

Development Status and Trends of Coal and Gas Outburst Prediction and Early Warning Technologies in China Over the Past Decade

Yi Zhang^{1, 2}

¹China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400039, China;

²State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400039, China.

Abstract: Coal and gas outburst is a major disaster in coal mining, posing a severe threat to the life safety of miners and coal mine production. Over the past decade, China has made remarkable progress in the field of coal and gas outburst prediction and early warning technologies, evolving from static index methods to multi-source information fusion-based early warning and upgrading from traditional monitoring approaches to the application of intelligent technologies. This paper elaborates on the development trajectory of coal and gas outburst prediction and early warning technologies in China over the past decade, encompassing advancements in foundational theoretical research, prediction method models, monitoring equipment development, and early warning system construction. It analyzes the current challenges faced by these technologies and provides an outlook on future development trends, aiming to offer technical references for safe coal mine production and drive the advancement of coal and gas outburst prediction and early warning technologies to a higher level.

Keywords: Coal and Gas Outburst; Prediction and Early Warning Technology; Development Over the Past Decade; Intelligence; Multi-Source Information Fusion

1. Introduction

Coal and gas outburst is an extremely complex dynamic phenomenon that occurs during coal mining operations. Within an extremely short period, a large amount of coal and gas suddenly erupts from the coal seam, causing significant casualties and property losses, and severely restricting the safe and efficient production of coal mines. China is one of the countries most severely affected by coal and gas outburst disasters worldwide[1-2]. As the depth of coal mining continues to increase and mining intensity keeps rising, the risk of coal and gas outbursts is growing, and the prevention and control situation is becoming increasingly severe.

Accurate and timely prediction and early warning are crucial for effectively preventing coal and gas outburst accidents. Over the past decade, China's coal industry has placed great emphasis on the research and development as well as the application of coal and gas outburst prediction and early warning technologies. Numerous achievements have been made in foundational theoretical research, prediction method models, monitoring equipment development, and early warning system construction, leading to continuous improvements in technological levels and providing strong guarantees for safe coal mine production[3]. A thorough investigation into the development status and future trends of coal and gas outburst prediction and early warning technologies in China over the past decade holds significant practical importance for further refining the relevant technological systems and enhancing the prevention and control capabilities against outburst disasters.

2. Development Progress of Coal and Gas Outburst Prediction and Early Warning Technologies in the Past Decade

2.1. Increasingly Diverse Prediction Method Models

2.1.1. Continuous Improvement of Conventional Static Prediction Technologies

Conventional static prediction technologies primarily rely on gas-geological analysis, single-indicator, and comprehensive indicator methods. Gas-geological analysis mainly involves dividing outburst-prone areas based on known gas parameters and geological structural conditions, combined with the distribution patterns of outburst hazards in mined areas and the geological occurrence conditions in unmined areas. Over the past decade, with the continuous advancement of geological exploration technologies and the increasing diversity of data collection methods, the accuracy and reliability of gas-geological analysis have significantly improved[4-5]. Through comprehensive analysis of a large amount of geological data and gas parameters, outburst-prone areas can be identified more accurately, providing a scientific basis for formulating subsequent outburst prevention measures.

The single-indicator method determines outburst hazards by testing regional and working face parameters through drilling operations and comparing them with critical values. The main parameters involved include drill cuttings quantity (S), initial velocity of gas emission from boreholes (q), drill cuttings gas desorption index (Δh_2 or K1), coal body failure type, and firmness coefficient (f). To enhance the prediction accuracy of the single-indicator method, scholars have conducted in-depth research on the sensitivity and

applicability of these indicators. Through extensive field trials and data analysis, they have optimized the critical values of each indicator, improving the prediction effectiveness of the single-indicator method under different geological conditions.

The comprehensive indicator method mainly considers the sensitivity and influencing factors of multiple prediction indicators and comprehensively determines outburst hazards based on certain rules, including comprehensive indicators D, K, and R values. Over the past decade, the comprehensive indicator method has continuously evolved and improved. Scholars have introduced more influencing factors and more complex calculation models, enhancing the prediction accuracy and reliability of the comprehensive indicator method. For example, some studies have incorporated geological factors such as coal seam depth, thickness, and dip angle, as well as mining technical factors such as mining methods and support methods into the comprehensive indicator system, enabling the comprehensive indicator method to more comprehensively reflect the hazards of coal and gas outbursts.

2.1.2. Rapid Development of Dynamic Continuous Prediction Technologies

Static prediction has certain limitations. For instance, prediction methods often rely on drilling operations to obtain fixed-point and spot-check indicators, which involve cumbersome processes and significant human operational influences. Moreover, static prediction is limited to "point prediction" spatially and struggles to meet continuous prediction requirements temporally. To improve the accuracy of outburst prediction and enhance outburst prevention technology levels, numerous scholars have conducted extensive research on outburst hazard prediction and monitoring and early warning over the past decade, aiming to grasp outburst hazards in real-time[6-7]. They have formed a multi-type cross-prediction and monitoring and early warning system from two aspects: gas dynamic emission indicators and emerging geophysical technologies. Gas emission-related indicators mainly include V30 and KV. V30 is the ratio of gas emission volume to blasting coal yield within 30 minutes after blasting at the working face, while KV is the coefficient of variation of gas emission volumes in different cycles during roadway gas emission. Although these indicators reflect the average gas emission over a certain period, their prediction accuracy needs further improvement due to the consideration of a single research factor. Over the past decade, scholars have enhanced the prediction accuracy based on gas emission indicators by introducing more gas emission parameters and more complex analysis methods. For example, some studies have utilized time series analysis and neural network methods to model and predict gas emission data, enabling more accurate capture of the dynamic change patterns of gas emission and early prediction of outburst hazards.

Geophysical monitoring and early warning methods have developed rapidly over the past decade, including technologies such as microseismic, acoustic emission (geophone), electromagnetic radiation, ground-penetrating radar, and seismic wave CT. When coal-rock materials deform or fracture under the action of external or internal forces, they often release strain energy in the form of elastic waves, a phenomenon known as acoustic emission/microseismic activity. Microseismic monitoring technology is a real-time, dynamic, and continuous geophysical method that utilizes low-frequency microseismic information generated by coal-rock fractures to study coal-

rock structure and stability. It is widely applied in disaster monitoring fields such as coal and gas outbursts, rock bursts, and water inrush.

Over the past decade, scholars have conducted in-depth research on the spatial distribution and evolution of microseismic activity, waveform characteristics (amplitude-frequency, duration, frequency band energy, etc.), and time-series monitoring indicators and methods during the outburst process. For example, by analyzing the fault activation mechanical mechanism of outburst coal seams under mining influence, researchers have utilized high-precision microseismic monitoring systems to study the spatial-temporal distribution and evolution patterns of microseisms during tunneling, analyzing and obtaining the microseismic response patterns of geological anomaly areas within the mining range. Studies have shown that microseismic event clusters during working face tunneling are generally distributed around roadways, and rock mass energy release caused by fault displacement between the upper and lower plates due to mining is the main reason for fault-activated microseismic activity. Through real-time monitoring of faults within the mining influence range, geological anomalies such as fault activation can be promptly detected, providing a basis for accurate early warning of coal and gas outbursts.

2.1.3. Continuous Innovation in Mathematical Model Prediction Methods for Outburst Hazards

The influencing factors in the development process of coal and gas outburst disasters exhibit complex nonlinear characteristics. Although various prediction indicators have demonstrated good correlations with outburst hazards, relying solely on a single indicator is insufficient to meet the demand for ideal prediction accuracy. To address the challenges of determining critical values for prediction indicators and comprehensively determining outburst hazards by integrating multiple indicators, scholars have attempted to utilize various mathematical theoretical models to improve the accuracy of outburst prediction over the past decade[8-10]. Currently, commonly used mathematical models for outburst prediction include fuzzy mathematical models, neural network models, and support vector machine models. Fuzzy mathematical models can quantify some factors with unclear boundaries and difficult quantification. By establishing a fuzzy comprehensive evaluation model, they comprehensively consider the impact of multiple influencing factors on outburst hazards, thereby improving prediction accuracy. For example, some studies have established a multi-indicator hierarchical identification comprehensive early warning model encompassing three major categories and more than ten factors, including objective outburst hazards, deficiencies in outburst prevention technical measures, and hidden dangers in outburst prevention management. Using fuzzy mathematical methods, they determined the weights and membership degrees of each indicator, achieving a comprehensive assessment of outburst hazards.

Neural network models possess powerful nonlinear mapping capabilities and self-learning and adaptive abilities, enabling them to automatically learn the complex relationships between outburst hazards and various influencing factors from a large amount of historical data, thereby improving prediction accuracy. Over the past decade, with the rapid development of artificial intelligence technology, deep learning models have found increasingly widespread applications in coal and gas outburst prediction. For example, a gas concentration prediction and outburst

prevention early warning system based on Long Short-Term Memory (LSTM) networks can train on a large amount of collected gas concentration data, effectively learning the nonlinearity and rapid convergence of gas concentration changes, alleviating the gradient disappearance and explosion problems during data training, and predicting gas concentration change trends in advance, providing a basis for outburst early warning.

Support vector machine models are machine learning methods based on statistical learning theory, featuring good generalization capabilities and robustness, and achieving high prediction accuracy with small sample sizes. Over the past decade, scholars have improved the application effects of support vector machines in coal and gas outburst prediction by optimizing their kernel functions and parameters. For example, some studies have applied methods based on spectrograms and support vector machines (SVM) to the identification of coal mine gas and coal dust explosions. By extracting and classifying features from spectrograms, they achieved accurate identification of gas and coal dust explosions, providing new means for early warning and prevention of coal mine disasters.

2.2. Breakthroughs in Monitoring Equipment Research and Development

2.2.1. Research and Application of High-Precision Sensors

High-precision sensors are crucial components of coal and gas outburst monitoring and early warning systems, and their performance directly affects the accuracy and reliability of monitoring data. Over the past decade, China has achieved significant breakthroughs in the research and development of key sensors such as gas sensors, microseismic sensors, and acoustic emission sensors.

New-type gas sensors have achieved millisecond-level response times, enabling real-time and accurate monitoring of gas concentration changes. For example, the CWH200 coal seam gas content and pressure rapid measurement instrument developed by the China Coal Research Institute adopts non-dispersive infrared technology with an accuracy of ± 0.05 MPa. It can directly and rapidly measure, store, record, upload, and print the gas content and pressure of coal seams at mining working faces in coal mines within 10 minutes, greatly improving the efficiency of gas monitoring.

The performance of microseismic sensors and acoustic emission sensors has also continuously improved, enabling them to more sensitively capture weak signals generated by coal-rock fractures. By optimizing the structure and materials of sensors, their sensitivity and anti-interference capabilities have been enhanced, reducing noise interference and making monitoring data more accurate and reliable. For example, the microseismic monitoring system developed by the China Coal Technology and Engineering Group adopts high-precision microseismic sensors, enabling real-time monitoring of coal body fracture conditions in front of mining working faces and providing important evidence for outburst early warning.

2.2.2. Emergence of Intelligent Monitoring Equipment

With the rapid development of intelligent technologies, intelligent monitoring equipment has found widespread applications in the field of coal and gas outburst monitoring and early warning. Intelligent drilling rigs are typical representatives, integrating monitoring functions for various parameters such as drilling pressure, torque, and gas emission

volume. They can provide real-time feedback on drilling parameters and gas emission conditions during the drilling process. Through real-time monitoring and analysis of these parameters, abnormal conditions during drilling, such as coal body fracture and abnormal gas emission, can be promptly detected, providing early signals for outburst early warning. For example, by applying intelligent drilling rigs to optimize drilling layout schemes in the Huainan mining area, the gas drainage rate has increased by 20%. Meanwhile, early warning of outburst hazards can be issued in advance based on parameter changes during drilling, buying valuable evacuation time for construction personnel.

In addition, intelligent monitoring equipment such as portable rapid measurement instruments and adaptive hole-sealing devices continues to emerge. Portable rapid measurement instruments offer advantages such as simple operation and portability, enabling rapid measurement of coal seam gas parameters and providing timely evidence for formulating on-site outburst prevention measures. Adaptive hole-sealing devices can automatically adjust hole-sealing parameters based on the actual conditions of boreholes, improving hole-sealing quality and ensuring gas drainage effects.

2.3. Gradual Improvement in Early Warning System Construction

2.3.1. Widespread Application of Multi-Parameter Fusion Early Warning Modes

Most domestic coal mines adopt multi-parameter fusion early warning modes, incorporating key parameters such as gas concentration, air pressure, coal body temperature, drill cuttings quantity, and initial velocity of gas emission from boreholes into real-time monitoring networks[11-14]. Through fusion analysis of these multi-source data, a more comprehensive reflection of the hazards of coal and gas outbursts can be achieved, improving the accuracy and reliability of early warning. For example, an intelligent early warning platform established in a coal mine in Shanxi integrates 12 categories of data, including geological structure and mining progress. Utilizing big data analysis and artificial intelligence algorithms, it conducts in-depth mining and fusion analysis of multi-source data, achieving precise early warning of outburst hazards.

2.3.2. Continuous Emergence of Intelligent Early Warning Systems

With the rapid development of technologies such as artificial intelligence, big data, and cloud computing, intelligent early warning systems have found widespread applications in the field of coal and gas outburst early warning. Some advanced early warning systems introduce deep learning algorithms, enabling them to automatically learn the characteristics and patterns of outburst hazards from a large amount of historical data and achieve autonomous judgment and early warning of outburst hazards. For example, outburst precursor feature recognition technology based on deep learning can conduct real-time monitoring and analysis of multi-source data such as gas emission, microseismic activity, and acoustic emission, issuing early warning signals 20-30 minutes in advance and buying valuable time for personnel evacuation and the implementation of outburst prevention measures.

In addition, some early warning systems possess intelligent decision-making functions, enabling them to automatically generate corresponding outburst prevention measure

recommendations based on early warning results and guide on-site personnel in timely and effective prevention and control. For example, the comprehensive outburst early warning system developed by the Chongqing Research Institute of the China Coal Technology and Engineering Group is based on a GIS platform and adopts a component-based architecture. It consists of subsystems such as gas-geological analysis, borehole trajectory monitoring, gas drainage compliance evaluation, outburst prevention dynamic management, gas emission analysis, mine pressure monitoring analysis, and hidden danger investigation and management, as well as an early warning information platform. This system can automatically generate outburst prevention measure schemes based on early warning results and promptly convey them to relevant personnel through the early warning information platform, improving the timeliness and effectiveness of outburst prevention measures.

3. Challenges Faced by Current Coal and Gas Outburst Prediction and Early Warning Technologies

3.1. Insufficient Adaptability of Models Due to Complex Geological Conditions

China's coalfield geological structures are extremely complex, with significant variations in coal seam occurrence conditions, geological structural features, and gas parameters across different regions. For instance, there are marked differences in the outburst mechanisms between highly outburst-prone mines in the southwest and coalfields in North China. In the southwest, coal seams are strongly influenced by tectonic movements, resulting in the development of tectonic coal, high gas pressure, high gas content, and a high risk of outbursts. In contrast, coal seams in North China are relatively stable, with less developed tectonic coal and relatively lower gas parameters. The complexity of these geological conditions makes it difficult for universal early warning models to be precisely applicable to all mines, necessitating targeted adjustments and optimizations based on the actual conditions of each mine, which increases the difficulty of developing and applying early warning models.

3.2. Immaturity of Multi-Source Information Fusion Technology

Coal and gas outbursts are complex processes influenced by multiple factors, requiring comprehensive early warning based on multi-source information. However, multi-source information fusion technology is not yet mature, with the spatial-temporal matching accuracy of dynamic gas emission data, stress field change data, and geological structural data needing improvement. Discrepancies exist in collection time, spatial location, and data format among different types of data. Effectively fusing these multi-source data to extract feature information that accurately reflects outburst risk poses a significant challenge. Additionally, issues such as data redundancy and information conflicts arise during the fusion process, necessitating further research into effective data fusion algorithms and models to enhance the accuracy and reliability of multi-source information fusion.

3.3. Issues at the Field Application Level

At the field application level, some mines face problems such as insufficient sensor density and delayed maintenance,

affecting data collection quality. Sensor density directly impacts the completeness and accuracy of monitoring data; overly sparse sensor deployment may result in missing monitoring data in critical areas, preventing timely detection of outburst risk signals. Sensor maintenance is also crucial, as the harsh underground environment in coal mines exposes sensors to factors like dust, moisture, and electromagnetic interference, leading to performance degradation or damage. Delayed maintenance affects data accuracy and reliability, thereby impacting early warning effectiveness. Furthermore, some mines do not prioritize early warning systems sufficiently, with issues such as inadequate operator training and imperfect early warning response mechanisms, preventing the full utilization of early warning systems.

3.4. Need for Improvement in Technical Standards and Regulations

The current "Detailed Rules for Prevention and Control of Coal and Gas Outbursts" mandates the implementation of comprehensive four-in-one outburst prevention measures. However, discrepancies exist in the implementation standards of early warning response mechanisms across different provinces. For example, in Guizhou's newly revised local standards in 2023, the early warning response time was reduced from 30 minutes to 15 minutes, imposing higher demands on data transmission rates and decision-making systems. The lack of uniform technical standards and regulations across regions poses challenges for technology promotion and industry management. Additionally, with the emergence of new technologies such as intelligent early warning systems and novel monitoring equipment, existing standards and regulations may not fully meet the development needs of these technologies, necessitating timely revisions and improvements to ensure standardized and rational application of new technologies.

The application of new technologies also requires supporting infrastructure and technical support, increasing the cost and difficulty of technology promotion.

4. Future Development Trends in Coal and Gas Outburst Prediction and Early Warning Technologies

4.1. Establishment of a National Unified Big Data Platform for Coal and Gas Outbursts

In the future, establishing a national unified big data platform for coal and gas outbursts will become a significant trend. This platform will integrate relevant data from coal and gas outbursts across various mining areas, including geological structural data, gas parameter data, monitoring and early warning data, and outburst accident case data, enabling cross-mining area data sharing and comparative analysis. Through in-depth mining and analysis of vast amounts of data, the platform can identify patterns and characteristics of coal and gas outbursts under different geological conditions in various regions, providing rich data support for optimizing and improving early warning models. Simultaneously, the big data platform can offer data query, analysis, and early warning services to coal mining enterprises, helping them promptly understand their outburst risk status, implement targeted outburst prevention measures, and enhance safety production levels.

4.2. Development of Intelligent Early Warning Models with Self-Learning Capabilities

With the continuous advancement of artificial intelligence technology, developing intelligent early warning models with self-learning capabilities will be a future development direction. These models can automatically adjust parameters and structures based on the actual conditions of different mines, achieving accurate prediction of outburst risks. For instance, intelligent early warning models based on deep learning can be trained with extensive historical data to learn the complex relationships between outburst risks and various influencing factors, continuously self-optimizing and improving during practical applications. When geological conditions or mining methods in mines change, intelligent early warning models can automatically adapt to these changes, adjust prediction strategies, and enhance early warning accuracy and reliability. Furthermore, intelligent early warning models can be integrated with mine production systems for real-time monitoring and early warning, providing more intelligent safeguards for coal mine safety production.

4.3. Promotion of Research and Application of Novel Monitoring Equipment

Future efforts will continue to promote the research and application of novel monitoring equipment, enhancing the spatial-temporal resolution and accuracy of data collection. For example, developing nanoscale gas sensors can further improve the sensitivity and precision of gas sensors, enabling more accurate monitoring of gas concentrations. Distributed fiber optic temperature measurement devices can achieve continuous and real-time monitoring of coal body temperatures, promptly detecting abnormal temperature changes and providing crucial evidence for outburst early warning. Additionally, more intelligent and integrated monitoring equipment, such as multifunctional integrated monitoring probes capable of simultaneously monitoring multiple parameters like gas concentration, temperature, pressure, and microseismic activity, will be developed to reduce equipment installation quantity and space occupation while improving monitoring efficiency and reliability.

4.4. Strengthening the Application of 5G Communication Technology and Edge Computing

The integration of 5G communication technology and edge computing is transforming traditional early warning models. A pilot mine in Inner Mongolia deployed a 5G+edge computing early warning system, relocating data processing from surface computer rooms to underground switches, reducing response latency from 5 seconds to 0.3 seconds. This architectural innovation buys valuable time for emergency evacuation in outburst scenarios, enhancing early warning timeliness and effectiveness. In the future, the application of 5G communication technology and edge computing in coal and gas outburst early warning will be further strengthened, enabling real-time, high-speed data transmission and rapid processing. By deploying more edge computing nodes underground, monitoring data can be processed and analyzed locally, reducing data transmission latency and improving early warning system response speed. Simultaneously, the high bandwidth and low latency characteristics of 5G communication technology support the transmission of more

diverse data types, such as high-definition video surveillance data and 3D geological model data, providing richer information support for early warning systems.

5. Conclusion

Over the past decade, China has made significant progress in the field of coal and gas outburst prediction and early warning technologies, with continuous deepening of basic theoretical research, enrichment of prediction methods and models, breakthroughs in monitoring equipment research and development, and gradual improvement of early warning system construction. However, current technologies still face challenges such as insufficient adaptability of models due to complex geological conditions, immaturity of multi-source information fusion technology, issues at the field application level, and the need for improvement in technical standards and regulations. In the future, coal and gas outburst prediction and early warning technologies will develop towards establishing a national unified big data platform, developing intelligent early warning models with self-learning capabilities, promoting research and application of novel monitoring equipment, and strengthening the application of 5G communication technology and edge computing. Through continuous technological innovation and application promotion, the accuracy and reliability of coal and gas outburst prediction and early warning in China will be further enhanced, providing stronger safeguards for coal mine safety production and driving the high-quality development of China's coal industry.

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