

Application of Outburst Early Warning Technology based on Gas Emission Characteristics in Coal Mine

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Abstract

To address the existing limitations of current coal and gas outburst prediction techniques employed and to enhance the overall capacity for preventing and controlling gas-related disasters, a strategic approach leveraging the dynamic characteristics of gas gushing was adopted for early warning purposes. Utilizing these insights, we developed a robust early warning index system and a sophisticated early warning model, which were integrated to construct a tailored coal and gas outburst early warning system. This system was designed to capitalize on the unique dynamic gas gushing characteristics observed at Pingshu Mine, ensuring high relevance and effectiveness. Subsequently, the efficacy of this newly established early warning system was rigorously tested through field verification at two critical locations within Pingshu Mine: the 81111 end road and the 81111 return airway. The results of these tests were highly encouraging, demonstrating an impressive early warning accuracy rate of 80%. This outcome underscores the system's reliability and its positive impact on enhancing safety measures. The implemented system offers a suite of advanced functionalities, including real-time monitoring, online data analysis, intelligent early warning generation, and the prompt dissemination of alerts regarding potential coal and gas outburst disasters. These capabilities collectively represent a significant leap forward in mine outburst prevention technology, providing a substantial boost to safety standards and facilitating the safe and efficient operation of Pingshu Mine.

Keywords

Coal Mine; Coal and Gas Outburst; Gas Emission; Early Warning System.

1. Introduction

Shanxi Pingshu Mine, a subsidiary of Shanxi Yangmei Group Shouyang Coal Management Co., Ltd., stands as one of the key mines that have undergone renovation and expansion under the auspices of Yangmei Group. With an impressive actual annual output of 3.0 million tons (Mt/a), the mine faces significant challenges due to the identified risk of coal and gas outbursts in its No.81 and No.15 coal seams [1-3]. Specifically, the No.81 coal seam exhibits a maximum gas pressure of 1.15 MPa and a gas content of 13.78 m³/t, while the No.15 coal seam presents even higher risks with a gas pressure of 2.48 MPa and a gas content of 20.74 m³/t. During actual mining operations, the mine has encountered gas dynamic phenomena, including frequent occurrences of drilling blowholes and drill bit clamping during the drilling process, underscoring the pressing need to address gas-related hazards. These gas disasters pose a critical bottleneck, hindering the high-yield, efficient, and sustainable development of Pingshu Mine.

To mitigate the risks associated with coal and gas outbursts, Pingshu Mine has implemented regional and local "four-in-one" comprehensive outburst prevention measures, adhering to the guidelines stipulated in the Regulations on Prevention and Control of Coal and Gas Outbursts [4]. However, the current methodologies employed for regional prediction and measure effect evaluation, primarily relying on coal seam gas content measurements [5], as well as local prediction and measure result tests, which mainly utilize drilling cuttings gas desorption index K_1 and drilling cuttings volume methods, are inherently static and discontinuous. Theoretically, these approaches can be classified as sampling inspection methods, which are technologically flawed. Furthermore, these techniques are susceptible to various influencing factors, including changes in coal seam occurrence, drilling layout, sampling methods, human factors, and instrument precision, leading to the inevitable occurrence of false negatives (low indicator readings).

Moreover, with the continuous advancement and refinement of comprehensive mechanization in mine mining operations and the accelerated pace of mining front progression, the stress state of coal and rock formations ahead of the working face has become increasingly complex [6]. In the event of a coal and gas outburst disaster at a fully mechanized mining face, the consequences could be catastrophic and irreversible, further exacerbating the severity of such incidents. Therefore, it is imperative to research and apply a non-contact, continuous prediction method for outbursts. By establishing a network connection with the mine's gas monitoring system, this approach enables real-time collection and analysis of gas gushing data from underground working faces, facilitating automatic monitoring of all outburst-prone working faces across the entire mine. It conducts comprehensive outburst risk analysis, evaluation, and early warning, thereby realizing the automation of mine outburst early warning systems. This advancement holds tremendous significance for the localized prevention and control of coal and gas outbursts at Pingshu Mine, enhancing safety standards and promoting sustainable mining practices.

2. The Principle of Outstanding Early Warning Technology based on Gas Emission Characteristics

The characteristics of gas emission are governed by numerous influencing factors, including the gas content in coal, gas desorption characteristics of coal, coal permeability, mining technology, and mining techniques. However, not all factors affecting gas emission are outburst-influencing factors. Moreover, a single gas emission characteristic often conceals multiple outburst-influencing factors, which may counteract each other. The technical principle underlying the outburst early warning system based on gas emission characteristics lies in establishing characteristic indicators that reflect outburst-influencing factors by identifying the coupling relationship between the dynamic characteristics of gas emission and these factors (since changes in outburst-influencing factors such as gas content in coal, coal structure, and permeability can, to a certain extent, affect the dynamic variations in gas emission). The reason these indicators can serve as a continuous means of outburst prediction is primarily due to their continuity in both time and space [7-10].

Therefore, it can be inferred that underground gas monitoring data can relatively clearly reflect the outburst risk of coal ahead of the working face, as illustrated in Figure 1. By acquiring gas emission data through the mine safety monitoring system and conducting real-time analysis of the inherent characteristics in the time series of gas concentration, potential information related to coal and gas outbursts can be extracted, enabling the identification and early warning of outburst risks.

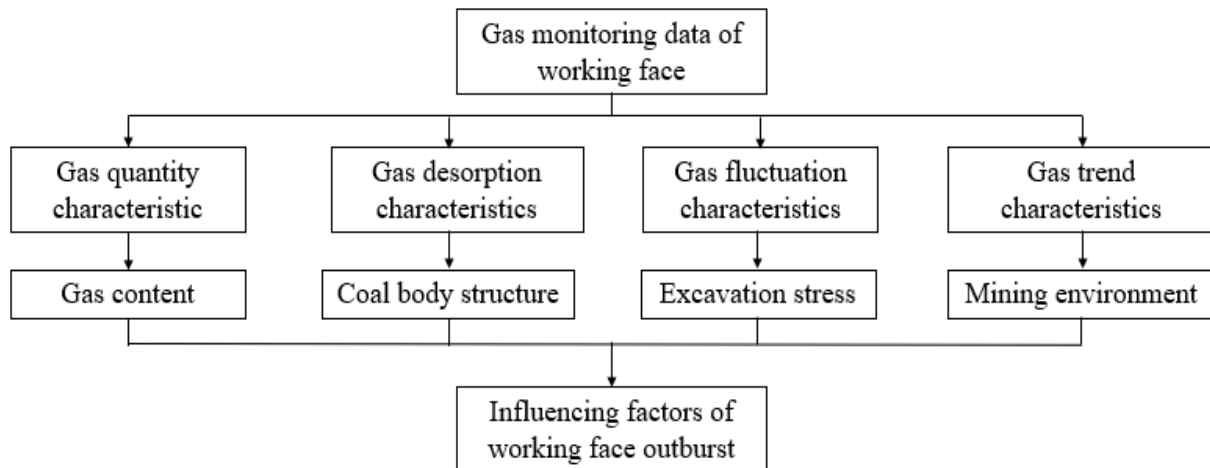


Figure 1. The relationship between gas gushing characteristics and outstanding hazards

3. Research on Outstanding Early Warning Indicators and their Critical Values based on Gas Emission Characteristics

Based on the relationship between gas emission characteristics and outburst hazards, from the perspective of spatiotemporal continuity, outburst early-warning systems based on gas emission are primarily classified into two types of indicators, which include:

(1) Regional Environmental Early-Warning Indicators

These indicators are used to predict and provide early warnings of outburst hazards in working faces across relatively large areas. Spatially, they generally offer advance warnings 5 to 10 meters ahead, and temporally, they typically provide 1 to 2 days' notice of potential outburst hazards. Their main purpose is to provide auxiliary technical references for the implementation of outburst prevention measures at mine working faces.

(2) Local Environmental Early-Warning Indicators

These indicators focus on predicting and providing early warnings of outburst hazards within smaller, localized areas of working faces. Spatially, they usually offer advance warnings 2 to 5 meters ahead, and temporally, they typically provide notice 1 to 3 work shifts in advance of potential outburst hazards. Their primary role is to offer auxiliary technical references for mining and excavation operations at mine working faces.

Meanwhile, the selection criteria for outburst prediction indicators in mines generally involve a comprehensive analysis of several indicators to assess their sensitivity and accuracy, including:

(1) Predicting outstanding risk

$$\eta_1 = \frac{n_1}{N} \tag{1}$$

Where η_1 is the predicted prominent risk rate, %; n_1 is the number of times the critical value is exceeded in the prediction, times; N is the total number of predictions.

(2) Prediction highlighting accuracy

$$\eta_2 = \frac{n_2}{n_1} \tag{2}$$

Where η_2 is the prediction accuracy rate of outburst, %; n_2 is the number of times that the critical value is exceeded in the prediction, times, including the total number of times of actual outbursts, the predicted holes with nozzle holes and other obvious outburst omens.

(3) Prediction of unremarkable risk rate

$$\eta_3 = \frac{n_3}{N} \tag{3}$$

Where η_3 is the predicted non-prominent risk rate, %; n_3 is the number of times the critical value is not exceeded in the prediction, times.

With the least number of predictions, capturing the most threats is the highest purpose of highlighting the selection of predictors. In the early warning system, the predicted outburst risk rate and the predicted non-prominent risk rate can actually reflect the overall outburst risk situation of the working face. Generally, the outburst prediction rate is less than 3%, which means that the regional outburst prevention effect is ideal, and the outburst prediction rate exceeds 3%. At 3% to 10%, local or regional outburst prevention measures need to be strengthened, and if it exceeds 10%, careful operation is required.

(4) Prediction is not outstanding accuracy

$$\eta_4 = \frac{n_4}{n_3} \tag{4}$$

Where η_4 is the accuracy rate of predicted non-prominence, %; n_4 is the number of times that the predicted non-prominence danger is really not prominent, times.

My country's existing conventional prediction indicators K_1 value, Δh_2 , q value and other outburst prediction accuracy are generally above 95%, and there will be some differences according to the sensitivity of different coal seams. The predicted outburst risk face rate η_1 represents the proportion of predicted outburst dangerous areas in the total predicted section. On the premise of ensuring the accuracy of the prediction, the smaller the η_1 , the better, that is, the smaller the range of outburst prevention measures that need to be taken. According to the production practice of mining outburst coal seams at home and abroad, the real outburst section accounts for about 5% to 10% of the outburst coal seam area, and considering the accuracy of outburst prediction, the value of η_1 should not be less than 10%, and the value of η_1 is too small. Prognostic indicators are not sensitive. The accuracy rate of predicting non-prominence should reach 100%. Considering the complexity of prominence, the current requirement is that $\eta_4 \geq 95\%$. Theoretically, the appropriate critical value can make $\eta_1, \eta_2, \eta_3, \eta_4$ all reach the optimal value range. Because, if the critical value is set low, η_1 and η_4 will increase, η_2 and η_3 will decrease, the accuracy of predicting outburst will increase, and the accuracy of predicting outburst will decrease. If the critical value is set high, η_1 and η_4 will decrease, and η_2 and η_3 will increase. As a result, although the engineering quantity of outburst prevention measures is reduced, it is not safe.

Table 1. Pingshu Mine early warning rules

Mine	Alert category	Normal	Threat	Danger
Pinshu Mine	Trend warning	A < 1.0	1.0 ≤ A < 1.2	A ≥ 1.2
	Status alert	B < 0.7	0.7 ≤ B < 1.0	B ≥ 1.0
A Normal	On the premise that the parameters are set correctly, there is no abnormality in the occurrence of gas and coal seams at 5~10m in front of the working face, and the expected content is about A*10m ³ /t			
A Threat	Under the premise that the parameters are set correctly, there are abnormal occurrences of 5~10m gas and coal seam in front of the working face, and the expected content is about A*10m ³ /t. It is recommended to take anti-outburst measures on the working face and discharge the gas in front of the working face.			
A Danger	On the premise that the parameters are set correctly, there are obvious abnormalities in the gas and coal seams in the 5~10m in front of the working face, and the expected content is about A*10m ³ /t. It is recommended to take anti-outburst measures at the working face and discharge the gas in front of the working face.			
B Normal	There is no abnormal change in coal structure, gas content and initial gas desorption velocity within the current 1~3m range of the working face			
B Threat	There are abnormal changes in coal structure, gas content, and initial gas desorption velocity within the current 1~3m range of the working face. It is recommended to check the coal structure, soft coal thickness or gas content of the working face on-site, find the source of the abnormality, and take targeted measures			
B Danger	There are significant abnormal changes in coal structure, gas content, and initial gas desorption velocity within the current 1~3m range of the working face. It is recommended to check the coal structure, soft coal thickness or gas content of the working face on-site, find the source of the abnormality, and take targeted measures			

Based on the outburst hazard characteristics of the coal seams in Pingshu Mine, targeted early-warning methods have been selected, focusing on two aspects: detecting local anomalies in gas occurrence and identifying changes in coal mass structure caused by variations in coal mass and geological structures. Consequently, a trend early-warning indicator A for gas quantity and a state early-warning indicator B representing coal mass structure have been established. The specific indicators and their critical values are detailed in Table 1.

4. System Construction and Its Application

4.1. Construction of Early Warning System for Coal and Gas Outburst

The Dynamic Analysis System for Mine Gas Emission (referred to as the "KJA System" for short) primarily obtains gas concentration data from the working face underground by installing gas sensors downhole or utilizing the existing comprehensive mine monitoring system. Subsequently, based on the tunnel parameters set in the control terminal, it automatically calculates the outburst risk indicators for the current working face according to the dynamic characteristics of gas emission. These indicators are then disseminated through the early-warning client, short message terminals, or web pages. To cut costs, the Pingshu Mine's KJA outburst early-warning system obtains gas concentration data from the existing monitoring system. The gas monitoring system in Pingshu Mine employs the KJ2000N system produced by the Safety Measurement Department of Beijing Changcheng Aeronautical Measurement and Control Technology Research Institute under AVIC. To avoid the need for secondary development of data interfaces, the data uploading tool that comes with the KJ2000N system is installed and used on the early-warning server, enabling it to generate real-time gas data files locally. Effective gas data is then extracted from the TXT files via the data transmission end of the KJA System and transferred into the KJA System database. The early-warning server collects the incoming real-time monitoring data at a frequency of $V_1 = 10\sim 60$ seconds per instance and stores it in its entirety. The system is capable of intelligently identifying monitoring data, automatically filtering out invalid downhole monitoring data, and then calculating early-warning indicators based on the mine working face parameters entered through the KJA administrator's control terminal. Early-warning information is subsequently disseminated through various terminals. The main operational, analytical, and setting functions of the KJA outburst early-warning system are all implemented on the KJA client.

4.2. Application Effects

According to incomplete statistics, since the Pingshu Mine's early-warning system was officially put into operation on June 29th, it has released 4,029 pieces of information (excluding statistics for working faces that had already been excavated before September), with a cumulative footage advancement of over 1,800 meters. Among these, 3,656 normal information alerts were issued, accounting for 90.74%. Alarms were triggered in 49 sections, with a total of 373 early warnings issued, including 216 threat warnings, representing 5.36% of the total warnings, and 157 danger warnings, accounting for 3.9%. The primary reason for the relatively high early-warning frequency is attributed to the elevated warning rates in the 81111 return airway and the 81111 tail entry, which reached 44%. Additionally, the K_1 -P coal sample tests conducted by the project team also demonstrated that gas extraction from the No. 81 coal seam is challenging, which, to a certain extent, underscores the severity of the outburst threat at this working face, as shown in Table 2.

The key to demonstrating the effectiveness of the KJA early-warning system lies in the accuracy rate of predicting outburst risks. To verify the early-warning performance of the system at Pingshu Mine, the mine organized a project team to conduct a comparative tracking analysis test from September 26th to November 2nd. The project team primarily adopted a verification

method involving on-site measurements and observations after early warnings were issued. Specifically, they compared the actual measured K_1 values, gas contents, and geological information at the working face with the early-warning results released by the system to validate its accuracy.

Table 2. Statistical overview of early warning information in Pingshu Mine

Number	Working face	Number of warnings	Warning section	Number of threats	Dangerous times
1	81111 Main lane coal head	357	12	57	101
2	81111 Sub-lane coal head	357	6	34	16
3	81106 Main lane coal head	357	5	17	16
4	81106 Sub-lane coal head	357	4	19	13
5	15205 Sub-lane coal head	357	5	13	2
6	15107 Sub-lane coal head	357	5	12	3
7	81109 Working face	102	3	16	1
8	15103 Working face	357	0	0	0
9	15107 Main lane coal head	357	2	8	0
10	15205 Main lane coal head	357	2	6	0
11	81104 Working face	357	0	0	0
12	W East belt lane coal head	357	5	34	5

This investigation mainly focused on the 81111 tail entry and the 81111 return airway. From September 26th to October 31st, the 81111 tail entry had a cumulative footage advancement of 106 meters, and the 81111 return airway also advanced 106 meters. A total of 34 early warnings were issued, occurring in 7 sections, with 3 sections in the 81111 tail entry triggering alarms and 4 sections in the 81111 return airway doing so.

(1) Analysis of Early-Warning Effectiveness in the 81111 Tail Entry

1) On October 10th, alarms were triggered during three shifts in the 81111 tail entry. On October 11th, the measured gas content was $10.77 \text{ m}^3/\text{t}$, and slight changes were observed in the coal seam at the working face. On October 12th, mining operations were halted to pre-drain gas from the working face.

2) Starting from October 20th, alarms were continuously triggered during 13 shifts in the 81111 tail entry. On October 20th, 21st, and 22nd, eight pressure relief holes were added and verified as qualified before production resumed. On October 23rd, the gas content was measured at $14.97 \text{ m}^3/\text{t}$, and the K_1 value reached 0.46, leading to the cessation of excavation. Eight pre-drainage holes were arranged. On October 26th, geophysical exploration and drilling revealed a normal fault 4 meters ahead.

3) Starting from October 29th, alarms were triggered during four shifts in the 81111 tail entry. On October 30th, a geological structure was identified ahead, but its nature remained undetermined before the data was collated.

(2) Analysis of Early-Warning Effectiveness in the 81111 Return Airway

1) Starting from October 6th, three alarms were triggered in the 81111 return airway. On October 6th, changes were observed in the coal seam, and a geological structure was

anticipated 7 meters ahead. In reality, a collapse column X55 was encountered. Fourteen pressure relief holes were added and verified as qualified before production resumed.

2) Starting from October 9th, two alarms were triggered in the 81111 return airway. On October 9th, changes were observed in the coal seam, and the collapse column X55 was exposed. Ten pressure relief holes were added and verified as qualified before production resumed.

3) Starting from October 23rd, three alarms were triggered in the 81111 return airway. On October 23rd, the K_1 value was 0.43, and the measured gas content was $10.59 \text{ m}^3/\text{t}$. Mining operations were halted to pre-drain gas, and production resumed after verification.

4) Starting from October 26th, six alarms were triggered in the 81111 return airway. On October 28th, the K_1 value was 0.43, and six additional pressure relief holes were constructed.

In summary, during the comparative verification process at Pingshu Mine, such situations occurred multiple times. From September 26th to November 2nd, there were 15 instances in total, of which 12 on-site re-inspections revealed partial abnormalities, while 3 were considered false alarms due to the absence of significant abnormalities. The early-warning accuracy rate reached 80%, indicating good early-warning performance.

5. Conclusion

(1) The KJA outburst early-warning indicators for Pingshu Mine have been determined, namely, trend early-warning indicator A representing gas volume and state early-warning indicator B representing coal body structure. The critical values are as follows: $A < 1.0$ indicates a normal condition, $1.0 \leq A < 1.2$ represents a threat, and $A \geq 1.2$ denotes a dangerous situation; $B < 0.7$ indicates a normal condition, $0.7 \leq B < 1.0$ represents a threat, and $B \geq 1.0$ denotes a dangerous situation.

(2) Based on the existing comprehensive gas disaster early-warning system platform of the Chongqing Coal Science Research Institute and taking into account the actual situation of Pingshu Mine, adaptive development has been carried out on the KJA outburst early-warning system, the KJA short message publishing platform, and the KJA outburst early-warning website. As a result, a coal and gas outburst early-warning system suitable for Pingshu Mine has been established.

(3) Through the verification of the early-warning effects in the 81111 tail entry and 81111 return airway of Pingshu Mine, the early-warning accuracy rate reached 80%, demonstrating good performance. The system has achieved functions such as real-time monitoring, online analysis, intelligent early warning, and timely dissemination of coal and gas outburst disasters. This has significantly enhanced the mine's outburst prevention technology level and promoted safe production in the mine.

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