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Construction and Application of the Evaluation System for Achieving Standards in Coal Mine Gas Drainage

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Abstract: In view of the characteristics of Yanghe Coal Industry's "three-soft" thick coal seam, low permeability, complex geological structure, and high outburst risk, a gas extraction compliance evaluation system integrating extraction parameter monitoring, extraction law analysis, intelligent drilling design, online effect evaluation, and comprehensive compliance assessment has been constructed. This system forms a full-process closed-loop management and control model encompassing "design - monitoring - analysis - evaluation - assessment". The research results indicate that the prediction error for the total drilling footage of gas extraction in the 31111 working face is 7.65%, and the prediction error for the drilling footage per ton of coal is 4.6%. The system enables online evaluation of the gas extraction effect in the 31111 working face, displaying the extraction rate, residual gas content, and compliance status of each section in real time. It provides technical support and engineering demonstration for the intelligent management and control of gas extraction compliance in outburst mines.

Keywords: Gas extraction, Compliance evaluation, Intelligent analysis, Outburst mine, Three-soft coal seam.

1. Introduction

China's coal resources are characterized by complex geological conditions, and a high proportion of coal and gas outburst mines. Gas disasters remain the primary factor restricting the safe and efficient production of coal mines [1]. Gas extraction is the core method for gas control in outburst mines, and achieving compliance in gas extraction is the fundamental guarantee for implementing the gas control policy of "extraction before construction, extraction before driving, and extraction before mining" and preventing outburst accidents [2-3]. The "Interim Provisions on Compliance of Coal Mine Gas Extraction" explicitly requires that outburst mines must achieve compliance in coal seam gas extraction and establish a compliance evaluation system for gas extraction. However, due to limitations in coal seam geological conditions, extraction techniques, monitoring methods, and management models, most mines still face issues such as discontinuous monitoring of extraction parameters, a lack of in-depth understanding of extraction laws, inaccurate evaluation of extraction effects, and untimely evaluation of extraction compliance, which seriously affect the effectiveness of gas control and the coordination between mining and tunneling operations.

Yanghe Coal Industry is affiliated with Zhengzhou Coal Industry (Group) Co., Ltd. The mine field is located in the Xinmi Coalfield in Henan Province. The main minable coal seam, Coal Seam II_1, is a typical "three-soft" unstable thick coal seam, with a thickness ranging from 0 to 25.86 m and an average of 5.83 m. The coal seam dip angle ranges from 5° to 24°, with a low permeability coefficient. The geological structure is well-developed, with locally high gas content and gas pressure. The absolute gas emission rate of the mine reaches 31.12 m^3/min, classifying it as a coal and gas outburst mine. The mine has long employed multiple extraction methods, including cross-seam boreholes, in-seam boreholes, and high-level drilling sites. However, traditional extraction management primarily relies on manual monitoring, empirical design, and post-event evaluation, leading to three prominent issues: First, extraction parameters depend on regular manual inspections, resulting in delayed and discontinuous data that cannot reflect dynamic changes in extraction. Second, the design of extraction boreholes does not incorporate regional gas geological conditions and extraction laws for differentiated layouts, leading to both wasted engineering efforts and the presence of extraction blank zones. Third, the evaluation of extraction compliance relies on manual data aggregation and on-site sampling tests, which are time-consuming, inefficient, and susceptible to human interference, making it difficult to meet the requirements of intelligent mine construction and safe production.

In recent years, with the development of intelligent coal mining and big data technologies, the transition of gas extraction management and control towards informatization, intelligence, and refinement has become an inevitable trend [4-6]. Scholars both domestically and internationally have conducted extensive research on gas extraction parameter monitoring, extraction law prediction, and extraction effect evaluation, developing technical equipment such as extraction pipeline network monitoring devices, extraction radius investigation equipment, and extraction effect evaluation software. However, there has been relatively little research on integrated extraction compliance evaluation systems specifically tailored for "three-soft" thick coal seams and structurally complex mines. Moreover, most existing research focuses on single functions and has not achieved full-process closed-loop management and control encompassing extraction design, monitoring, analysis, evaluation, and compliance assessment. Based on this, this paper takes Yanghe Coal Industry as the engineering background to construct a gas extraction compliance evaluation system, enabling intelligent management and control of the entire gas extraction process and automatic evaluation of extraction compliance. This aims to address the challenges of refined management and precise determination of extraction compliance in outburst mines, providing a reference for mines with similar conditions.

2. Gas Extraction Conditions and Technical Challenges in the Mine

2.1. Mine Geology and Gas Occurrence Characteristics

The mine field of Yanghe Coal Industry is located at the axial part of the middle section of the Xinmi Synclinorium, generally exhibiting a monoclinic structure. It is characterized by the development of secondary folds such as the Xinmi Complex Syncline and the Shuicheyuan Anticline, as well as 116 faults. Slide structures are well-developed, resulting in complex geological conditions. Coal Seam II_1 is the main minable coal seam, classified as a "three-soft" coal seam with soft coal, weak roof and floor rock properties, poor permeability, and difficulties in gas migration, which easily leads to the formation of gas-rich zones.

Through laboratory parameter measurements and on-site investigations, the primary controlling factors for gas occurrence in the coal seam were determined to be coal seam thickness, burial depth, and elevation. Prediction models for gas content and gas pressure were established as follows:

$$W=0.698D+0.083H+0.085h-14 \quad (1)$$

$$P=0.0433D+0.005H+0.0047h-0.97 \quad (2)$$

Where: W is the gas content in m^3/t; P is the gas pressure in MPa; D is the coal seam thickness in m; H is the burial depth in m; and h is the elevation in m.

The original gas content of the coal seam ranges from 3.66 to 5.60 m^3/t, with residual gas content ranging from 3.96 to 5.24 m^3/t. The coal seam permeability coefficient ranges from 0.02221 to 0.29130 $m^2/(MPa^2 \cdot d)$, classifying it as a low-permeability coal seam, which poses significant challenges for gas extraction.

2.2. Current Status of the Mine's Gas Extraction System

The mine employs a combined gas extraction mode utilizing both surface pump stations and underground fixed pump stations. Gas extraction systems are installed separately in Mining Areas 31, 32 and 42, with extraction methods including pre-extraction through cross-seam boreholes, pre-extraction through in-seam boreholes, extraction from high-level drilling sites, and extraction via buried pipes in the upper corner. The primary extraction equipment consists of 2BE series water ring vacuum pumps, with one in operation and one as a standby, ensuring stable extraction negative pressure.

Under the traditional gas extraction management model, borehole design determines hole spacing, depth, and layout based on experience, without incorporating differentiated designs based on regional gas content and permeability. Gas extraction parameters (flow rate, concentration, negative pressure, temperature) are manually inspected and recorded, with long intervals between data collections, making it impossible to reflect the extraction status in real time. The evaluation of extraction effects primarily relies on periodic sampling to test gas content, without achieving dynamic tracking. The assessment of extraction compliance requires manually organizing data from borehole construction, extraction measurement, and gas content testing, resulting in a cumbersome process with a long cycle time, making it difficult to achieve process-oriented management and control.

3. Construction of the Gas Extraction Compliance Evaluation System

The gas extraction compliance evaluation system serves as the core subsystem of the hidden danger investigation, management, and early warning system for coal and gas outburst disasters at Yanghe Coal Industry. Following the principles of "data-driven, model-supported, intelligent analysis, and closed-loop control," it adopts a five-layer architecture consisting of the "perception layer-transmission layer-data layer-model layer-application layer" to achieve intelligent management and control throughout the entire gas extraction process. This system primarily comprises five functional modules: real-time monitoring of extraction parameters, intelligent analysis of extraction patterns, intelligent design of extraction boreholes, online evaluation of extraction effects, and automatic assessment of extraction compliance, meeting the demands for on-site extraction management and control.

(1) Real-time monitoring module for extraction parameters

By installing GD4 gas drainage parameter monitoring sensors and WGC-II gas drainage pipeline gas parameter measuring instruments on the main, branch, and sub-branch extraction pipes, parameters such as extraction flow rate, gas concentration, negative pressure, and temperature are monitored in real time. Data is collected at a frequency of once per minute and automatically stored in a database. The system supports historical data queries, trend curve plotting, and abnormal data alarms. When sudden changes in extraction concentration or flow rate occur, it immediately triggers audible and visual alarms and SMS notifications to remind management personnel to investigate and address faults.

(2) Intelligent analysis module for gas extraction patterns

Based on on-site measured extraction data, a nonlinear fitting method is employed to establish a functional relationship between the pure gas flow rate per kilometer of borehole and extraction time, accurately fitting the extraction attenuation pattern. The system automatically analyzes differences in extraction patterns across different regions, drilling sites, and time periods, determining the corresponding relationship between extraction radius and extraction time, providing a basis for the design of extraction boreholes and the determination of extraction duration. Taking the 31111 working face as an example, after 180 days of extraction, the extraction volume per meter of borehole within the control range reached 3.25 m^3, and the gas content decreased by 0.27 m^3/t.

(3) Intelligent design module for extraction boreholes

By integrating gas geological data, coal seam occurrence data, and extraction pattern data, intelligent design functions for in-seam and cross-seam boreholes are developed, supporting two design modes: fixed number of boreholes and fixed borehole spacing. This enables automatic calculation of borehole parameters, automatic generation of trajectories, and automatic drawing of construction diagrams. The design process is as follows: ① Import the mining engineering plan and gas geological map of the working face. ② Set parameters such as control range, extraction radius, borehole spacing, and drilling height. ③ The system uses a trial-and-error approximation method to optimize borehole layout, ensuring full coverage, no blank zones, and minimal engineering volume. ④ Automatically output parameters such as borehole azimuth, inclination, depth, and drilling

coordinates, generating plan, profile, and three-dimensional diagrams.

For regions such as structural belts and thick coal seams, the system automatically increases borehole density, and for thin coal seams and low gas zones, it appropriately reduces the number of boreholes, achieving differentiated design.

(4) Online evaluation module for extraction effects

Based on extraction monitoring data, borehole construction data, and gas geological data, indicators such as extraction rate, total extraction volume, residual gas content, and extraction compliance time are calculated in real time. The extraction effects in different regions are visually displayed in the form of cloud maps, automatically identifying weak extraction areas and blank zones. Evaluation indicators include: ① Extraction rate: the ratio of actual extraction volume to theoretical extractable volume. ② Residual gas content: the measured value of gas content in the coal seam after extraction. ③ Extraction compliance radius: the effective influence radius that meets extraction standards. ④ Extraction uniformity: the degree of variation in extraction effects across regions.

The system supports multi-dimensional evaluation by working face, drilling site, and section, dynamically updating evaluation results to achieve full-process tracking of extraction effects.

(5) Comprehensive assessment module for extraction compliance

In accordance with the "Interim Provisions on Compliance of Coal Mine Gas Extraction," a multi-indicator integrated extraction compliance assessment model is established, comprehensively considering indicators such as extraction rate, residual gas content, gas pressure, extraction uniformity, and implementation of measures to achieve automatic determination of extraction compliance.

The assessment process is as follows: ① The system automatically collects data on borehole construction, extraction measurement, gas content testing, and ventilation parameters. ② It verifies each item against assessment standards. ③ It automatically generates an extraction compliance assessment report, marking compliant and non-compliant areas. ④ For non-compliant areas, it automatically prompts for additional borehole drilling or extended extraction time, forming a closed-loop control mechanism.

Assessment criteria: Residual gas content $\leq$ 8 m³/t, gas pressure $\leq$ 0.74 MPa, extraction rate meeting mine regulations, no extraction blank zones, are deemed as compliant extraction.

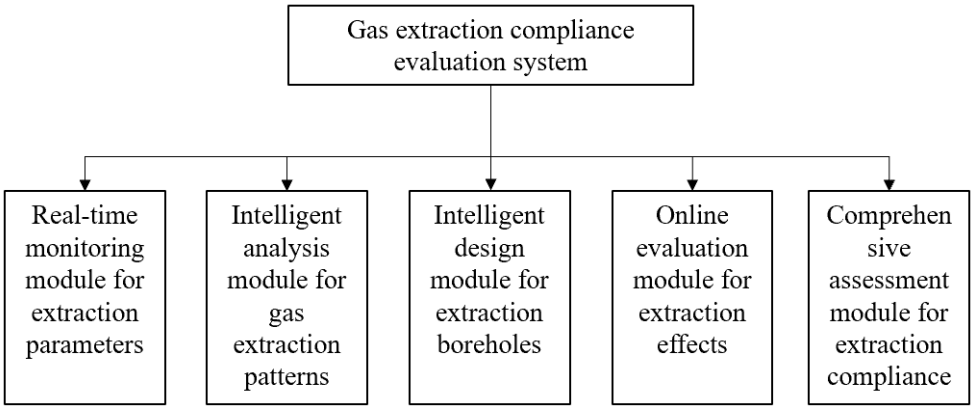

Figure 1. Construction of the gas extraction compliance evaluation system

4. Industrial Application of the System

4.1. System Deployment and Implementation

The system has been comprehensively applied in Mining Area 31 of Yanghe Coal Industry, with a particular focus on Working Faces 31111, 31091, and 31151. Working Face 31111 is located on the eastern wing of Mining Area 31, with a strike length of 1,600 m, an inclination length of 139 m, a coal seam thickness ranging from 2.0 to 16.0 m (averaging 7.52 m), and a gas content ranging from 3.9 to 6.33 m³/t. It employs a combined control method of pre-extraction through cross-seam boreholes and extraction through in-seam boreholes, serving as a typical application working face for the system. The specific deployment and implementation are as follows:

(1) Hardware deployment: Ten sets of GD4 gas drainage parameter monitoring sensors and seven sets of WGC-II gas drainage pipeline gas parameter measuring instruments were installed at the extraction pump station, drilling sites, and pipelines in Mining Area 31. Additionally, DGC gas content measuring devices, deep-hole rapid sampling devices, and borehole trajectory monitoring equipment were installed to enable real-time collection of extraction and borehole parameters.

(2) Software deployment: The gas extraction compliance evaluation system software was installed on the mine early warning server, and a database was established. Initial data entry was completed for gas geological data, borehole construction data, and historical extraction data.

(3) Personnel training: Technical personnel from the ventilation district and extraction team were organized to undergo system operation training, enabling them to master functions such as data viewing, parameter setting, design generation, and evaluation and assessment, ensuring the normal operation of the system.

Trial run and optimization: The system underwent a three-month trial run, during which the fitting parameters for extraction patterns, the prediction model for extraction radius, and the compliance assessment thresholds were optimized to enhance the system's applicability and accuracy.

4.2. Analysis of Application Effects

(1) Accurate fitting of extraction patterns

The planned daily output for Working Face 31111 is 3,910 tons per day. With a reduction in gas content of 1 m³/t after extraction as the compliance criterion, and based on the extraction radius investigation conducted by Henan Polytechnic University as the extraction pattern, the total estimated drilling footage for the entire extraction process in Working Face 31111 is expected to be 230,711 m, with an estimated drilling footage per ton of coal of 0.0936 m.

However, when using the extraction pattern derived from fitting the extraction measurement data from the working face, the total estimated drilling footage is expected to be 213,186 m, with an estimated drilling footage per ton of coal of 0.0893 m. This indicates a prediction error of 7.65% for the total drilling footage and 4.6% for the drilling footage per ton of coal.

(2) Dynamic evaluation of extraction effects

The system enables online evaluation of the extraction effects in Working Face 31111, displaying the extraction rate, residual gas content, and compliance status for each section in real time. The non-compliant, observation-required, and compliant areas are distinguished using red, yellow, and green colors, respectively. During the extraction process, the system promptly identified two areas with weak extraction, prompting the drilling of additional boreholes to eliminate extraction hazards and ensure balanced extraction.

5. Conclusion

In response to the characteristics of Yanghe Coal Industry's "three-soft" (soft roof, soft coal, and soft floor) thick coal seam, low permeability, complex geological structure, and high outburst risk, a gas extraction compliance evaluation system has been constructed. This system integrates functions such as extraction parameter monitoring, extraction pattern analysis, intelligent borehole design, online effect evaluation, and comprehensive compliance assessment, forming a full-process closed-loop management and control model encompassing "design - monitoring - analysis - evaluation - assessment".

The prediction error for the total drilling footage in Working Face 31111 is 7.65%, and the prediction error for the drilling footage per ton of coal is 4.6%. The system enables online evaluation of the extraction effects in Working Face 31111, displaying the extraction rate, residual gas content, and compliance status for each section in real time. It effectively addresses challenges such as inadequate gas extraction, imprecise compliance assessment, and coarse management and control in "three-soft" thick coal seams, providing technical support and engineering demonstration for intelligent management and control of gas extraction compliance in outburst mines.

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