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Research and Application of Gas Concentration Prediction Model in the Upper Corner of the Working Face

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Abstract

To prevent gas concentration overruns in the upper corner of coal mining faces in coal mines and avert gas accidents on the working face, this study analyzes the influencing factors of gas concentration in the upper corner. A prediction model for gas concentration in the upper corner is established based on chaos theory, and an analysis of influencing factors and trend prediction are conducted in conjunction with the gas concentration in the upper corner of a specific mine's working face. The results indicate that gas concentration in the upper corner is influenced by multiple factors, including gas occurrence and migration patterns, the dynamic characteristics of the ventilation system, the disturbance effects of mining techniques, and the level of production management and control. The maximum Lyapunov exponent of the selected gas concentration time series is 0.068>0, indicating chaotic characteristics. In a phase space with a time delay of 4 and an embedding dimension of 3, the model parameters are a = 1.2217 and b = -1.0447. The absolute errors of the prediction results range from [-0.024, 0.031], the relative errors range from [-2.82%, 3.99%], and the root mean square error is 0.0149. The prediction results closely align with actual conditions, providing valuable guidance for gas management on the working face.

Keywords

Coal mine working face; upper corner; gas concentration overrun; influencing factors; time series; chaos theory; trend prediction.

1. Introduction

The over-limit of gas concentration in the upper corner poses a significant hazard to the safe production of coal mining faces, and effectively preventing gas accumulation in the upper corner is a crucial aspect of preventing gas accidents on the working face [1-2]. Over an extended period, scholars both domestically and internationally have conducted systematic research on the mechanisms of gas accumulation in the upper corner and its prevention and control technologies, achieving notable progress in theoretical analysis and engineering practice [3-5]. Lv Pin et al. [6] applied grey system control theory to establish a corresponding dynamic prediction and analysis model, which can effectively reflect the variation patterns of gas in the upper corner of coal mining faces during practical application. Chen Shuai [7] constructed a BP neural network prediction model for gas emission concentration in the upper corner of the 22301 mining face at Cuncaota Coal Mine, with an average prediction error of the model being less than 10%. Liang Yunpei et al. [8] developed a gas concentration prediction model for the upper corner of coal mining faces based on the FEDformer-LGBM-AT architecture. However, the time series of gas concentration in the upper corner exhibits strong nonlinear characteristics, and its dynamic evolution process aligns with the typical features of chaotic

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systems. Chaos theory is a discipline that studies nonlinear phenomena in dynamic systems, revealing unpredictable behaviors arising from sensitive dependence on initial conditions in deterministic systems. Based on this, the author analyzes various factors influencing changes in gas concentration in the upper corner and establishes a gas concentration prediction model for the upper corner based on chaos theory. This model can accurately predict short-term trends in gas concentration, offering significant theoretical guidance for coal mines in preventing gas accidents.

2. Factors Influencing Gas Concentration in the Upper Corner

During the underground production process in coal mines, the gas concentration in the upper corner of the working face is influenced by multiple interacting factors, with its accumulation mechanism closely related to the unique underground environment. This paper systematically elucidates the key factors affecting gas concentration in the upper corner from four dimensions: gas occurrence and migration patterns, the dynamic characteristics of the ventilation system, the disturbance effects of mining techniques, and the level of production management and control.

(1) Source-sink characteristics of gas occurrence and migration

The occurrence state of coal seam gas serves as the material basis determining gas concentration in the upper corner. The dynamic equilibrium between adsorbed and free gas in coal is jointly regulated by geostress, temperature, and coal quality parameters. Under deep mining conditions, increased geostress reduces coal porosity, but the gas pressure gradient rises significantly, accelerating gas desorption rates during mining. Particularly when coal seam permeability falls below a critical threshold, gas emissions exhibit nonlinear surge characteristics, with such sudden emissions prone to causing abrupt increases in gas concentration in the upper corner.

The complexity of gas migration pathways in the goaf is another crucial influencing factor. As the working face advances, the porous media region formed by roof caving experiences gas migration driven by both buoyancy and pressure gradients. Numerical simulation studies demonstrate that in U-type ventilation systems, deep-seated gas in the goaf accumulates in the upper corner under concentration gradient effects, forming a typical "gas pool" phenomenon. Gas from adjacent seams, which infiltrates into the goaf of the current coal seam through interlayer fractures, converges with the gas from the current seam in the upper corner region, making this location a "hotspot" for gas accumulation.

(2) Dynamic regulation capacity of the ventilation system

The ventilation method decisively influences the airflow field in the upper corner. Traditional U-type ventilation systems create a right-angle bend at the end of the working face, resulting in a low-velocity recirculation zone in the upper corner. Particle Image Velocimetry (PIV) experiments confirm that wind speeds in this region can drop to less than one-fifth of those in the main airflow zone, significantly weakening gas dilution capacity. Y-type ventilation, by increasing the number of return airways, effectively shortens gas migration pathways but requires precise control of air volume distribution among the roadways to prevent the formation of new accumulation zones.

The stability of the ventilation power system directly affects gas dilution effectiveness. Issues such as fluctuations in the operating conditions of the main mine fan, improper positioning of local fans, or air leakage from ducts can all reduce the effective air volume in the working face. Particularly when the air supply falls below a critical threshold, gas concentration in the upper corner exhibits an inverse exponential relationship with the air supply. Additionally, uneven resistance distribution in the ventilation network can induce pressure differential changes at both ends of the working face, altering goaf air leakage volumes and subsequently affecting gas migration fluxes.

(3) Disturbance effects of mining techniques

The mining method significantly impacts gas emission intensity. During fully mechanized top-coal caving mining, the micro-fracture network generated by top-coal fragmentation serves as a rapid gas release pathway. Field monitoring data indicate that gas emissions during the top-coal caving stage can reach 2-3 times those during coal cutting stages, with prolonged emission durations. When mining thick coal seams in layers, gas emissions from lower layers exhibit a clear increasing trend under the influence of gas pressure from upper layer goafs.

Roof management methods directly influence the spatial structure of gas migration in the goaf. When employing the full-caving method for roof management, periodic roof collapse induces dynamic changes in the "three zones" of the goaf, with gas emissions from the caving zone exhibiting intermittent characteristics. Backfill mining, by altering roof deformation mechanisms, effectively suppresses gas emissions from the goaf, but the permeability of backfill materials must be strictly controlled below the 10^{-6} m^2 range. The advancing speed of the working face has a dual effect on gas accumulation: overly rapid advancement may prevent the roof from collapsing fully, creating spaces for gas accumulation; conversely, overly slow advancement prolongs gas release times, increasing accumulation risks.

(4) Control Effectiveness of Production Management

The optimized configuration of gas extraction systems is a critical technical means for controlling gas concentration in the upper corner. High-level borehole extraction can reduce gas emissions from the goaf by 30%-50% by intercepting gas in the roof fracture zone. Low-level borehole extraction, acting directly on the goaf near the upper corner, effectively blocks the upward diffusion pathway of gas. The extraction negative pressure and borehole layout parameters need to be dynamically adjusted based on the coal seam permeability coefficient. When the extraction flow rate and gas emission rate reach dynamic equilibrium, the gas concentration in the upper corner can be stably maintained below the safety threshold.

The completeness of the monitoring and early warning system directly affects accident prevention and control effectiveness. Methane sensors in the upper corner should be positioned on the return air side, 200-300 mm from the roof, with a response time meeting the $T90 \leq 20s$ requirement. A multi-sensor fusion monitoring system can predict accumulation trends 15-30 minutes in advance by analyzing the spatiotemporal evolution patterns of gas concentration. Among emergency response measures, wind barrier diversion technology can increase wind speed in the upper corner by 40%-60%, but the angle of the wind barriers needs to be regularly adjusted to adapt to changes in the ventilation system. Hydraulic fracturing for permeability enhancement can reduce gas emissions at the source by increasing coal seam permeability, but the fracturing fluid formulation must be strictly controlled to avoid weakening coal body strength.

(5) Coupling Mechanism of Multiple Factors

The aforementioned factors exhibit complex nonlinear coupling relationships in actual production. For example, changes in ventilation methods can disturb the airflow field in the goaf, thereby affecting gas migration pathways. Increased mining intensity leads to a surge in gas emissions, and when this exceeds the dilution capacity of the ventilation system, optimizing extraction parameters alone may not effectively control gas concentration. Numerical simulation studies indicate that when the air volume, advancing speed, and gas extraction rate of the working face satisfy a specific matching relationship, optimal control of gas concentration in the upper corner can be achieved. This multi-parameter collaborative regulation mechanism provides a new theoretical basis for gas management.

3. Prediction of Gas Concentration in the Upper Corner

Gas concentration, as a characteristic parameter of the gas control system, encompasses information on the long-term evolution of all variables within the system. By studying the chaotic behavior of the system through the gas concentration time series, gas concentration predictions can be made directly based on the objective laws calculated from the series.

3.1. Chaos Theory

Chaos theory is a mathematical theory that investigates the hidden regularity behind seemingly random and disordered behaviors in nonlinear dynamical systems, revealing the potential intrinsic randomness and unpredictability within deterministic systems. Currently, the primary methods for distinguishing the chaotic nature of time series domestically and internationally include power spectrum analysis, principal component analysis, Poincare section method, Lyapunov exponents, and the C-C method, among which the Lyapunov exponent method is widely applied. The Lyapunov exponent λ represents the average exponential rate of convergence or divergence between adjacent trajectories in the phase space of the system. In directions where $\lambda<0$, the phase volume of the system contracts, the motion is stable, and it is insensitive to initial conditions; in directions where $\lambda>0$, trajectories rapidly diverge, and long-term behavior becomes sensitive to initial conditions, indicating chaotic motion; $\lambda=0$ corresponds to a critical state. Therefore, whether the maximum Lyapunov exponent is greater than zero can serve as a criterion for determining whether a time series is chaotic.

In a chaotic system, the evolution of any component is determined by its interactions with other components. The original laws of the system can be extracted and restored from a batch of time series data of a certain component, which represents a trajectory in a high-dimensional space, namely, the chaotic attractor. To predict the development trend of a time series based on historical information, the reasonable selection of the time delay τ and the embedding dimension m is crucial for ensuring prediction accuracy. The C-C method utilizes the correlation integral to simultaneously estimate the time delay τ and the time window t_w. The time delay τ ensures that the data in the time series are interdependent without relying on the embedding dimension m; whereas the time window t_w depends on m, and τ varies with m. The embedding dimension can be determined based on the time delay and the time window.

3.2. Prediction Using the Weighted First-Order Local Method

Generally, the prediction accuracy of commonly used prediction methods, ranked from highest to lowest, is as follows: first-order local method, weighted zero-order local method, zero-order local method, and global method. Therefore, this paper employs the weighted first-order local method to predict gas concentration, with the specific steps outlined below:

Reconstruct the phase space. Reconstruct the phase space of the gas concentration time series based on the embedding dimension m and time delay τ determined by the C-C method.

Identify neighboring points. Take the last phase point in the phase space as the central point X_k, and select several trajectory points closest to the central point as the relevant points X_{ki} (where i = 1, 2, …, q). Let the distance between point Y_{ki} and the central point Y_{ki} be d_i, and assume d_m is the minimum value among d_i. Define the weight of point Yki as follows:

$$P_i = \frac{\exp\left[-c\left(d_i - d_m\right)\right]}{\sum_{i=1}^{q}\exp\left[-c\left(d_i - d_m\right)\right]} \tag{1}$$

Where, c is a coefficient, generally taken as c = 1; where i = 1, 2, …, q.

Perform prediction calculations. The first-order weighted local linear fitting formula is: $X_{ki+1}=ae+bX_{ki}$, when $m\geq1$,

$$\begin{cases} a\times e+b\sum_{i=1}^{q}P_iX_{ki}=\sum_{i=1}^{q}P_iX_{ki+1} \\ a\sum_{i=1}^{q}P_ie\times X'_{ki}+b\sum_{i=1}^{q}P_iX_{ki}\times X'_{ki}=\sum_{i=1}^{q}P_iX'_{ki}X_{ki+1} \end{cases} \tag{2}$$

Where, e=(1,1,...,1)T, and a, b are undetermined coefficients that can be obtained using the linear regression method. Then, substitute them into the prediction formula to make predictions.

Make predictions using the prediction formula.

$$Y_{k+1}=ae+bY_k \tag{3}$$

The last numerical value in the vector Y_{k+1} calculated each time represents the predicted value. This predicted value is then appended to the end of the known data array, and the process continues to predict the next value. The maximum number of prediction steps, $MaxStep$=1/λ.

3.3. Error Analysis

Error refers to the difference between predicted values and actual values, primarily stemming from description errors, observation errors, truncation errors, and rounding errors. It is commonly quantified using absolute error (y- y'), relative error (δ), and root mean square error (RMSE). By analyzing and comparing the discrepancies between predicted and measured gas concentrations, we can evaluate the accuracy of the trend prediction model for gas concentration in the upper corner. This analysis provides valuable insights for optimizing the prediction model.

$$\delta=\frac{y-y'}{y'}\times 100\% \tag{4}$$

$$RMSE=\sqrt{\frac{(y_1-y'_1)^2+(y_2-y'_2)^2+\cdots+(y_n-y'_n)^2}{n}} \tag{5}$$

Where, y represents the predicted value, and y' represents the actual (true) value.

4. Engineering Example

The N2202 working face at the engineering test site serves as the first mining face in the northern No. 2 mining district of a certain mine. The open-off cut of the working face is 280 m long, employing the top-coal caving mining method with an average daily raw coal output of 12,000 tons. The gas content is 15 m^3/t, classifying it as a high-production and high-gas working face. The "U+L" ventilation system is adopted, with the gas drainage roadway positioned outside the return airway and interconnected via cross-drifts. Ahead of the working face advancement, the cross-drifts are sealed, while those in the gob area behind are open, allowing air leakage from the working face to flow towards the cross-drifts behind and into the gas drainage roadway. Due to the high gas content and production rate of the working face, coupled with the use of the top-coal caving mining method, the upper corner of the working face may still experience excessive gas concentrations despite the assistance of a dedicated gas drainage roadway, necessitating enhanced gas management in the upper corner.

A total of 300 gas concentration data points from the upper corner during the morning shift were selected, as illustrated in Figure 1. The trend prediction was conducted using the gas concentration chaos prediction model constructed in this paper, with the C-C method employed to simultaneously determine the time delay τ and embedding dimension m. According to chaos theory, the relationships between the chaotic system parameters ΔS and S_{cor} and time are shown in Figure 2. The time delay τ was identified as t=4, corresponding to the first minimum

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of ΔS, while the time window t_w was determined as t=7, corresponding to the minimum of Scor. Consequently, the embedding dimension m was calculated to be 3. Using the small data volume method, the maximum Lyapunov exponent λ of the gas concentration time series was found to be 0.068 > 0, indicating the chaotic nature of the time series and the feasibility of using this model for prediction, with a single prediction step count of *MaxStep*=15. In the phase space with a time delay τ=4 and embedding dimension m=3, the model parameters were determined as a=1.2217 and b=-1.0447.

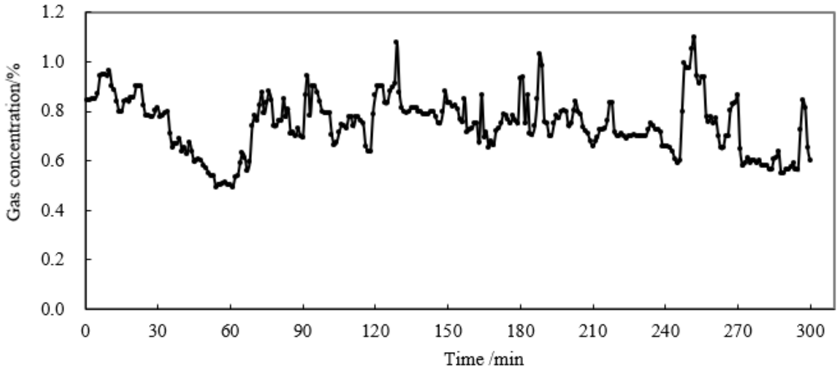

Figure 1 Gas concentration in the upper corner of the N2202 working face

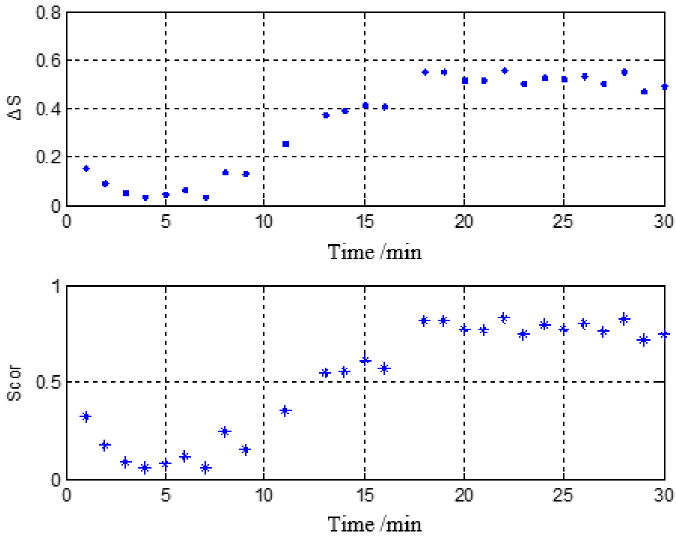

Figure 2 Determination of time delay and embedding dimension using the C-C method

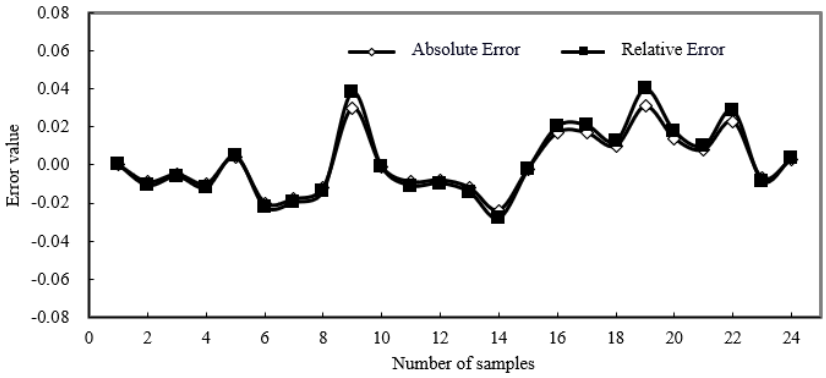

Figure 3 Prediction error

Due to inherent limitations in both the prediction model and sensor measurements, there exists a certain degree of error between the model's predicted values and the sensor's measured values. The absolute error, relative error, and root mean square error (RMSE) for this trend prediction of gas concentration in the upper corner were calculated, as depicted in Figure 3.

The absolute error ranges from [-0.024, 0.031], the relative error spans from [-2.82%, 3.99%], and the RMSE is 0.0149. These results indicate a strong agreement between the predicted values and the sensor-measured values, meeting the precision requirements for engineering applications.

5. Conclusion

(1) The gas concentration in the upper corner is influenced by multiple factors, including gas occurrence and migration patterns, the dynamic characteristics of the ventilation system, the disturbance effects of mining techniques, and the level of production management and control. The N2202 working face features a high gas content in the coal seam and high production rates, utilizing the top-coal caving mining method. Despite the assistance of a dedicated gas drainage roadway, excessive gas concentrations may still occur in the upper corner of the working face.

(2) A gas concentration prediction model for the upper corner was established based on chaos theory, and short-term predictions of gas concentration trends in the upper corner of the N2202 working face were conducted. The prediction results showed an absolute error range of [-0.024, 0.031], a relative error range of [-2.82%, 3.99%], and an RMSE of 0.0149, indicating a good agreement between the predicted results and actual conditions.

(3) Given the presence of noise in the gas concentration time series, future efforts should focus on incorporating denoising capabilities into the gas concentration prediction model for the upper corner to enhance the accuracy and duration of gas concentration trend predictions.

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References

[1] GUO Fei. Mechanism and Control Technology of Gas Overlimit at Upper Corner of Fully Mechanized Mining Face in Low Gas Mine[J]. Modern Mining, 2024, 40(10): 207-209+213.

[2] WANG Weiwei, MA Qiang. Cause Analysis and Prevention of Gas Concentration Overlimit at Upper Corner of Fully Mechanized Mining Face[J]. Inner Mongolia Coal Economy, 2019, (03): 110+160.

[3] LI Hangzhou, WANG Fei, LIU Hongwei, et al. Research on the Influence of Air Curtain on Gob Air Leakage and Gas Accumulation at Upper Corner[J]. Mining Research and Development, 2024, 44(10): 167-173.

[4] CUI Cong. Discussion on Prevention Methods for Gas Overlimit at Upper Corner of Mining Face[J]. China Coal, 2022, 48(04): 48-53.

[5] ZHU Xianwei, CAI Hongliang, ZHANG Xiaolei, et al. Research on Prevention Technology of Gas Accumulation at Upper Corner of Fully Mechanized Mining Face[J]. Coal Technology, 2014, 33(11): 15-17.

[6] LYU Pin, MA Yunge, ZHOU Xinquan. Research and Application of Dynamic Prediction Model for Gas Concentration at Upper Corner[J]. Journal of China Coal Society, 2006, (04): 461-465.

[7] CHEN Shuai. Study on Gas Emission Concentration Prediction at Upper Corner of Mining Face in Cuntao Coal Mine[J]. Shaanxi Coal, 2019, 38(02): 21-24.

[8] LIANG Yunpei, LI Shang, LI Quangui, et al. Gas Concentration Prediction at Upper Corner of Coal Mining Face Based on FEDformer-LGBM-AT Architecture[J]. Journal of China Coal Society, 2025, 50(01): 360-378.