

Research Progress on Gas Concentration Prediction Methods in Coal Mine Working Faces

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Abstract: Gas concentration prediction in coal mine working faces is a crucial aspect of ensuring safe coal mine production. This paper systematically reviews the current research status of gas concentration prediction methods in coal mine working faces, encompassing traditional prediction methods, artificial intelligence-based prediction methods, multi-source data fusion prediction methods, and prediction methods for special environments. It analyzes the advantages, disadvantages, and applicable scenarios of each method, pointing out existing issues in current research, such as insufficient data quality and quantity, weak model generalization ability, and high real-time requirements. Finally, it provides an outlook on future research directions, suggesting the strengthening of interdisciplinary integration, the development of new sensor technologies, and the construction of intelligent prediction platforms to enhance the accuracy and reliability of gas concentration prediction and provide robust safeguards for safe coal mine production.

Keywords: Coal mine working face; Gas concentration prediction; Artificial intelligence; Multi-source data fusion; Research progress.

1. Introduction

As a vital energy industry in China, coal mines play a pivotal role in economic development. However, numerous safety hazards exist during coal mine production, with gas accidents being one of the major disasters threatening safe coal mine operations [1]. Gas, primarily composed of methane, is highly flammable and explosive. When its concentration in coal mine working faces reaches a certain range, it can trigger gas explosions, coal and gas outbursts, and other accidents in the presence of an ignition source or high temperature, resulting in severe casualties and property losses [2].

Accurate prediction of gas concentration in coal mine working faces is key to preventing gas accidents [3-5]. By grasping the changing trend of gas concentration in advance, timely measures such as ventilation and gas extraction can be taken to control gas concentration within safe limits, effectively avoiding gas accidents. Therefore, research on gas concentration prediction methods in coal mine working faces holds significant theoretical and practical value. In recent years, with continuous technological advancements, remarkable progress has been made in gas concentration prediction methods for coal mine working faces. From traditional methods based on statistics and geological analysis to methods utilizing emerging technologies such as artificial intelligence and big data, the accuracy and reliability of predictions have continuously improved [6-9]. This paper systematically reviews the current research status of gas concentration prediction methods in coal mine working faces, analyzes the advantages, disadvantages, and applicable scenarios of each method, points out existing issues in current research, and provides an outlook on future research directions, aiming to offer references for research on gas concentration prediction in coal mine working faces.

2. Traditional Gas Concentration Prediction Methods in Coal Mine Working Faces

2.1. Statistical prediction methods

Statistical prediction methods were among the early commonly used approaches for gas concentration prediction, mainly including linear regression analysis and time series analysis. Linear regression analysis establishes a linear relationship model between gas concentration and relevant influencing factors (such as mining depth, coal seam thickness, ventilation volume, etc.), using historical data for parameter estimation to predict future gas concentration. Time series analysis treats gas concentration as a sequence varying with time, establishing an appropriate time series model (such as the Autoregressive Moving Average (ARMA) model and the Autoregressive Integrated Moving Average (ARIMA) model) for prediction by analyzing the statistical characteristics of the sequence (such as the autocorrelation function and partial autocorrelation function).

Statistical prediction methods have the advantages of simple principles and ease of implementation, and can achieve certain results in predicting stationary time series. However, gas concentration in coal mine working faces is influenced by various complex factors, exhibiting significant non-stationarity and non-linearity. Statistical prediction methods generally show limited accuracy in handling such problems and struggle to meet the demands of actual production.

2.2. Grey theory prediction methods

Grey theory is a method for studying problems with small amounts of data and poor information uncertainty. Grey prediction models describe the development and change laws of a system through grey differential equations. In gas concentration prediction, grey theory uses exponential curve fitting to process historical gas concentration data and

establish grey prediction models (such as the GM(1,1) model) for prediction.

Grey theory prediction methods do not require a large amount of historical data and are computationally simple, capable of reflecting the changing trend of gas concentration to a certain extent. However, due to its assumption of methane saturation conditions and the use of exponential curve fitting, the prediction accuracy of this method is generally limited, especially showing a decline in accuracy in long-term predictions.

2.3. Geostatistical analysis methods

Geostatistical analysis methods establish gas prediction models by analyzing the relationship between gas and geological factors based on mine geological data. The main geological factors considered include coal seam thickness, coal seam burial depth, coal-rock combination, geological structures, and coal quality. Through statistical analysis of a large amount of mine geological data and gas concentration data, quantitative relationships between gas concentration and geological factors are identified to predict gas concentration in unknown areas.

Geostatistical analysis methods can fully consider the influence of geological factors on gas concentration, providing certain geological bases for gas prevention and control. However, the relationship between geological factors and gas concentration is complex and diverse, and is also affected by various factors such as mining activities. This method has certain limitations in practical applications, and its prediction accuracy needs improvement.

2.4. Numerical simulation methods

Numerical simulation methods predict gas emission volume and indirectly predict gas concentration by simulating the migration and distribution laws of gas in mines through computers. Common numerical simulation methods include the finite difference method, finite element method, and discrete element method. These methods divide the mine area into multiple small units, obtain the gas distribution in mines through computer solutions based on the basic equations of gas migration (such as the mass conservation equation and momentum conservation equation) combined with boundary and initial conditions.

Numerical simulation methods can visually display the gas migration process and distribution laws in mines, providing scientific bases for formulating gas prevention and control measures. However, this method requires accurate geological parameters and boundary conditions, and the calculation process is complex, imposing high requirements on computer performance. Additionally, numerical simulation results often deviate from actual situations to some extent and need to be corrected in conjunction with actual monitoring data.

3. Artificial Intelligence-Based Gas Concentration Prediction Methods in Coal Mine Working Faces

3.1. Neural network prediction methods

Neural networks are computational models that simulate the structure of human brain neurons, possessing powerful non-linear mapping capabilities and self-learning abilities. In gas concentration prediction, commonly used neural network models include the Multi-Layer Perceptron (MLP), Back Propagation (BP) neural network, and Radial Basis Function

(RBF) neural network. These models establish non-linear relationship models between inputs and outputs by learning historical gas concentration data and data on relevant influencing factors to predict future gas concentration.

Polish scholars Tutak M et al. used gas concentration values measured by a sensor system in the longwall area of a mine in the Silesian Coal Basin to establish a prediction model based on a multi-layer perceptron network. The predicted values showed only minor errors compared to the actual values, indicating certain advantages of neural networks in gas concentration prediction. However, neural network models also have some drawbacks, such as the tendency to fall into local optimal solutions during training, difficulty in determining model structures, and the need for a large amount of sample data for training, performing poorly in small sample problems.

3.2. Support vector machine prediction methods

Support Vector Machines (SVMs) are machine learning methods based on statistical learning theory that achieve data classification and regression by finding an optimal hyperplane. In gas concentration prediction, the Support Vector Regression (SVR) model transforms the gas concentration prediction problem into a regression problem, improving the models generalization ability by minimizing structural risk.

Support vector machine prediction methods have the advantages of a solid theoretical foundation and strong generalization ability, especially suitable for predicting small sample data. Compared to neural networks, support vector machines can avoid the problem of falling into local optimal solutions and are relatively less sensitive to model parameter selection. However, support vector machines have high computational complexity and long training times when processing large-scale data, limiting their widespread application in practice.

3.3. Deep learning prediction methods

Deep learning is a popular research direction in the field of artificial intelligence, automatically learning high-level feature representations from data by constructing deep neural network models. In gas concentration prediction, commonly used deep learning models include Recurrent Neural Networks (RNNs) and their variants Long Short-Term Memory (LSTM) networks and Gated Recurrent Units (GRUs), as well as Convolutional Neural Networks (CNNs).

RNNs and their variants can handle time series data, capturing long-term dependencies in gas concentration time series, suitable for complex scenarios of gas concentration prediction. LSTMs and GRUs effectively solve the problems of gradient vanishing and gradient explosion in traditional RNNs by introducing gating mechanisms, enabling better learning of non-linear features in gas concentration time series. CNNs excel at processing spatial data and can improve prediction accuracy by combining spatial distribution information of gas concentration.

Deep learning-based gas concentration prediction methods can automatically extract high-level features from data, improving prediction accuracy and precision. Meanwhile, deep learning models have strong generalization ability and can adapt to gas concentration prediction under different environments and working conditions. However, training deep learning models requires a large amount of data and

computational resources, and the model structures are complex with difficult parameter adjustments, imposing high technical requirements on researchers.

4. Multi-Source Data Fusion-Based Gas Concentration Prediction Methods in Coal Mine Working Faces

4.1. Necessity of data fusion

Gas concentration in coal mine working faces is influenced by various factors. In addition to the aforementioned geological and mining factors, environmental factors (such as temperature, humidity, and air pressure) and equipment operation factors (such as the operating status of ventilation fans and gas extraction pumps) also play a role. A single data source can only reflect partial information about gas concentration, making it difficult to comprehensively and accurately predict changes in gas concentration. Therefore, fusing multi-source data and comprehensively utilizing information from various data sources can improve the accuracy and reliability of gas concentration prediction.

4.2. Multi-source data fusion methods

Multi-source data fusion methods mainly include data-level fusion, feature-level fusion, and decision-level fusion. Data-level fusion directly fuses raw data collected by multiple sensors and then performs feature extraction and model training. This method can retain the most original information but imposes high requirements on sensor accuracy and synchronization. Feature-level fusion first extracts features from each data source and then fuses the extracted features before establishing a prediction model. This method can reduce data volume and improve fusion efficiency, being a commonly used multi-source data fusion method at present. Decision-level fusion first establishes independent prediction models for each data source to obtain their respective prediction results and then fuses these prediction results to obtain the final prediction result. This method has good fault tolerance but may lose some useful information.

4.3. Multi-source data fusion prediction models

In multi-source data fusion prediction, commonly used models include fusion models based on Bayesian theory, fusion models based on Dempster-Shafer (D-S) evidence theory, and fusion models based on neural networks. Fusion models based on Bayesian theory use Bayesian formulas to fuse the prior probabilities and conditional probabilities of multiple data sources to obtain posterior probabilities for prediction. Fusion models based on D-S evidence theory combine the basic probability assignments of multiple data sources to obtain the fused basic probability assignment for decision-making. Fusion models based on neural networks take multi-source data as inputs to the neural network and achieve data fusion and prediction through the neural networks self-learning and adaptive capabilities.

Multi-source data fusion-based gas concentration prediction methods can fully utilize information from various data sources, improving prediction accuracy and reliability. However, multi-source data fusion also faces issues such as data synchronization, data conflicts, and increased model complexity, which require further research and solutions.

5. Gas Concentration Prediction Methods in Coal Mine Working Faces under Special Environments

5.1. Gas concentration prediction in deep heading working faces

With the continuous increase in coal mine mining depth, gas problems in deep heading working faces have become increasingly prominent. Deep heading working faces have complex geological conditions, high ground stress, high gas pressure, large gas emission volume, and more intense and complex changes in gas concentration due to the influence of heading activities. Traditional gas concentration prediction methods perform poorly in deep heading working faces, necessitating the research of special prediction methods suitable for deep environments.

The spectral acoustic method provides a new approach for gas concentration prediction in deep heading working faces [10]. This method extracts feature information related to gas concentration by analyzing the propagation characteristics of artificial acoustic signals in coal seams. Grey Relational Analysis (GRA) and Hierarchical Cluster Analysis (HCA) are used to screen indicators closely related to gas concentration from the indicators of artificial acoustic signals obtained through the spectral acoustic method. The Simulated Annealing Algorithm (SAA) with an iterative annealing strategy is employed to determine the total number of modal components K and the penalty coefficient α in Variational Mode Decomposition (VMD). The optimized VMD decomposes noisy gas concentration signals into several modal components with different frequencies but relatively stable. The SAA random perturbation strategy is used to verify the optimal value of the smoothing factor σ of the Generalized Regression Neural Network (GRNN) optimization model, which effectively predicts each modal component and reconstructs the prediction results. Research shows that the "decomposition-prediction-aggregation" mechanism can effectively suppress noise interference and significantly reduce non-linear complexity, thereby improving the accuracy of the prediction model. Compared to four control models, the VMD-SAA-GRNN optimization model based on the spectral acoustic method demonstrates stronger generalization ability and higher accuracy in dynamic gas concentration prediction.

5.2. Gas concentration prediction in gas outburst-prone areas

Coal and gas outbursts are severe disasters in coal mine production, and accurately predicting gas concentration in gas outburst-prone areas is crucial for preventing outburst accidents. Gas concentration in gas outburst-prone areas is influenced by various outburst-inducing factors, such as coal seam gas pressure, gas content, coal mechanical properties, and geological structures, exhibiting more complex changing patterns.

In gas concentration prediction in gas outburst-prone areas, the relationship between outburst-inducing factors and gas concentration needs to be comprehensively considered. A multi-factor coupling method can be adopted to establish a gas concentration prediction model incorporating outburst-inducing factors. For example, combining geostatistical analysis, numerical simulation, and artificial intelligence methods to analyze the influence mechanisms of outburst-

inducing factors on gas concentration and construct a multi-factor coupling gas concentration prediction model. Meanwhile, real-time monitoring data can be used to dynamically update and correct the model, improving prediction accuracy and real-time performance.

6. Existing Issues in Research and Future Development Directions

6.1. Issues in prediction methods

(1) Data quality and quantity issues

The performance and prediction accuracy of gas concentration prediction models highly depend on the quality and quantity of data. However, in practical applications, gas concentration data often have issues such as missing values, anomalies, and noise, which affect model training and prediction effects. Additionally, due to the complexity and uncertainty of coal mine production, obtaining a sufficient quantity and high quality of historical data is also challenging.

(2) Model generalization ability issues

There are significant differences in geological conditions, mining processes, and environmental factors among coal mine working faces. The gas concentration change patterns may vary among different mines or even different working faces within the same mine. Therefore, gas concentration prediction models are required to have strong generalization ability to meet prediction demands under different environments and working conditions. However, most current prediction models are trained and validated on specific datasets, with limited generalization ability, and may experience a decline in prediction accuracy in practical applications.

(3) Real-time requirement issues

Coal mine production is a dynamic process, and gas concentration can change at any time. To timely take measures to prevent gas accidents, gas concentration prediction methods are required to have high real-time performance, enabling rapid and accurate prediction of gas concentration. However, some complex prediction models, such as deep learning models and multi-source data fusion models, have high computational complexity and long prediction times, making it difficult to meet real-time requirements.

6.2. Outlook on future research directions

(1) Strengthening interdisciplinary integration

Gas concentration prediction in coal mine working faces is a complex problem involving geology, mining engineering, computer science, mathematics, and other disciplines. In the future, interdisciplinary integration should be strengthened, fully leveraging the theoretical and technological advantages of each discipline to jointly conduct research on gas concentration prediction. For example, combining geological exploration technology and computer simulation technology to study the occurrence and migration laws of gas in coal seams; utilizing artificial intelligence and big data technology to develop more accurate and efficient gas concentration prediction models.

(2) Developing new sensor technologies

Sensors are key devices for obtaining gas concentration data, and their performance directly affects data quality and prediction accuracy. In the future, research and development efforts should be increased to develop gas sensors with high precision, high reliability, strong anti-interference ability, and

good real-time performance. For example, researching new gas sensors based on optical, acoustic, and electrochemical principles to improve the detection sensitivity and selectivity of sensors for gas concentration.

(3) Building intelligent prediction platforms

An intelligent prediction platform integrating data collection, transmission, processing, analysis, and prediction should be constructed to achieve automation and intelligence in gas concentration prediction. The intelligent prediction platform can integrate multi-source data and use advanced data fusion and prediction algorithms to predict and warn gas concentration in real time. Meanwhile, the platform can also provide decision support functions, offering reasonable suggestions and measures for safe coal mine production based on prediction results.

(4) Strengthening practical application research

Currently, most gas concentration prediction methods are still in the laboratory research stage, and their practical application effects need further verification. In the future, practical application research should be strengthened, applying research results to actual coal mine production, and continuously optimizing and improving prediction methods through feedback from actual data. Meanwhile, a comprehensive prediction effect evaluation system should be established to evaluate the accuracy, reliability, and real-time performance of prediction methods in an all-round way, providing a basis for the promotion and application of prediction methods.

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