ISSN: 2688-8645

Coal and Gas Outburst Early Warning Technology: Research Status, Key Bottlenecks and Development Trends

Wenjie Liu [1, 2]

[1] State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400039, China

[2] CCTEG Chongqing Research Institute, Chongqing 400039, China

Abstract

Coal and gas outburst is one of the most destructive dynamic disasters in coal mining, posing a severe threat to coal mine safety production and miners' lives. This paper systematically summarizes the research status of coal and gas outburst early warning technologies. Firstly, it elaborates on the mechanism of outbursts and the theoretical basis for early warning; then, it focuses on analyzing early warning methods based on the fusion of multi-source information such as gas emission dynamics, acoustic emission/microseism, electromagnetic radiation, and geophysical methods, and comments on their principles, applications, advantages, and disadvantages; subsequently, it discusses the latest applications and challenges of new-generation information technologies such as big data, artificial intelligence, and the Internet of Things in the field of outburst early warning; finally, it looks forward to the future development trends of outburst early warning technologies, pointing out that multi-field coupled intelligent perception, deep fusion of multi-source information, intelligent early warning models and decision-making platforms, and a new early warning paradigm based on digital twins are the main future development directions. The research results provide theoretical references and technical ideas for improving the level of coal and gas outburst early warning technologies and realizing the intrinsic safety of coal mines.

Keywords

Coal and Gas Outburst; Early Warning Technology; Research Status; Key Bottlenecks; Development Trends.

1. Introduction

Coal and gas outburst is a complex dynamic phenomenon resulting from the combined action of ground stress, gas pressure, and the physical and mechanical properties of coal. In an extremely short period, it ejects a large amount of coal and rock mass into the excavation space and emits high-volume fraction gas, which is highly likely to cause serious consequences such as equipment damage, casualties, and even mine abandonment[1-2]. China is one of the countries most severely affected by coal and gas outburst disasters in the world. With the gradual depletion of shallow coal resources, a large number of mines have entered the deep mining stage. Deep mining faces a complex environment of high ground stress, high gas pressure, low permeability, and strong excavation disturbance, leading to an increasing trend in the frequency and intensity of outburst disasters. Traditional single early warning methods and means can no longer meet the actual needs of current coal mine safety production[3]. Therefore, constructing a set of accurate, real-time, and reliable coal and gas outburst early warning systems to achieve advanced identification and effective prevention and control of disasters has become a major scientific problem and key technical challenge urgently needing to be solved in the field of coal mine safety. Over the past few decades, scholars at home and

ISSN: 2688-8645

abroad have carried out a large number of systematic studies on outburst mechanisms, precursor information identification, and early warning technologies, achieving fruitful research results[4]. Especially in recent years, the rapid development of sensing technology, communication technology, and information technology has provided new development opportunities for multi-parameter, multi-dimensional, and intelligent outburst early warning[5-6]. Based on this, this paper comprehensively summarizes the research progress of coal and gas outburst early warning technologies, deeply analyzes the advantages and disadvantages of existing technologies, and looks forward to the future development directions in combination with the development trend of cutting-edge technologies, aiming to promote the research in this field to a deeper level and a higher level.

2. Mechanism of Coal and Gas Outburst and Theoretical Basis for Early Warning

The effectiveness of early warning technology is based on a deep understanding of the disaster occurrence mechanism[7]. At present, the widely recognized comprehensive hypothesis on the mechanism of outburst in academic circles at home and abroad holds that outburst is the result of the combined action of three core factors: ground stress, gas, and the physical and mechanical properties of coal. Its evolution process can be roughly divided into four stages: preparation, initiation, development, and termination. In the preparation stage, excavation activities trigger the redistribution of stress in the coal mass in front of the working face, forming a stress concentration area and a stress relief zone, and the coal mass is damaged and develops fractures; in the initiation stage, the high ground stress causes the coal mass to break instantaneously, and the high-pressure gas is rapidly desorbed and expanded, carrying broken coal to erupt into the excavation space; in the development stage, the ejected coal-rock and gas mixture flow is self-sustaining and continuously impacts the roadway; the entire outburst process stops only when the internal energy of the coal-rock mass is completely released or encounters an obstacle.

The theoretical basis for early warning lies in that before the initiation of an outburst, changes in the three core factors and their interactions will trigger a series of observable physical and chemical effects, namely "precursor information". This information mainly includes:

(1) Stress-strain precursors: Acoustic emission and microseismic signals generated by micro-fractures in coal and rock masses; changes in drilling cuttings volume and initial gas emission velocity of boreholes caused by stress concentration.

(2) Gas precursors: Abnormal changes in the absolute gas emission volume, emission concentration, and emission dynamics of the working face; increases in coal gas desorption indicators (Δh_2, K_1 values).

(3) Geophysical precursors: Abnormal electromagnetic radiation, ground sound, and infrared radiation generated during the fracture process of coal and rock.

(4) Coal structure precursors: Thickening of soft coal seams, reduction of coal strength, etc.

The core of early warning technology is to use various sensors to real-time capture the abnormal changes of these precursor information, and realize the advance prediction of disasters by establishing the mapping relationship between the information and outburst risk.

3. Research Status of Main Outburst Early Warning Technologies

According to the different precursor information relied on, the existing outburst early warning technologies can be divided into the following categories:

3.1. Early Warning Technology Based on Dynamic Characteristics of Gas Emission

Gas is the energy source and dynamic medium for the occurrence of outbursts, and its emission dynamics is one of the most direct and sensitive indicators reflecting outburst risks[8]. This type of technology mainly includes:

(1) Initial gas emission velocity method of boreholes: Evaluate the outburst risk of coal mass at a specific depth section of a borehole by measuring the gas emission volume per unit time. This method is a core local early warning indicator recommended by China's "Regulations on Prevention and Control of Coal and Gas Outburst" and is widely used. However, it is a point measurement with a large workload and is easily affected by human factors such as borehole sealing quality and operation technology.

(2) Drilling cuttings gas desorption index method (K_1, Δh_2): Invert the gas content and desorption capacity of coal mass by measuring the gas desorption rate or pressure of drilling cuttings under certain conditions. This indicator can well reflect the physical and mechanical properties and gas potential of coal mass, and is also an important indicator stipulated by regulations. It also has the limitation of point and intermittent measurement.

(3) Early warning based on absolute gas emission volume of the working face: Calculate the absolute gas emission volume by monitoring the real-time gas concentration and air volume of the entire working face or return airway. When there are abnormal dynamics such as sudden increase, sudden decrease, or continuous high value, it may indicate changes in the stress state of coal mass, fracture development, or impending outburst risk. This method can realize continuous and areal monitoring, but it is easily interfered by non-geological factors such as air volume changes and production rhythm, and needs to be comprehensively judged in combination with other indicators.

(4) Gas dynamic response under acoustic/vibration excitation: An emerging research direction that observes changes in gas emission dynamics after actively applying acoustic or vibration excitation to coal mass. When the coal mass is in a state of stress concentration or damage, its permeability and gas desorption characteristics are more sensitive to excitation, and this technology is expected to become an active detection technology.

3.2. Early Warning Technology Based on Acoustic Emission (AE)/Microseism (MS)

When coal and rock masses are fractured and damaged under stress, they will release elastic waves, namely acoustic emission (small-scale) or microseismic (large-scale) signals. Monitoring these signals can effectively invert the fracture location, intensity, and development process inside coal and rock, thereby realizing outburst early warning[9-10]. This technology mainly arranges sensor arrays around the excavation area to capture AE/MS signals generated by coal and rock fractures, and evaluates the stress concentration degree and damage range of coal and rock masses through methods such as source location, energy rate calculation, and frequency domain analysis. Before an outburst, there are usually significant changes in the frequency, energy, and b-value of AE/MS events. This technology can realize continuous, real-time, and three-dimensional monitoring of large-scale rock masses, and can intuitively reflect the incubation process of dynamic disasters. It has been successfully applied in both rock burst and outburst early warning. However, the underground environment has strong noise interference (such as excavation machinery and transportation equipment), making the extraction and identification of effective signals a major problem; the cost of sensor deployment is high, and the monitoring sensitivity for deep areas is limited; the current research on the quantitative corresponding relationship between signal characteristics and outburst risk still needs to be deepened.

3.3. Early Warning Technology Based on Electromagnetic Radiation (EMR)

When coal and rock masses are loaded and fractured, electromagnetic radiation is generated due to the separation and movement of charges at the tip of crack propagation. The characteristics of EMR signals are closely related to the stress state and damage degree of coal and rock. This technology uses antenna sensors to receive EMR signals generated by coal and rock fractures, and predicts outburst risks by analyzing the change trends of parameters such as their intensity, pulse count, and frequency[11]. Generally, the EMR intensity and pulse count increase with the increase of load, and a "relative calm period" may appear before impending instability. EMR technology has the advantages of non-contact, continuous, and real-time monitoring, and is sensitive to coal mass damage. Countries such as Russia and Poland are in a leading position in the application of this technology, and China has also carried out a lot of research and practice. However, its signals are also easily interfered by electromagnetic waves from electromechanical equipment, and the propagation attenuation law is complex. The universality of quantitative early warning models needs to be improved.

3.4. Multi-source Information Fusion Early Warning Technology

In view of the shortcomings of single early warning indicators such as one-sided information and low reliability, integrating multi-source information such as ground stress, gas, and geophysics for comprehensive early warning has become a consensus and development trend[12]. The levels of information fusion include data-level fusion (direct fusion of raw data), feature-level fusion (fusion after feature extraction), and decision-level fusion (comprehensive decision after independent judgment by each method). At present, the latter two are mainly used in research and application. In the early stage, simple methods such as weighted average, fuzzy comprehensive evaluation, and expert systems were mostly adopted. For example, a fuzzy comprehensive evaluation model including indicators such as drilling cuttings volume S, gas desorption index K_1, and initial gas emission velocity q of boreholes was constructed to determine the risk level. Multi-source information fusion has effectively improved the accuracy and reliability of early warning, but most of the existing fusion systems adopt "static" weighting or rule-based judgment, which do not deeply explore the complex nonlinear coupling relationships between multi-source information, and the adaptability and intelligence level need to be improved.

4. Application and Challenges of New-generation Information Technologies in Outburst Early Warning

The rise of technologies such as big data, artificial intelligence (AI), and the Internet of Things (IoT) has provided powerful tools for breaking through the bottlenecks of traditional early warning technologies[13-15].

(1) Coal mine safety monitoring systems (such as gas monitoring, personnel positioning, and video monitoring) have accumulated massive time-series and spatial data. Using big data technologies (such as Hadoop and Spark) to store, clean, manage, and perform parallel computing on these multi-source, heterogeneous, and high-dimensional data is a prerequisite for discovering hidden laws and valuable information from them.

(2) AI algorithms, especially machine learning (ML) and deep learning (DL), have shown great potential in mining complex nonlinear relationships in data and constructing intelligent early warning models. By using historical monitoring data and outburst cases, the early warning problem can be transformed into a classification (dangerous/no dangerous) or regression (quantification of danger degree) problem. Algorithms such as support vector machine (SVM), random forest (RF), gradient boosting tree (such as XGBoost), long short-term memory network (LSTM), and convolutional neural network (CNN) are widely used to construct

ISSN: 2688-8645

intelligent early warning models integrating multiple precursor information, and their prediction accuracy is generally higher than that of traditional methods. Unsupervised learning (such as isolation forest and autoencoder) is used to learn patterns from normal data to automatically detect abnormal precursors; time-series networks such as LSTM are used to predict the future trends of key indicators such as gas emission volume to realize advanced early warning. However, the performance of AI models is highly dependent on high-quality and large-scale training data. Outburst accidents themselves are low-probability events, and positive samples (outburst cases) are extremely scarce, resulting in a serious problem of sample imbalance; the poor interpretability of models (the "black box" problem) affects the trust and adoption of early warning results by on-site coal mine personnel.

(3) IoT technology deploys a large number of intelligent sensors to form a perceptual layer neural network, realizing comprehensive, accurate, and real-time perception of all-round information of people, machines, environment, and management. Intelligent sensors used for outburst early warning are developing towards the direction of low power consumption, self-organizing network, high precision, and multi-parameter fusion (such as integrating stress, gas, and acoustic monitoring), providing richer and more reliable data sources for early warning.

5. Prospects for Development Trends

Based on the current research status and technological development, the future coal and gas outburst early warning technologies will show the following development trends:

(1) Development towards "Multi-field Coupling-Intelligent Perception". Future monitoring data collection will no longer be limited to a single parameter, but will strive to build a three-dimensional and all-round intelligent perception network covering multi-field information such as ground stress field, fracture field, gas field, and temperature field. Developing integrated intelligent sensors capable of simultaneously monitoring multiple parameters such as stress, gas pressure, concentration, microseism, acoustic emission, and resistivity, and realizing automatic data collection, edge computing, and wireless transmission are the keys to breaking through the perception bottleneck.

(2) Development towards "Deep Fusion of Multi-source Information". Beyond simple information superposition and weighting, in-depth research will be conducted on the nonlinear cooperative evolution mechanism of ground stress, gas, and coal structure under multi-field coupling. Using advanced technologies such as knowledge graphs and deep learning, realize deep feature extraction and fusion of multi-source information driven by both data and mechanism models, and establish more accurate and reliable early warning models.

(3) Development towards "Intelligent Early Warning-Decision-making Platform". Based on cloud platforms, big data, and AI technologies, build an intelligent comprehensive early warning platform integrating data integration, real-time analysis, intelligent early warning, disaster simulation, and emergency decision-making. This platform can not only automatically issue early warning information but also intuitively display dangerous areas, evolution processes, and possible consequences through visualization technology, providing scientific decision support for managers and realizing the closed-loop management of "monitoring-early warning-disposal".

(4) Development towards a New Paradigm of "Digital Twin-Intelligent Early Warning". Digital twin technology provides a new paradigm for outburst early warning. By constructing a virtual digital mine that accurately maps the physical mine, integrating geological, monitoring, and production real-time data, and embedding multi-field coupling mechanism models and AI early warning models, real-time simulation, dynamic deduction, and advanced preview of the incubation process of outburst disasters can be carried out in the digital space. Thus, the active assessment and early warning of outburst risks under different mining schemes can be realized,

transforming passive response into active prevention and control, and ultimately moving towards a new stage of safety in smart mines.

6. Conclusion

(1) Coal and gas outburst early warning technology has developed from single-index monitoring to multi-source information fusion early warning. Monitoring technologies based on geophysical methods such as gas dynamics, acoustic emission/microseism, and electromagnetic radiation each have their advantages but also have certain limitations.

(2) New-generation information technologies such as big data, artificial intelligence, and the Internet of Things are deeply integrated into the field of outburst early warning, significantly improving the depth of data processing, the accuracy of early warning models, and the breadth of perception. However, they also face challenges such as data quality, sample imbalance, and model interpretability.

(3) Future outburst early warning technologies will develop towards intelligent perception of multi-field information, deep fusion of multi-source data, construction of intelligent early warning decision-making platforms, and ultimately a new paradigm of intelligent early warning based on digital twins. This is a systematic project requiring the cross-integration of multiple disciplines such as mining engineering, geology, mechanics, and information science, and is of great significance for realizing the safe and efficient mining of deep coal mines.

Acknowledgments

The study was supported by the State Key Laboratory at China Coal Technology and Engineering Group Chongqing Research Institute (2025ZDYF09).

References

[1] Du Feng, Wang Kai, Sun Jiazhi, et al. Macro-Meso Failure Characteristics and Energy Mechanism of Deep Stress-Dominated Coal and Gas Outbursts[J/OL]. Journal of China Coal Society, 1-22[2026-01-07].

[2] Liu Yi, Lu Shouqing, Zhao Kang, et al. Literature Review and Research Progress on Prediction Indicators of Coal and Gas Outbursts Based on CiteSpace[J]. Safety in Coal Mines, 2025, 56(05): 30-39.

[3] Yang Ke, Guo Penghui, Yuan Liang, et al. Research Progress on Main Controlling Factors and Mechanisms of Typical Dynamic Disasters in Deep Coal Mining[J]. Journal of China Coal Society, 2025, 50(07): 3466-3487.

[4] Zhang Chaolin, Wang Peizhong, Wang Enyuan, et al. Development History and Prospects of Coal and Gas Outburst Mechanisms in China over the Past 70 Years[J]. Coal Geology & Exploration, 2023, 51(02): 59-94.

[5] Cao Kang, Li Zhonghui, Yu Desheng, et al. Research on Precursor Characteristics and Comprehensive Early Warning of Coal and Gas Outbursts in Driving Faces[J]. Coal Science and Technology, 2020, 48(11): 147-152.

[6] Zhang Zhigang, Zhang Qinghua, Liu Jun. Research Progress and Prospects of Early Warning Systems for Coal and Gas Outbursts and Compound Dynamic Disasters in China[J]. Journal of China Coal Society, 2024, 49(S2): 911-923.

[7] Liang Yunpei, Zheng Menghao, Li Quangui, et al. Research Status of Prediction and Early Warning for Coal and Gas Outbursts in China[J]. Journal of China Coal Society, 2023, 48(08): 2976-2994.

[8] Deng Ganbo. Application of Dynamic Analysis System for Gas Emission Characteristics in Yanghe Coal Industry[J]. Inner Mongolia Coal Economy, 2020, (19): 54-55.

[9] Yang Huiming. Acoustic Emission Monitoring Technology and Early Warning Experimental Study of Deep Stress-Type Outburst Disasters[J]. Safety in Coal Mines, 2017, 48(02): 17-20+25.

[10] Heng Xianwei, Fu Jinlei, Li Qingsong, et al. Microseismic Dynamic Response and Multi-Parameter Indicator Early Warning Method for Outburst Coal Seams[J]. Journal of Hunan University of Science & Technology (Natural Science Edition), 2022, 37(04): 1-8.

[11] Wang Enyuan, Li Zhonghui, Li Dexing, et al. Application of Electromagnetic Radiation Monitoring Technology and Equipment in Coal and Gas Outburst Monitoring and Early Warning[J]. Safety in Coal Mines, 2020, 51(10): 46-51.

[12] Ning Xiaoliang. Dynamic Early Warning Model for Coal and Gas Outbursts Based on Multi-Source Information Fusion[J]. Mining Safety & Environmental Protection, 2020, 47(03): 1-5+16.

[13] Zhao Xiaoliang. Early Warning Technology for Coal and Gas Outbursts Based on Big Data[J]. Energy and Energy Conservation, 2023, (02): 162-164.

[14] Zhang Qingqing. Research on Intelligent Early Warning System for Coal and Gas Outbursts Based on FOA-RF Model[J]. Shaanxi Coal, 2024, 43(07): 152-155+161.

[15] Li Wantong, Xia Fangfang, Zhu Yini, et al. Research Progress on Risk Assessment and Early Warning of Coal and Gas Outbursts Based on Machine Learning[J]. China Coal, 2024, 50(07): 52-62.