The research of coal seam gas pressure and initial gas emission characteristics of borehole

Jianhua Zeng | Shixiang Tian | Guiyi Wu | Yunjun Zuo
Shiqing Xu | Peng Pei | Chen Wang

INTRODUCTION

Coal and gas outburst is one of the main potential threats in underground coal mines, which affects the safety and productivity. For decades, a large quantities of experiments in laboratories and fields have been performed. Nevertheless, due to the complexity of outburst mechanisms, it is difficult to predict the outburst danger precisely. The commonly recognized factors such as gas pressure, in situ stress, coal physical properties, combined with coal energy, and geological variables have been thoroughly discussed. However, with increasing depth of mining, there is a higher outburst risk in coal seams. In deep mining, unmined coal tends to be soft with high gas contents. The coal structure is easier to be crushed and smashed under larger in situ stress compared to the shallow layers. Thus, it is of great urgency to effectively predict and prevent the coal and gas outbursts in the long run.

Coal and gas outburst is a kind of dynamic phenomenon and mainly driven by gas pressure. The coal seams are prone to be fractured, and outburst process will be largely...
accelerated with the presence of high gas pressure. By and large, the phenomenon of outbursts is the process of coal energy dissipation, which is accompanied by instantaneous ejection of pulverized coal and gas. Most of the outbursts accidents are associated with coal gas pressure, especially in China, combining with other parameters, it is predominated in outbursts identification, and with threshold of 0.74 MPa to indicate the outbursts prone of the coal seams. Nevertheless, consider the coal strength, some researchers proposed that thresholds in weak coal can be 0.3 MPa, and in hard coal, the accepted pressure is between 0.6 and 1 MPa. For coal seams with outbursts prone, there is a certain gas pressure threshold to provoke outbursts. It was observed that the intensity of gas outburst is positively correlated with gas pressure. Some researchers also found that the gas pressure may induce the outbursts through weakening the coal mechanical properties. In accordance with Klinkenberg effect, in gas-bearing coal seams, the coal permeability first decreases and then increases with the increasing gas pressure. Meanwhile, previous studies revealed that coal gas pressure is highly correlated to pore adsorption and desorption features, which can characterize the coal permeability simultaneously. Overall, to indicate coal and gas outburst, the key problem here is to accurately determine the value of gas pressure.

Coal gas pressure under natural condition is relatively difficult to determine at the heading face. Under the disturbance of mining, coal fractures propagated within the in situ stress concentrated zone. In those fractures and pores, gas desorbs fast and emits quickly into the environment, which further affects the measurement of gas pressure. While in unmined coal seams, gas pressure keeps in a primitive condition in relative terms, and the coal gas adsorption and desorption are under a dynamic equilibrium. In drilling process, with a rapid increase in stress and instantaneous change in gas pressure around the surface of borehole, the desorbed gas emits into borehole constantly. The gas emission will be varied in minutes with the decay of gas pressure in the coal seams. However, due to its short duration, this fact is usually neglected by researchers. The gas emission is not representative and uncorrelated with primitive gas pressure in short time later. Therefore, only the feature of initial gas emission can be an efficient indicator to characterize the primitive gas pressure in coal seams with the consideration of other parameters. Thus, there is a high necessity to further study the relationship between gas pressure and initial gas emission.

This paper aims at proving the feasibility to identify the outbursts danger through initial gas emission. The numerical and theoretical analysis preliminarily revealed the correlation between gas pressure and initial gas emission. Further, the laboratory experiment under determination of initial gas emission was also presented in this work. And the characters of initial gas emission were analyzed under different gas pressures.

2 | THEORETICAL AND NUMERICAL ANALYSIS

2.1 | Theoretical analysis of initial gas emission characteristics in the borehole

The initial gas emission characteristics of borehole is closely related to factors including radius of borehole, drilling depth, in situ stress, drilling time, coal physical properties, and gas pressure. Under the disturbance of drilling process, the path of gas seepage varied in different sites, which is shown in Figure 1.

The initial gas emission of borehole is divided into three parts through: experiments data comparison, gas diffusion, and seepage analysis.

1. During the drilling process, a fractured spherical surface is formed around the head of the drill, and the radius of spherical fractured zone is \( R_{p1} \). Meanwhile, affected by the drilling disturbance, the pressure in spherical fractured zone changing with a constant gas emits into the borehole. This part of gas flow is named as the spherical unstable flow.

2. In a cylindrical zone of \( R_{p2} \), the desorbed gas flows into the borehole through the fractures, which forms a radical unstable flow around the borehole.

3. The gas emits from coal particles is included in the volume of gas emission of the borehole. In a microscopic perspective, the gas emission from coal particles could be taken as unstable spherical flow in finite volume.

Assumed homogeneity of the coal seams in a finite distance, to simplify the process of gas flow in borehole, some assumption was made as follows:

1. The coal gas seepage process obeys the Darcy's law and law of conservation of mass.

2. Gas emission in fractures is taken as a low velocity laminar flow.

FIGURE 1 Gas emission path of borehole
3. The coal gas is taken as ideal gas, and the emission in coal seams is an isothermal process.

Thus, following the above-mentioned laws, gas seepage equations in radical, spherical, and coal particles can be deduced as follows.

The cylindrical unstable gas flow of borehole is shown in Equation 1.

\[
\frac{\partial P}{\partial t} = a_1 \left[ \frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} \right] \tag{1}
\]

The initial condition: \( t = 0, P = P_0 = p_0^2 \)

Boundary condition: \( r = R_1, P = P_1 = p_1^2, 0 < t < \infty \);
\( r \rightarrow \infty, P = P_0 = p_0^2, \frac{\partial P}{\partial r} = 0, 0 < t < \infty \).

Using Laplace transform, the equation 2 was obtained as follows:

\[
rT''(r,S) + T'(r,S) + \frac{S}{a_1} r \left[ T(r,S) - \frac{P_0}{s} \right] = 0 \tag{2}
\]

Substitute Equation 2 with initial condition and boundary condition, the Equation 3 can be deduced as follows. Normally, due to the complexity of Equation 3, the gas flow \( q \) needs to calculate aided with computer.

\[
\frac{P_0}{s} - T(r,S) = \frac{P_0 - P_1}{s} K_0 \left( \frac{S}{a_1} r \right) \tag{3}
\]

Treat the Equation 3 with dimensionless transform, quantity of gas emission was obtained.

\[
q = \frac{\lambda Y (p_0^2 - p_1^2)}{R_1} \tag{4}
\]

In Equation 4, where \( Y \) is the dimensionless number of gas emission in borehole.

The partial differential equation of spherical unstable flow is shown in Equation 5, and the radius of coal particles is the integral within \([0, R_1] \).

\[
\frac{\partial P}{\partial t} = a_1 \left[ \frac{\partial^2 P}{\partial r^2} + \frac{2}{r} \frac{\partial P}{\partial r} \right] \tag{5}
\]

Gas emission from head of the drill:
Initial condition: \( r = 0(t > 0), \frac{\partial P}{\partial r} = 0 \).

Boundary condition: \( r = R_1, P = P_1 = p_1^2, 0 < t < \infty \);
\( r \rightarrow \infty, p = P_0 = p_0^2, \frac{\partial p}{\partial r} = 0, 0 < t < \infty \).

Using Laplace transform, the Equation 6 was obtained as follows:

\[
rT(r,S) - \frac{rP_0}{s} = Ach \frac{S}{a_1} r + Bsh \frac{S}{a_1} r \tag{6}
\]

Substitute Equation 6 with initial condition and boundary condition, we can obtain:

\[
E_0 = \frac{p - P_1}{P_0 - P_1} = 1 - \frac{R_1}{r} \left[ \text{erf} \left( \frac{1 - \frac{L}{R_1}}{2\sqrt{F_0}} \right) - \text{erf} \left( \frac{1 + \frac{L}{R_1}}{2\sqrt{F_0}} \right) \right] \tag{7}
\]

According to Darcy’s law:

\[
q = -\frac{\lambda}{r} \frac{\partial P}{\partial r} \bigg|_{r=R_1} \tag{8}
\]

To obtain the equation between gas pressure gradient and quantity of gas emission, substitute Equations 7 the gas seepage equation can be deduced as Equation 9.

\[
q = \frac{(P_0 - P_1)}{R_1} \left[ \frac{r}{R_1} + \sqrt{\frac{\lambda a_1}{4\pi p_0^{1.5}} t} \right] \tag{9}
\]

Gas flow of coal particles:

Initial condition: \( r = 0(t > 0), \frac{\partial p}{\partial r} = 0 \)

Boundary condition: \( r = R_1(t > 0), P = P_1 = p_1^2 \);
\( r = 0(t > 0), \frac{\partial p}{\partial r} = 0 \).

Using Laplace transform, the Equation 10 was obtained as follows:

\[
rT(r,S) - \frac{rP_0}{s} = Ach \frac{S}{a_1} r + Bsh \frac{S}{a_1} r \tag{10}
\]

Substitute Equation 10 with initial condition and boundary condition, we can obtain:

\[
E_0 = \frac{p - P_1}{P_0 - P_1} = \frac{R_1}{r} \left[ \text{erf} \left( \frac{1 - \frac{L}{R_1}}{2\sqrt{F_0}} \right) - \text{erf} \left( \frac{1 + \frac{L}{R_1}}{2\sqrt{F_0}} \right) \right] \tag{11}
\]

In Equation 11, where \( F_0 = \frac{a_1 t}{R_1^2} \), and \( F_0 \) is the dimensionless number of time.
Because the gas seepage in homogeneity coal obeys the Darcy’s law, the gas emission of borehole wall can be expressed as:

\[ q = -\lambda \frac{\partial P}{\partial r} \bigg|_{r=R_1} \]  

(12)

Consequently, the gas emission in coal particle can be deduced as follows:

\[ q = \frac{\lambda}{2R_1 \sqrt{F_0}} \left( p_0^2 - p_1^2 \right) \exp \left( -F_0 + 1 \right) \]  

(13)

where \( P \) is gas pressure of coal, MPa; \( q \) is the gas emission per unit time; \( \lambda \) is the permeability coefficient of coal seam; \( t \) is time of desorption, seconds; \( a_1 \) is constant; \( R_1 \) is radius of borehole, m; \( p_0 \) is the initial gas pressure of coal seams, MPa; \( p_1 \) is gas pressure in borehole, MPa.

2.2 | Numerical simulation of initial gas emission from the borehole under different gas pressure

Numerical simulation is an efficient method to pre-validate the hypothesis before experiments. By analyzing the physical model of coal, the gas emission in coal seams can be idealized and the process of fractures development can be visualized. In this paper, the numerical simulation of COMSOL Multiphysics was used to analyze the initial gas emission in the borehole. An ideal physical coal model was built with 1.5 m in length, 2 m in height and width, and the diameter of borehole is 42 mm, which is shown in Figure 2. Meanwhile, the rest of the parameters were determined in laboratory condition using coal samples from Weishe coal mine and shown in Table 1.

Moreover, to imitate the similar stress condition, the left, right, and back sides were defined as normal displacement faces and the bottom face was fixed. According to the effective stress function, the in situ stress \( F \) from overlying strata was loaded on upper side and the front side was set as free. To simplify the simulation process, coal gas from infinite distance was neglected. In addition, the distance within 20 times of borehole radius was taken as effective area.

Coal gas pressure has narrow correlation with coal gas distribution and coal permeability. The gas pressure in simulation was chosen as a variable to figure out the effect of gas pressure in initial gas emission. The simulation was performed under the stress of 900 m depth of coal seam, and drill the 1 m length borehole in 180 seconds. Meanwhile, to eliminate the interference of moisture, the moisture content was set as 5.6%. With a gas pressure gradient of 0.5 MPa, the simulation gas pressure increased from 0.5 to 3 MPa. Ultimately, the curve of gas emission in 180 seconds under different gas pressure was obtained and shown in Figure 3.

As shown in Figure 3, under different gas pressure, the initial gas emission increased rapidly with the drilling process. In initial stage, the coal ahead of the drill was crushed and a distressed zone formed around the drill. With the increasing permeability of coal, the coal gas desorbed fast in distressed zone and emits into borehole quickly. Following the drilling process, there were more fractures developed. Subsequently, the instantaneous initial gas emission increased. Besides, the desorbed gas from coal particles contributed to the initial gas emission. However, from the perspective of the whole drilling process, the increasing rate of initial gas emission was in a declining tendency. Meanwhile, the coal gas out of the range of drilling disturbance will not emit into the fractures and borehole.

On analyzing the simulation result, it is found that there is an obvious positive correlation between gas emission and gas pressure. Especially when the gas pressure was 1.5 MPa, the gas emission increased following the drilling process and

Table 1: Physical parameters of coal samples

| Item              | Value       |
|-------------------|-------------|
| Kinetic viscosity | 1.85e-5 pa·s|
| Gas density       | 0.716 kg/m³|
| Porosity          | 9%          |
| Poisson ratio     | 0.45        |
| Elasticity modulus| 673 MPa     |
| Coal density      | 1350 kg/m³  |
| Internal friction angel | 22°       |
| Cohesion          | 0.137 MPa   |
| Temperature       | 303 K       |
| Compressibility   | 1.1         |
then reached a relative equilibrium. On comparing the gas emissions under different gas pressure, a more obvious increase in gas emission from 0.5 to 1 MPa and then from 2.5 to 3 MPa is found, which quietly fits with the feature of coal gas desorption according to the previous research.35-37

To directly clarify the correlation between initial gas emission and gas pressure, the initial gas emission volume of borehole in 180 seconds was obtained by integral algorithm, and the result is shown in Table 2.

Using the data of gas pressure and initial gas emission, the fitting line of gas pressure and volume of initial gas emission was obtained (Figure 4). The liner fitting line shows a higher correlation with relative coefficient $R^2 = 0.9925$. Moreover, the equation of the two factors was obtained as Equation

$Q = 74.658P + 50.883$

(14)

According to the results of fitting line and fitting equation, it is concluded that there is a clear liner correlation between gas pressure and volume of initial gas emission, which gives a certain guidance to the following experiments.

### EXPERIMENTAL PROCEDURE

To validate the simulation results, an experiment was performed under desorption and adsorption of CO$_2$ and N$_2$. The adsorption and desorption capacity of CO$_2$ and N$_2$ are similar to CH$_4$, and they are commonly used in lab experiments.21,37,38 In this experiment, CO$_2$ and N$_2$ were chosen to substitute CH$_4$, in which the accuracy and comparison

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**TABLE 2** Volume of gas emission under different gas pressure gradient

| Gas pressure/MPa | Volume of gas emission/L |
|------------------|--------------------------|
| 0.50             | 79.83                    |
| 1.00             | 128.86                   |
| 1.50             | 169.25                   |
| 2.00             | 204.99                   |
| 2.50             | 237.92                   |
| 3.00             | 268.64                   |

**FIGURE 3** Initial gas flow of borehole under different gas pressure

**FIGURE 4** Fitting curve of volume of gas emission and gas pressure under simulation

**FIGURE 5** The coal samples in experiment
between the determination results can be ensured. The detailed experiment procedure was described as follows.

The experiment coal specimens from Weishe coal mine were manufactured following the procedure of crush, water content control, sealed storage and briquette compaction (Figure 5). Through 12 hours vacuum extraction, the vacuum condition in coal chamber can be ensured, and the coal chamber is loaded with 100 kN axial stress. While pumping the CO₂ or N₂ into coal, the coal is sealed under 100 kN pressure and is kept pumped for about 48 hours to reach the adsorption and desorption equilibrium. Afterward, gas pressure and loading stress of coal chamber is checked in advance to continue the experiment.

The device sketch in Figure 6 is designed for the determination of initial gas emission. It consists of the simulated coal seams part and gas emission determination part. As shown in sketch, a casing is installed outside of drill stem, and during the drilling process, the coal particles will squeeze into the coal storage container and seal the backside of the pipe. Two types of gas flow sensors with one gas tube are installed in the middle part of pipe, and the gas flow through the tube can be detected by the sensors, which subsequently transfer the data to computer. Moreover, during the drilling process, only the gas flow in 1000 mm depth needs to be determined, and the drilling distance will be controlled by the displacement

FIGURE 6 Experiments device sketch and physical map (1—hydraulic press, 2—coal, 3—gas flow sensor, 4—casing tube, 5—coal storage can, 6—42 mm diameter drill, 7—electric motor, 8—displacement sensor, 9—gas cylinder, 10—PC)

FIGURE 7 Real-time gas emission under different gas pressures (CO₂)
sensor. Thus, the real-time initial gas emission data during the drilling process can be obtained.

# RESULTS AND DISCUSSION

1. The initial gas emission of borehole under CO₂ condition in the first 300 seconds was obtained by the small and large sensors and shown in Figure 7.

In four figures, the average gas emission was calculated and shown in red dashed line. It is obvious in figures that the gas emission during the whole drilling process fluctuated around the average line. However, in Figure D, while the coal sample was under 0.374 MPa CO₂ condition, the gas tube was found cracked with constant gas leaked. The leakage situation reflected by a significant decline in gas emission in the last 50 seconds which indicates the high sensitive of gas emission change in the borehole.

Following the drilling process, the initial gas emission increased by drilling depth and time. Meanwhile, the average gas emission increased followed the gradient of gas pressure. While the gas pressure was under 0.095, 0.192, 0.231, and 0.374 MPa, the corresponding average initial gas emission was 0.243, 0.346, 0.389, and 0.452 L/s. Thus, the initial gas emission of borehole and gas pressure indicated a positive correlation under CO₂ condition and it proved that the initial gas emission can be a potential method to characterize the pressure conditions of coal seams.

2. Besides the gas emission under CO₂ condition, the results of contrast experiments of initial gas emission under N₂ condition are shown in Figure 8.

Under desorption of N₂, the initial gas emitted from borehole increased, which follows the gradient of coal gas pressure as in CO₂ condition. Also, while the gas pressure of the coal chamber was under 0.412, 0.663, 0.675, and 0.918 MPa, the corresponding average initial gas emission was 0.123, 0.184, 0.194, and 0.311 L/s, which indicates the same positive correlation. In the perspective of obtained gas emission values in drilling process, the gas emission in initial stage changed greatly. Meanwhile, on analyzing the figures in detail, the value of abnormal instantaneous gas emission point in Figure D was over 1.5 L/s. The explanation for this phenomena is...
that the high-pressure desorbed gas released quickly under the initial disturbance of drilling, which quietly tallies the higher outburst risks in initial stage of coal uncovering than in other periods.

Following the drilling process, with less coal uncovered, the initial gas emission gradually went into a stable stage. Considering the gas emission under different gas pressures, the difference of gas pressure between Figure B and Figure C was only 0.012 MPa while the corresponding difference of initial gas emission was 0.01 L/s. The high sensitive of correlation validated the true connection of gas pressure and initial gas emission and proved the possibility to identify the outburst danger of coal through initial gas emission.

Integrate the instantaneous gas flow rate to obtain the volume of initial gas emission in the whole drilling process. The fitting curve of gas pressure and volume of initial gas emission is shown in Figure 9.

As shown in the Figure 9, there is a clear liner correlation between gas pressure and volume of initial gas emission for the same coal sample under the constant surrounding stress. The volume of initial gas emission increased with the gas pressure gradient. And the fitting line of CO₂ is above the N₂, which means the volume of initial gas emission is much larger than N₂ under the same gas pressure. The fitting results quite fit the coal desorption features of experimental reality. In CH₄ condition, the initial gas emission situation would be similar to CO₂ and N₂. Moreover, the fitting line would fall in between CO₂ and N₂ under reasonable inference.

Thus, while in coal seams, under the adsorption of coal gas (mostly CH₄), the volume of initial gas emission of borehole can be an effective indicator to identify the outburst danger of coal seams.

5 | CONCLUSION

In this paper, the law of adsorption and desorption of coal gas in the borehole has been investigated. The unstable gas flow in cylindrical, spherical, and coal particles of borehole was revealed through theoretical analysis. Using the ideal physical drilling model, it showed a preliminary correlation between coal seam gas pressure and initial gas emission.

By contrast adsorption and desorption experiments of CO₂ and N₂, the initial gas emission under different gas pressure gradient was obtained. It is concluded that there is a narrow positive correlation between gas pressure and volume of initial gas emission in the borehole. During the drilling process, the initial gas emission increased with gas pressure gradient, and due to the saturated adsorption capacity of coal, tendency of gas emission rate deduced. Furthermore, with the drilling depth of the borehole, the gas emission under CO₂ environment reached a relative desorption equilibrium while the gas emission decreased constantly under N₂ environment. And desorption of gas emission under CO₂ was higher than N₂, which quite fit the actual practice. Moreover, under a 0.012 MPa difference of gas pressure in N₂, the corresponding difference of gas emission was 0.01 L/s, which indicates the high sensitive correlation between gas pressure and initial gas emission. Thus, according to the features of CH₄, it is concluded that the situation would be same with CO₂ and N₂. Thus, it has been validated in this paper that initial gas emission could be an effective substitution method to identify the outburst danger in process of coal uncovering.

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ORCID

Jianhua Zeng https://orcid.org/0000-0001-9051-4475
Peng Pei https://orcid.org/0000-0002-9616-5066
Chen Wang https://orcid.org/0000-0001-9847-851X

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