Acoustic emission monitoring technology for coal and gas outburst

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Abstract
In recent years, with the increase in mining depth and strength, coal-rock gas dynamic disasters, such as coal and gas outburst, have shown an increasing trend. Acoustic emission (AE) technology has been viewed as a promising method that can effectively forecast coal and gas dynamic disasters. This paper first tests the AE characteristics of coal and rock samples during loading. Then, self-developed AE continuous monitoring and early warning equipment is used to monitor and predict the coal and gas outburst dynamic disasters on the working face. And it is found that the coal samples primarily show ductile failure, and the AE exhibits the evolutionary characteristics of “rise-peak-fall”. The rock samples primarily exhibit brittle failure, and the AE evolution mode is almost no falling stage. Coal and gas outbursts occur after the stress peak. Before coal and gas outbursts occur, there is a clear increasing trend in the AE ahead of the gas concentration variation. When the gas-bearing coal is damaged by the load, the coal body first breaks due to the stress, and the AE value increases. Then, due to the fracture of the coal body, the crack penetrates, gas rushes out, and the gas concentration increases. The research results can provide an advanced technical method for the monitoring and early warning of coal–rock gas dynamic disasters, and improve the prediction accuracy for dynamic disasters.

KEYWORDS
acoustic emission, coal and gas outburst, early warning, monitor

1 | INTRODUCTION

Coal and gas outburst and other gas-bearing coal-rock dynamic disasters have severely restricted the improvement of coal mine production and economic benefits, placing great psychological pressure on mine workers.1,2 As the mine enters deep horizontal mining, the coupling effects of gas, ground stress, and coal structure in the coal containing gas become increasingly complicated. Coal and gas dynamic disasters, such as coal and gas outbursts, show an increasing trend.3,4 Advanced technical means are used to obtain the precursor characteristics of coal and gas outbursts, to achieve effective monitoring and early warning of outburst disasters, which is the premise for coal and gas outburst prevention and control.

The current single static prediction methods use such indices as the borehole gas emission initial velocity q (critical value 5 L/min), cuttings amount S (critical value 6 kg/m), and drill cuttings gas desorption index Δh2 (critical value 200 Pa).5-7 These methods can only reflect the indicators and changes of a certain factor of coal–rock gas dynamic disaster,
and not realize dynamic continuous prediction and early warning. And from the analysis of the measured indicators recorded by the on-site personnel, there are few cases where the indicators exceed the critical value, but there will still be abnormal phenomena in the working surface, such as coal cannons, gas emission abnormalities, and gas overrun. The occurrence of coal–rock gas dynamic disasters has a preparation process from qualitative change to quantitative change, that is, the process from small fracture to failure of coal rock. The energy release during the process of strain energy release during deformation and failure of coal and rock is accompanied by changes in the gas emission of the coal body. AE is the release of energy from coal and rock mass in the wave form to be received by sensors. The AE continuous monitoring technology for coal–rock gas dynamic disasters is a non-contact geophysical prediction method, and is dynamic and continuous in time and space.\(^{8-11}\) Moreover, this method only requires a small amount of work, does not occupy special working time, does not affect production, and has the technical advantages which the traditional forecast technologies do not have. The AE continuous monitoring technology is an effective monitoring technology urgently needed for mine safety management.\(^{12-15}\)

A thorough and detailed research on AE-related indicators and their changing laws is an important direction for predicting and understanding coal–rock gas dynamic disasters. As early as the 1940s, the USA has predicted rock bursts with AE technology and monitoring systems.\(^{16}\) In the 1980s, the UK conducted an experiment on coal and gas outburst prediction at the Cynheire mine in South Wales coal fields using an AE prediction system.\(^{17}\) In recent years, Russian researchers found that the frequency of AE signals in coal and gas outburst zone is narrower than that of signals in noncoal and gas outburst risk zones, and the AE signals in coal and gas outburst zone mostly concentrate in the high-frequency range.\(^{18}\) Zhao et al.\(^{19}\) proposed that the total events, large events and energy parameters of AE can better reflect the characteristics of AE activities and that the increase in total events and the sharp increase in major events are signs of outburst. He et al.\(^{20}\) analyzed the coupling relationship between damage and AE of coal and rock mass and discussed the feasibility of using AE to evaluate the risk of rock burst. Jiang et al.\(^{21}\) studied the AE of the entire process of coal sample failure. By comparing and analyzing the characterization parameters of AE, it was found that the AE ringing event could be used as one of the important parameters for coal–rock dynamic disaster prediction.\(^{22-25}\) Wang et al.\(^{26-28}\) applied the AE and electromagnetic radiation (EMR) system to coal and gas outburst monitoring and early warning and achieved good early warning results, which significantly improved the accuracy of outstanding warnings. Through relevant research, it is found that the current research on the AE precursor characteristics of gas-bearing rock mass failure is primarily conducted under laboratory conditions. Due to the complexity and variability in field conditions, the narrow working face, and unfavorable conditions, such as high temperature and humidity, the requirements for the accuracy, sensitivity, and anti-interference ability of equipment are high. Therefore, using AE to monitor and provide early warning of coal and gas outbursts is not ideal, and successful cases are rare.\(^{29,30}\)

During the mining period of the F15-24080 working face in the Pingdingshan No. 10 Mine, although the conventional coal and rock dynamic disaster prediction methods were adopted to predict and inspect the outburst dangers of the working face,\(^{31,32}\) it was not possible to accurately and reliably predict the outburst dangers of the working face. Therefore, no effective outburst prevention measures were taken to prevent the occurrence of abnormal dynamic phenomena. Looking for a more effective method to achieve the noncontact, small-area regional, real-time continuous and accurate prediction of coal and rock dynamic disasters is an important premise for comprehensively grasping the outburst dangers in front of the mining face, and making reasonable and effective gas control measures. It is of great significance to realize high efficiency and safety production of mine.

Therefore, based on the research basis of the predecessors and the actual situation of the mine, this paper first studies the AE characteristics of coal and rock under load conditions in the laboratory, and then designs the installation method of AE sensors to avoid interference and acquire accurate AE signals in the failure process of the original coal and rock masses, and then on-site AE monitoring of the coal and gas outburst process is conducted along with in-depth analysis of the monitoring results. This paper is an important reference and has practical value for the effective on-site monitoring and early warning of coal and rock dynamic disasters via AE technology.

## 2 | ACOUSTIC EMISSION EVOLUTION CHARACTERISTICS OF THE COAL AND ROCK FAILURE PROCESS

### 2.1 | Experimental system

The loading equipment is a TAW2000 microcomputer control triaxial testing machine. The maximum axial pressure is 2000 kN. The equipment can be tested for single-axis and three-axis loading, as shown in Figure 1. The AE monitoring equipment adopts the YSFS (A) AE equipment developed by the China Coal Science and Technology Group Chongqing Research Institute Co., Ltd., as shown in Figure 2. The type of AE sensor is SR150N resonant sensor,
the frequency response range is from 22 to 220 KHz, the resonant frequency is 150 KHz, and the sensitivity peak value is >75 dB.

2.2 | Sample preparation

Experimental coal and rock samples were taken from the F15-24080 working face in the Pingdingshan No. 10 Mine. The rock samples are fine sandstone. According to the sample preparation standard of the International Society of Rock Mechanics, the coal and rock mass are processed into $\Phi$ 50 mm × 100 mm cylindrical samples along the vertical bedding direction, and the nonparallelism of the two ends of the sample is <0.05 mm. Smooth the surface of coal and rock samples, dry the samples at 105-110°C for 24 hours, and remove the samples with obvious cracks. A part of the coal samples are shown in Figure 3.

2.3 | Experimental program

AE monitoring uses two channels to collect data simultaneously, and the two AE sensors are symmetrically arranged on both central sides of the coal rock sample. The contact surface of the sensor and the sample is adhesively coupled with Vaseline and fixed with tape. The test piece loading test and the AE monitoring system are shown in Figure 4. The AE data sampling rate is set to 1 MHz, and the threshold value of AE signal acquisition is set to 50 dB.

The sample is loaded via uniaxial compression at a loading rate of 0.005 mm/min, and the axial loading is synchronized with the AE monitoring. At the end of the experiment, the loading and AE acquisition are stopped at the same time.

2.4 | Experimental results

A total of seven AE tests of uniaxial coal rock compression failure were performed for different coal and rock samples. Among the samples, there are four raw coal samples (Nos. 1, 2, 3, and 4) and three rock samples (Nos. 5, 6, and 7). The experimental results are shown in Figures 5 and 6, respectively. The failure shapes of the coal and rock samples are shown in Figures 7 and 8.
It is observed from Figures 7 and 8 that the coal and rock samples have different compositions and structures, and the evolution modes of AE are different. The failure modes of coal and rock can be divided into two categories: brittle failure and ductile failure. Coal samples tend to undergo ductile failure with little brittle failure characteristics; the rock sample primarily exhibits brittle failure, whereas rock sample 6 has ductile characteristics.

2.4.1 Acoustic emission evolution characteristics of ductile damaged coal

The coal samples have the characteristics of low mechanical strength, soft texture and crack development. It is a typical ductile coal. The coal sample 1 is taken as an example to analyze the AE evolution characteristics in its failure process. It is observed from Figure 5 that the postpeak stress-strain curve of the coal sample failure process is complete, and the areas before and after the stress peak are equivalent. The AE evolution characteristics of coal specimens from the beginning of compression to the failure process can be divided into the following four stages:

1. Compaction stage: AB section. At this stage, only a small amount of AE signals generate from the coal body loading to the gradual closure of the microcracks in the coal body. The AE signals are primarily accompanied by the energy release caused by the contact and friction of the crack surface during the prestorage closure process of the coal body.

2. Elastic deformation stage: BC section. At this stage, the coal body is in the elastic deformation stage as a whole, and the AE ringing counts gradually increase with the increase in stress. In essence, many microcracks in the coal body begin to gradually appear and nucleate, and the coal body exhibits uniform global damage.

3. Yield stage (crack instability expansion stage): CD section. The AE ringing counts increase sharply with the
increase in stress, and gradually reach a maximum near the stress peak. At this stage, the coal body fissure enters an unstable development stage, the internal fissures rapidly expand, merge, and develop toward the aggregation as a macroscopic crack, and the coal body begins to appear localized damage. The rapid increase in AE activity is the main precursor of the instability of the coal body.

4. Postpeak strain softening stage: DE section. The AE ringing counts gradually reduce. Although the AE suddenly increases at the point of a sudden stress drop of the coal body, the overall trend is gradually reduced with the failure process; at this stage, the coal body is in the stage of gradual failure after peak stress, macroscopic cracks appear on the surface of the coal body, and the crack gradually penetrates into the main fracture surface, resulting in the instability of the coal body.

2.4.2 | Acoustic emission evolution characteristics of brittle fractured rock

The AE activity of brittle fracture rock specimens from compression to failure can be divided into a compaction phase, elastic deformation phase and yield instability expansion phase. Unlike the ductile coal, the brittle rock sample is destroyed immediately after the sharp increase phase, and the AE softening decline phase is almost nonexistent (or shorter).

Therefore, the AE characteristic parameters will suddenly increase during the coal rock failure process, which is the precursor information before the coal rock body is destroyed. We can effectively extract these AE characteristic parameters to capture the abnormal information of coal seams or rock formations and effectively predict the occurrence of abnormal conditions in a mine.
3.1 | Mine overview

The Pingding No. 10 Mine is located in the eastern part of Pingdingshan, Henan Province, China and is approximately 6.0 km from the center of the city. The administrative region belongs to the Weidong District of Pingdingshan (Figure 9). The Pingding No. 10 Mine was placed into operation in February 1964, with a designed production capacity of 1.2 million tons/year. Since then, the mine has undergone two renovations and expansions, with a maximum output of 3.16...
million tons in 2006. The north-south trend of the minefield is approximately 6.0 km long, and the east-west trend is 2.0-4.7 km wide. The minefield geographical coordinates: the east longitude is 113°19′20″-113°23′18″, and the north latitude is 33°44′47″-33°48′45″. The mining depth is from 40 m to −800 m, and the area is 20.6158 km². The mine adopts district-extracted ventilation, multilevel vertical and inclined wells, and underground mining of the D, E, F, and G coal seams.

3.2 Work surface overview

The F15-24080 mining face of the Pingdingshan No. 10 Mine (Figure 10) is located in the third stage of the west wing of F4 mining area. The east is close to the F4 track downhill, the west reaches the 26 exploration line, the south is the F15−24060 goaf, and the north is not mined. The ground surface position of the mining face is a chemical plant, and the working surface is buried at a depth of 631-900 m. The F15 coal seam is mined. The F15 and F16 coal seams combine in the outer section and separate in the inner section. The coal thickness in the joint zone is generally approximately 3.5 m. The working face has an effective length of 1579 m, a slope width of 205.3-219.8 m with an average of 215 m, a cut length of 215.4 m, a coal thickness of 1.6-2.6 m that is generally 2.2 m, and a coal seam inclination of 10-37° with an average of 24°.

The direct top of F15 coal seam is sandstone mudstone with a thin-layered carbonaceous mudstone, with a thickness of 4.6-14 m. The upper roof of F15 coal seam is fine sandstone to medium-grained sandstone with a thickness of more than 18 m. The bottom of F15 coal seam is mudstone with a thickness of 0-7.5 m. The F16 coal seam is 1.2-1.6 m thick under the bottom of the F15 coal seam.

The F15 coal is a blocky hard coal and powdered soft coal. The consistent coefficient of coal in the working surface is 0.2-0.6, the type of coal destruction is II (Destroyed coal), III (Strong destroyed coal), and the gas emission initial velocity is 6.84-7.53 L/min. The coal seam in the middle section of the mining face is single, the original gas pressure of the F15 coal seam is 2.23 MPa, and the gas content is 12.37 m³/t. During the drilling of gas drainage boreholes in high pumping laneway and in the coal seam, and during the laneway construction, some abnormal phenomena occurred many times, such as gas ejection, drill clamping, and coal cannons.

3.3 Coal and gas outburst disasters overview

A total of 156 coal and gas outbursts have been recorded in the history of the Pingdingshan coal mine Group, with coal and gas extrusion accounting for 73%. The average outburst coal quantity was 117.2 t/time, the average gas emission amount was 8633.6 m³/time. F coal seams had the highest number of outbursts, and the outburst coal quantity and gas emission amount were the largest. A total of 121 outbursts occurred in the eastern part of the Pingdingshan coalfield, where the mines have an obvious regional and striped feature. The Pingding No. 10 Mine is a serious coal and gas outburst mine. This mine has the most absolute gas emission in Henan Province. The main mining coal seams of D, E, F, and G are all coal and gas outburst coal seams. The recorded coal and gas outburst were highlighted 50 times, accounting for 32.05% of the total. Most of the coal and gas outbursts occurred in the geological structure failure zone, faults and outburst strips, and the positions where coal and gas outburst occurred are mostly characterized by ground stress anomalies, coal seam deep buried depth, occurrence abnormality, thickening and softening, high gas pressure, and gas occurrence imbalance, and so on.

At present, the F and G coal seams are buried approximately 900 m deep. With the increasing depth of the mining, the ground stress is also increasing, and the dynamic phenomena being dominated by the ground stress are increasingly apparent. Coal and gas outbursts are dominated by ground stress when the depth is more than 750 m, and below 900 m, the coal and gas outburst is combined with rock burst. During the outer section excavation process of the F15-24080 machine laneway, coal and gas outburst occurred at 38 m before the 8010 position on 2006. 3. 10. The outburst coal quantity was 159 t, and the gas emission amount was 4878 m³. During the excavation of the F15-24080 machine laneway, there are some abnormal phenomena such as drillhole gas ejection, drill clamping, and coal guns in the range of 500-590 m, 750-810 m, 1100-1130 m, 1200-1255 m and 1295-1400 m. The cuttings amount S is 6 kg/m and exceeds the
critical value (4.8 kg/m, which is made by the Pingdingshan No. 10 Mine) during the 35 m position before the 8042 position. In addition, gas anomalies occurred in faults and the syncline structures in the 800 m and 1000 m position of the F15-24080 machine laneway, and the phenomena on drillhole gas ejection and drill clamping occurred many times during the drilling.

4 | ON-SITE AE MONITORING OF COAL AND GAS OUTBURSTS

4.1 | Acoustic emission monitoring point arrangement

First, install the AE machine, AE sensors, and signal transmission cable in the mine, then install the real-time processing software on the ground computer, and then debug them to establish the real-time monitoring and early warning network system for AE (Figure 11). Thereafter, the YSFS (A) AE monitoring system is used to continuously monitor the mining process of the F15-24080 working surface and analyze the precursor information of the dynamic phenomena or disasters. Therefore, the coal mine gas dynamic phenomena or disasters on the test working face can be comprehensively identified and provide an early warning.

The YSFS (A) Mine Dynamic Disaster AE Real-Time Monitoring System (Figure 12) primarily consists of a monitoring host, power supply, serialized AE sensors, dedicated signal shielding cable and real-time processing analysis software. The system can process the AE signal through real-time analysis and processing software and transmit to the ground host computer through the industrial looped network for disaster identification. The entire system forms a ground and underground interactive system. The channel parallel real-time monitoring network has the advantages of advanced, dynamic, real-time and continuous prediction, which can effectively overcome the shortcomings of traditional prediction methods, such as point prediction, large engineering quantity and many human factors.

4.2 | Acoustic emission sensor installation process

The installation effect of the AE sensor directly affects the ability to receive the AE signals and the noise blocking effect. Reasonable installation for the sensor must meet the following conditions:

1. The sensor must be well-coupled to the coal and rock mass or have a good signal transmission medium;
2. The sensor should be easy to install;
3. The sensor should have good dust and water resistance.

The China Coal Science and Technology Group Chongqing Research Institute Co., Ltd. found that the hole bottom installation method of the AE sensor has the advantages of a strong signal receiving capability and anti-interference ability, which can meet the application needs of actual monitoring. However, the bottom hole installation method adopts the cement grouting fixing method, which is easily affected by the characteristics of the slurry and the coal-rock body, and the coupling incomplete phenomenon may occur, which leads to partial loss of the effective signals and affects the reliability of the early warning. Therefore, considering the coupling effect of the sensor and the ease of installation, we have designed a fork-mounted fixed-mount AE sensor with claws, as shown in Figure 13.

The fork-mounted fixed installation method has such advantages as simple installation, high coupling, strong signal receiving capability, and anti-interference. The sensor is tightly coupled with the rock mass through the claws, and as the deformation of the borehole becomes increasingly coupled. Not only can it be ruled out that the sensor is not tightly coupled with the borehole wall due to the characteristics of the slurry with the increase in time, but also the cumbersome grouting, difficulty in judging whether
the grouting is in place and the solidification coupling effect can be avoided. The monitoring scheme adopts this type of installation method.

4.3 | Acoustic emission characteristics of coal and rock failure

4.3.1 | Accidents overview

1. On 2013.7.3, when the shearer of the F15-24080 mining face cut down to shelves 91-99, the gas overrun occurred. The maximum gas concentration of the cutting hole probe reached 3.34% and that of the upper corner probe reached 4.7%. The probe inside the return airway reached 1.36%, and the probe outside the return airway was 1.69%. After calculation, the amount of gas generated was 276 m³, the outburst coal quantity was 35.84 t, and the gas emission of per ton of coal was approximately 7.7 m³/t. After on-site investigation, the rib spalling of coal wall was clearly between 126 and 70 shelves, and there were many longitudinal cracks from top to bottom. The crack width was approximately 2-5 mm, and there were two small normal faults with a drop of 0.4-0.6 m near to the position of 80 shelves. Mirror joints with obvious tectonic stress appeared at the coal wall, the coal walls were moved outward by 200-500 mm between shelves 84-71, and the borehole of the coal wall is obviously dislocated at the depth of 200-500 mm. The fault and cracks in the coal body were touched by inserting a hand into the hole. In this region, the maximum gas concentration is 1.3%-1.5%,
and a slight bottom drum of 100-200 mm occurred in
an approximately 6-9 m length under the bottom of the
shelves 84.

2. At the zero class on 2013.7.19, when the shearer of the
mining face cut down to shelves 65-72, the gas overrun
occurred. The gas concentration of the cutting hole probe
reached 4.8%, the upper corner probe reached 1.05%, the
wind probe reached 0.7%, and the wind outside probe was
1.79%. After calculation, the gas volume of the cutting
hole reached 217 m$^3$. After on-site investigation
(Figure 15), no structure was found in the mining face.
The coal wall was clear, the coal body was hard, and no
structural coal was found. From shelves 73 to 132, the coal
wall had cracks and coal flakes. Among them, shelves
73-86 had obvious cracks. The cracks develop from the
upper part of the coal wall to the deep part of the coal
body. The crack width is 0.02-0.27 m, and the depth is ap-
proximately 0.5-1.1 m; shelves 76-84 formed the floor
heave, the scarp- through the conveyor rose, the bottom
drum volume was approximately 0.4-0.66 m; in shelves
94-132 rib spalling appeared, the height was 0.1-1.2 m,
and the depth was approximately 0.4-0.6 m; and the max-
imum sinking of the roof between shelves 75-78 was
0.37 cm; and the roof between shelves 69 and 70 were
staggered, and sank approximately 16 cm.

4.3.2 Conventional indicators and AE
characteristics of the disaster evolution process

The initial test site of the site is within the range of 360-430 m
from the initial cut of the working face, and the time is from
2013.6.6 to 2013.7.31. During this period, the effect of the out-
burst prevention measures on the working surface was tested for
19 cycles. There were no test exceeding standard phenomena
in the two test indices of the gas emission initial velocity q and
the cuttings amount S, as shown in Figure 16. However, dur-
ing the drilling construction and the working face mining, there
were still many abnormal phenomena such as gas ejection, coal
cannons, rib spalling, and gas emission abnormalities. This phe-
nomena showed that the q and S indices were not sensitive to
the F15-24080 working face and unable to effectively reflect the
abnormalities in the working face.

The AE and gas concentration characteristics before the
two disasters are analyzed as follows.

1. The law of AE and gas concentration change before
and after the “7.3” coal and gas outburst

Figures 17 and 18 show the evolution of AE and gas con-
centration before and after the “7.3” disaster.
The AE index fluctuated greatly before the disaster and
was significantly higher than the normal regional indicator
level. The maximum ringing count reached 494, accom-
panied by a substantial energy release. Moreover, with the
approach of the disaster, the AE ringing count and energy
were generally increasing, and decreased significantly when
the disaster occurred. The gas concentration changed sharply
when the disaster occurs, and showed the tendency of sudden
increase (from 0.6% to 4.6%), and then it fluctuated rapidly,
until one hour after the disaster occurred it returned to the
basic value.

It is observed that the change in the AE parameters pre-
cedes that of the gas concentration. Therefore, the sudden in-
crease in AE can be used as a precursor feature of coal and
gas outburst disasters.

2. The law of AE and gas concentration change before
and after the “7.19” coal and gas outburst
Figures 19 and 20 show the variation in the AE and gas concentration before and after the “7.19” gas accident.

As observed from Figures 19 and 20, the AE ringing count and energy fluctuated before the disaster, and were significantly higher than the index level of the normal area. The maximum ringing count reached 163, and the maximum energy reached $76 \times 10^3$ mv$^2$. And the AE ringing count and energy were significantly reduced before the disaster. The change rule of gas concentration is similar to that of “7.3”: when the accident occurs, it reaches the maximum and then fluctuates.

Attach the actual situation at the site: the maximum test q value was 1.70 L/min when zone verification was executed in the morning shift on 2013. 7. 17, and the maximum drill cuttings amount $S$ was 3.5 kg/m. There was no indication that the index exceeded the limit. The 4 mild coal cannons occurred during the outburst prevention measures hole drilling in the night shift on 2013. 7. 18. Before the disaster occurred, the gas concentration curve of the working face did not have obvious abnormal fluctuations, and the gas emission was relatively stable. At the location of the disaster, the elevation of the working face was $-530$ to $-540$ m, the buried depth was approximately 690 m, and the stress was greater.

Therefore, the AE index can well reflect the abnormal situation in the working surface ahead of time, the sensitivity is clearly better than the routine test index, and the precursor information of the disasters are captured in the real-time monitoring process. This method reflects and warns the abnormal situation that may occur on the working face, especially for the coal-rock gas dynamic disaster dominated by ground stress.

4.4 | Relationship between the AE parameters and the gas concentration in the coal and gas outburst process

Before the coal and rock mass is affected by the mining, the stress is in a stable state, and the stress and gas pressure are relatively large in deep mining. With the progress of the
mining activities, the original rock stress state subjected to the coal and rock mass is broken, the instability and failure of the coal rock mass occur, and the AE activity is gradually increased with the energy release. At this time, due to the presence of gas in coal and rock mass, although the coal rock body has a certain degree of damage, it still maintains integrity as a whole, and the crack channel is not penetrated. In addition, 80% of the gas is adsorbed in the coal, and it takes a certain time for the gas in the adsorbed state to resolve into the free state. Therefore, before the coal rock mass complete failure, the gas concentration changes little and is in the normal level. When the coal and rock mass outside the gas protective layer is completely unstable and destroyed, the AE parameters increase to the maximum value, and then begin to decrease until they reach the normal value.

The gas desorption requires a certain period of time. The coal and gas outburst process can be described that, the instability and failure of the coal body under stress occur first, and then the coal and gas expansion energy formed by gas desorption throws the coal out and causes the gas to release into the roadway instantly. Therefore, the gas concentration in the roadway will suddenly increase and then slowly decrease. Due to the persistence of gas emission, the gas concentration will fluctuate somewhat, but it is smaller as a whole. About one hour after the outburst, the gas concentration returns to the normal level. During the gas concentration sudden increase and decrease to the normal level, the AE parameters are relatively stable and in the normal level, which are mainly due to the smaller rupture of coal mass and the less release of vibration energy during this process.

According to the above analysis, the AE intensity and frequency begin to increase abnormally in 2-3 hours before the occurrence of the outburst disasters, and it is in a relatively stable state before the increase without large fluctuations. The AE peak intensity is 2-3 times of that in the stationary period. Before the outburst occurs, the AE intensity returns to a relatively stable value. This precursory information indicates that the AE monitoring can make a good early response to the occurrence of coal and rock dynamic disasters. When the AE intensity shows a similar trend, the safety inspection in front of the mining face should be strengthened, and the construction safety should be observed to prevent the occurrence of coal and gas outbursts.

5 | CONCLUSIONS

A self-developed AE system was used to analyze the precursor characteristics of AE in the process of coal and gas outbursts. The primary conclusions are as follows:

1. The coal sample in the mine primarily exhibits ductile failure and has brittle failure characteristics; the failure characteristics of the rock sample primarily show brittle failure. The AE parameters of the coal sample increase sharply with stress, and the AE parameters reach a maximum near the stress peak. After the stress peak, the coal sample damage showed progressive failure. The AE of the coal body suddenly increased, there were multiple stress drops after the peak stress, and the corresponding AE value suddenly increased. The AE evolution characteristics of brittle fractured rock samples are similar to those of coal samples, but there is almost no softening and falling section.

2. The AE characteristics of the evolution process of coal and gas outburst were tested. It was found that the AE had a significant upward trend before the accident, and it preceded the gas concentration variation. In other words, the AE can provide advanced warning for coal-rock gas dynamic disasters.

3. During the evolution process of coal and gas outburst, due to the large stress, the crack propagation of the coal rock body occurs first such that the AE gradually increases. Gas desorbed after the crack in the coal cap covering the gas is penetrated. Due to the rapid release of gas expansion energy, the gas concentration increases, but the coal body ruptures less frequently, and the AE remains at a relatively stable low value. Coal and gas outbursts occur after the stress peak.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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