coal and gas outburst," *Mining Safety & Environmental Protection*, vol. 30, no. 6, pp. 1–3, 2003.

[18] L. Zhu, "On the expansion energy of gas in coal seam," *Journal of Coal Mine Safety*, vol. 1, no. 2, pp. 48–51, 1985.

[19] B. Xie, *Experimental Research on Characteristics of Coal Impact Damage Dynamics and Magnetic Field*, China University of Mining and Technology, Beijing, China, 2013.

[20] G. Niu, A. Yan, and M. Liu, "Experimental study on temperature variation during coal and gas outburst," *Journal of Hunan University of Science and Technology (Natural Science Edition)*, vol. 23, no. 4, pp. 245–248, 2002.

[21] Y. Jiang, Q. Zheng, and H. Liu, "An analysis on the energy of coal and gas outburst process," *Journal of Chongqing University*, vol. 36, no. 7, pp. 98–101, 2013.

[22] G. Liu, Z. Zhang, and Z. Song, "Adsorption experiments on CH_4 under the conditions of high temperature and pressure and equilibrium water," *Journal of China Coal Society*, vol. 37, no. 5, pp. 794–797, 2012.

[23] Z. Liu, Z. Li, and Y. Yang, "Experimental study of water on sorption and radial gas seepage of coal," *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. 3, pp. 586–593, 2014.

[24] D. Zhao, Z. Feng, and Y. Zhao, "Effects of liquid water on coalbed methane adsorption characteristics based on the adsorption kinetic theory," *Journal of China Coal Society*, vol. 39, no. 3, pp. 518–523, 2014.

[25] J. Wei, L. Wei, and D. Wang, "Experimental study of moisture content influences on permeability of coal containing gas," *Journal of China Coal Society*, vol. 39, no. 1, pp. 97–103, 2014.

[26] J. Wei, H. Qin, and D. Wang, "Seepage characteristics of coal mass containing gas considering moisture effect in loading-unloading confining pressure test," *Journal of Mining and Safety Engineering*, vol. 31, no. 6, pp. 987–994, 2014.

[27] X. Jiang and J. Gao, "Acoustic emission characteristics of coal and gas outburst under different moisture contents," *Journal of China Coal Society*, vol. 40, no. 5, pp. 1047–1054, 2015.

[28] C. Jiang, G. Yin, and J. Xu, "The effect of original moisture content in coal beds on coal and gas outburst risk level," *Journal of Chongqing University (Natural Science Edition)*, vol. 37, no. 1, pp. 91–95, 2014.

[29] X. Li and B. Nie, "Study on adsorption characteristics of water," *Journal of Taiyuan University of Technology*, vol. 37, no. 4, pp. 417–419, 2006.