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Digital Standardized Evaluation Method for the Pre-extraction of Coal Seam Gas by Boreholes along the Seam

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Abstract

The standardized evaluation of gas extraction relies on the data of coal reserves, gas reserves, gas pre-extraction, gas emissions, and borehole arrangement. This evaluation involves various parameters and complex calculations, thereby posing a huge challenge to coal mines. A digital standardized evaluation method for the pre-extraction of coal seam gas by boreholes along the seam was proposed and implemented to improve the evaluation ability of gas pre-extraction effect. On the basis of analysis, the evaluation of the basic conditions of gas pre-extraction was designed to have eight questions, which could be accomplished one by one by submitting the answers and supporting documents. Data models were established as eight entities and their relationships by analyzing the correlation of coal seam, coal gas, working face, boreholes, supporting documents, gas pre-extraction, and gas emissions. Three important algorithms adopting an iterative approach were proposed: the division algorithm for evaluating units, the algorithm for evaluating the uniformity of boreholes, and the algorithm for calculating the residual gas content. Then, supporting software was developed for the proposed method. After the control range was set and the auxiliary parameters were input, the software could extract associated data automatically, complete the evaluation process, and present the final conclusion in graphical form. Results show that, the proposed method successfully completes the evaluation of eight basic conditions and achieves the division of evaluating units and the uniformity evaluation of boreholes. The difference coefficient of the pre-extraction time of each evaluating unit is less than 30%, and the spacing of boreholes is less than 0.707R. In the on-site experiment, the residual gas content, which was 3.03 cubic meters per ton and equal to the measured value of 3.02 cubic meters per ton was calculated and presented immediately. The experiment verifies the accuracy and effectiveness of the proposed method. This study simplifies the standardized evaluation of the gas pre-extraction by boreholes along the coal seam, improves the control ability of the process, and plays a supporting role in preventing and avoiding gas disasters.

Keywords: Coal and gas outburst, Gas explosion, Standardized evaluation, Digital technology, Software

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1. Introduction

The rapid development of the Chinese economy has resulted in the gradual depletion of shallow coal resources and the rapid extension of coal mining to deep areas. The increase in mining depth and mining intensity complicates the conditions of the coal seam and increases the gas pressure, gas content, geological stress, and geothermal temperature, thereby leading to the frequent occurrence of coal and rock disasters [1]. Coal and gas outbursts and gas explosions, which can easily cause major or extremely severe accidents, are the two most serious types of coal mine disasters; thus, they have received widespread attention from the Chinese government and many scholars worldwide [2].

A coal and gas outburst is a phenomenon in which a large amount of coal, rock, gas, and CO_2 are rapidly ejected from the coal and rock layers into the mining workspace at an extremely fast speed within seconds to minutes during underground coal mining. Gas explosion refers to a chemical explosion accident caused by the contact of methane with a fire source when it mixes with air and reaches the combustion limit under certain conditions. Methane is the main component of coal gas; thus, hundreds or tens of thousands of cubic meters of gas are released into the workspace when a coal and gas outburst accident occurs. This scenario not only causes suffocation but also easily leads to gas explosions.

Gas pre-extraction is the fundamental measure for preventing and controlling the disasters of coal and gas outbursts and gas explosions in underground coal mining [3]. The standardized evaluation of the gas pre-extraction is the key to evaluating whether the coal seam has low gas content and whether the mining activities are safe. However, the evaluation work poses a huge challenge for coal mining enterprises because it requires the integration of a large amount of basic data, borehole parameters, gas pre-extraction parameters, gas emission parameters, and supporting documents. Moreover, the calculations are complex, and the workload is enormous. Many coal mining enterprises have to ask for the help of third-party organizations. Before the mining activity, each working face is generally evaluated only once to save costs. This approach is highly unfavorable for the process tracking of gas pre-extraction and lays the hidden dangers for the occurrence of gas disasters [4, 5]. The rapid development of digital technology and intelligent equipment gradually increases the amount of data generated during the process of gas pre-extraction and further increases the difficulty and complexity

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of the standardized evaluation for this process. How to leverage the advantages of digital technology and how to utilize various data fully to achieve the dynamic real-time evaluation of the gas extraction effect have become prevalent and urgent problems to be solved.

In this study, the pre-extraction of the coal seam gas by boreholes along the seam is taken as the research object. Moreover, a set of digital standardized evaluation methods is designed and implemented. This set includes the evaluation of basic conditions and three algorithms for the division of evaluating units, the uniformity of borehole distribution, and the calculation of the residual gas content. The method integrates various process data, such as the basic data of the working face, parameters of control range, and parameters of gas extraction and emission. It also achieves automatic calculation and graphic presentation through computer software technology. This study is useful for improving the dynamic evaluation ability of gas pre-extraction effect and in providing digital technical support for the prevention and control of gas disasters in coal mines.

2. State of the art

Scholars have conducted extensive studies on gas pre-extraction methods, evaluation methods of the effect of gas pre-extraction, and digital support. In terms of gas pre-extraction methods, Sanmiquel-Pera et al. [6] analyzed some gas explosion accidents by using the Spanish Research Institute method and the Feyer and Williamson method. They believed that insufficient gas emissions and safety training were the main causes of accidents and that improving the ability to evaluate the effect of gas emissions helps reduce the occurrence of accidents. However, they did not conduct a detailed analysis of the evaluation method. Slastunov et al. [7] studied how to use the hydraulic fracturing method to improve the effect of gas extraction. They also conducted experiments on the 2458, 2459, 2460, and 2460 working faces of the Kirova coal mine in Russia. Their study demonstrated that the hydraulic fracturing method can considerably improve the effect of gas extraction. However, the analyses on whether the extraction meets the standards and whether the subsequent mining activities can be carried out are insufficient. Liu et al. [8] established a three-dimensional gas–solid coupling model of the coal seam based on the assumption of fractured porous media. They analyzed the changes in the extraction radius during the gas pre-extraction by drilling along the coal seam, thereby providing support for designing boreholes. The results showed that the evaluation of the borehole uniformity is improved but not the evaluation of the gas pre-extraction effect. Berghe et al. [9] used the simulation techniques of molecular dynamics to investigate the effects of CO_2 and H_2O on the diffusion behavior of shale gas in the narrow slit-shaped nanopores of calcite [104]. They found that methane gas has the fastest flow rate, followed by ethane, whereas CO_2 and H_2O remain almost stationary. This finding theoretically supports the technology of using water as a water-based fracturing fluid for the displacement. It can also provide important references for the microscopic study of the mechanism of gas extraction. However, the researchers did not track and analyze the effect of gas extraction.

In terms of evaluating gas pre-extraction effect, Kazanin et al. [10] focused on the long-wall mining of the Kuznetsk Basin V. D. Yalevsky coal mine in Russia and found that the related gas emissions significantly increase when the mining production increases. The methods of gas control such as natural emission and gas extraction must be adopted to ensure the safety of coal mining; otherwise, production must be limited. They also analyzed the evaluation of the gas extraction effect, but the related algorithm is not described. Lin et al. [11] established a fluid–solid coupling model for the coal body containing gas to calculate the position of boreholes along the coal seam accurately. They also used the COMSOL Multiphysics software to simulate the influence of the geological and engineering factors on the effect of gas extraction. The effect of gas extraction was improved by optimizing parameters such as the borehole diameter, the spacing between boreholes, and the negative pressure. The achievements have a reference value for evaluating the uniformity of boreholes. However, they have little reference value for the evaluation of the extraction effect. Bressan et al. [12] analyzed the substitution of coal resources by investigating the coal gas in Australia and its impacts on the landscape of the Tangs agricultural production area in western Queensland. The results demonstrated the importance of gas as a clean energy source for sustainable social development. However, the authors mainly evaluated the ground landscape and did not analyze the methods of gas extraction and evaluation. Zhou et al. [13] used the method of numerical simulation by the COMSOL Multiphysics software and field experiments in the goaf of the 42201 working face of the Buertai coal mine to optimize the spacing parameters of insertion tubes and the negative pressure of extraction pipeline and improve the effect of gas extraction significantly. However, discussions on how to track the process of gas extraction dynamically and how to evaluate its effect are relatively few.

In terms of digital support, Kaledina et al. [14] developed an indicator system that determines the risk dynamics in an automatic mode based on the comprehensive analysis of various factors of the gas hazard. The digitization level of the gas emission and extraction is improved, and the status of the emission and extraction can be tracked. However, the system cannot standardize the evaluation, and the related discussions are few. In response to the difficulty of identifying abnormal conditions in the extraction of coal mine gas, Wu et al. [4] designed and implemented a cross-platform software for gas extraction. This software realizes functions such as collection of multisource data, analysis of extraction data, maintenance and management of the extraction equipment, and the fusion control of gas extraction. A warning or a push text message to the related managers is promptly issued when the abnormal condition occurs. The study effectively improved the management and control of the gas extraction process, but it did not form a comprehensive conclusion on the effect of gas extraction. Regarding the problems of invisibility and difficulty in detecting the blank zones in underground activities, Zhu et al. [5] proposed a three-dimensional simulation technique for extracting boreholes. This technique can display the drilling location and control range by importing the drawing of mining engineering and drilling data. The study provides a technical method of identifying blank zones and can effectively support the uniformity evaluation of boreholes. However, it cannot support the evaluation of gas extraction. Zou et al. [15] developed an online dynamic evaluation system for gas extraction based on the monitoring of a gas pipeline network. However, their data and parameters for calculation mainly come from the KJ90X system, a popular gas monitoring system of coal mines. Moreover, little consideration is given to the uniformity of borehole distribution. Álvarez-Fernández et al. [16] designed a PYROC device that uses pyrolysis to produce CO_2 instead of the traditional explosives for coal fracturing, thereby increasing the permeability of gas release while reducing operational risks, accelerating the discharge rate of gas extraction, and improving the efficiency of gas extraction. However, analysis of the residual gas content is lacking. Hua et al. [17] designed and implemented an app for gas extraction based on the COMSOL software by using coal parameters and gas parameters to simulate the attenuation law of gas flow rate. The app has a low error and supports the data analysis of gas extraction. However, the evaluation algorithms were not studied further. Sidorenko et al. [18] designed a gas detection system by using an Arduino Uno circuit board and an MQ-4 methane sensor. This system can dynamically detect the changes in the gas concentration in an unattended environment and provide data support for optimizing ventilation systems. The results are helpful for tracking and monitoring the process of gas extraction. However, the effect of gas extraction and the calculation of residual gas content were scarcely discussed.

The above analyses have studied the gas pre-extraction methods, the evaluation method of gas pre-extraction effect, and the digital support from different perspectives. They provide some support for the technology of gas pre-extraction and the work of standardized evaluation. However, some evident shortcomings can be found. First, the above methods only analyze the mechanism and the technology of gas extraction from a micro or macro perspective. However, their support for the extraction still needs to be improved further. Second, many scholars have conducted studies on digital systems for the evaluation of gas extraction, thereby providing some support for the tracking of gas extraction, the optimization of ventilation systems, the presentation of virtual scenes, and the uniformity analysis of boreholes. However, few studies treated the standardized evaluation as an independent issue, and the comprehensiveness and completeness are insufficient. The integration of standardized evaluation methods with engineering applications still needs to be strengthened. In response to these shortcomings, this study systematically analyzes the evaluation of the effect of gas pre-extraction by boreholes along the coal seam and regards it as a complete engineering process. The process includes five parts: the management of basic parameters, the evaluation of basic conditions, the division of evaluating units, the uniformity evaluation of boreholes, and the evaluation of gas pre-extraction effect. Digital technology is used to solve a series of application problems, such as large data volume, redundant storage, complex calculation, and difficult evaluation, thereby improving the real-time and dynamic performance of the standardized evaluation for gas pre-extraction.

The remaining part of this study is organized as follows. The section III briefly describes the theoretical model for evaluating the effect of gas pre-extraction by boreholes along the seam. Then, the functions, data models, and evaluation algorithms required for the model are analyzed and designed. The section IV presents the experiments conducted on the evaluation on site and verifies the correctness of the results through data comparison and analysis. The final section summarizes this study and provides conclusions.

3. Methodology

3.1 Evaluation method for the pre-extraction of coal seam gas by drilling along the seam

The pre-extraction of coal seam gas through boreholes along the seam is a commonly used method for regional gas pre-extraction. Given the large exposed area of the coal wall, this method, which has been widely used in China, has the advantages of easy drilling, low cost, high efficiency, and good effect. In this method, boreholes can be constructed synchronously with the excavation of the coal roadway in the working face. The boreholes are along the coal seam and can be constructed from the haulage way, airway, or crosscut to the coal body. The spacing between boreholes should not exceed 0.707 times the extraction radius ($0.707R$) to ensure the effect of gas pre-extraction. Moreover, the length of boreholes should cover the entire working face without creating blank zones. If the coal seam is thick, 2–3 rows of boreholes can be arranged to shorten the pre-extraction time and improve the effect of extraction. A certain number of oblique bedding boreholes can also be supplemented, as shown in Fig.1.

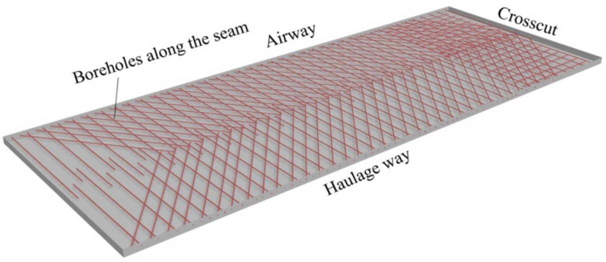


Fig. 1. Schematic of boreholes along the coal seam

The standardized evaluation of the effect of gas pre-extraction is based on the theory of gas flow, and numerical calculation methods are used to judge the residual gas content or pressure of the coal seam. The following four steps are included in engineering applications:

(1) Evaluation of basic conditions

The evaluation of basic conditions generally involves a qualitative assessment by multiple experts. It contains eight parts: the system of gas extraction, engineering plans, implementation plans, construction processes, evaluation methods, management rules, measurement methods, and testing conditions. Experts need to draw a conclusion based on the information on the on-site situation and related supporting documents. When the conclusion is not passed, the subsequent evaluation work cannot continue, and corresponding improvement measures must be implemented until the evaluation is passed.

(2) Division of evaluating units

According to the effective control range and the difference coefficient of the pre-extraction time of boreholes along the seam, the coal seam within the control range is divided into one or several evaluating units. The difference coefficient of pre-extraction time is the ratio of the difference between the longest and the shortest pre-extraction days to the longest day. It is calculated according to Equation (1).

$$\eta = \frac{T_{\max} - T_{\min}}{T_{\max}} \times 100\% \tag{1}$$

where η is the difference coefficient of pre-extraction time, $\%$; $T_{\max}$ is the longest pre-extraction days, d ; $T_{\min}$ is the shortest pre-extraction days, d .

(3) Uniformity evaluation of boreholes

Each evaluating unit is looped through, and the spacing between every two boreholes is analyzed to ensure that it is less than $0.707R$, where R is the extraction radius, m . When the spacing is greater than the critical value, a blank zone appears, and the evaluation does not pass.

(4) Evaluation of residual gas content

Based on the data of gas extraction and ventilation emission, the residual gas content is calculated, and it should meet the specified standards. The residual gas content is the gas content after a certain number of pre-extraction days and is calculated according to Equation (2).

$$W_{CY}=\frac{W_0G-Q}{G} \tag{2}$$

where W_{CY} is the residual gas content, m^3/t ; W_0 is the original gas content, m^3/t ; Q is the total amount of gas extracted from the evaluating unit, m^3 ; G is the coal reserves of the evaluating unit, t , which is calculated according to Equation (3).

$$G=(L-H_1-H_2+2R)(l-h_1-h_2+R)m\gamma \tag{3}$$

where L is the length of the evaluating unit along strike direction, m ; l is the length of the evaluating unit along dip direction, m ; H_1 and H_2 are the equivalent widths of gas pre-discharge for both ends of the roadway in the strike direction, m , and take a value of zero when there no roadway exists; h_1 and h_2 are the equivalent widths of gas pre-discharge for both ends of the roadway in the dip direction, m , and take a value of zero when no roadway exists; R is the extraction radius, m ; m is the average value of the coal seam thickness, m ; γ is the bulk density of the coal, t/m^3 .

H_1 , H_2 , h_1 and h_2 are usually determined by the actual measurement. When these parameters are difficult to obtain, they can also be determined by Table 1.

Table 1. Equivalent width of gas pre-discharge of the roadway

Exposure time (d)	Equivalent width of gas pre-discharge of coal types (m)		
	Anthracite	**Lean coal and coking coal**	**Fat coal, gas coal, and long-flame coal**
25	6.5	9.0	11.5
50	7.4	10.5	13.0
100	9.0	12.4	16.0
160	10.5	14.2	18.0
200	11.0	15.4	19.7
250	12.0	16.9	21.5
≥300	13.0	18.0	23.0

The equivalent width of low metamorphic coal can also be calculated by $0.808\times0.55t$, and the equivalent width of high metamorphic coal can also be calculated by $(13.85\times0.0183t)/(1+0.0183t)$, where t is the exposure time, d .

In summary, the standardized evaluation method for the pre-extraction of coal seam gas by boreholes along the seam can be described as the logical process shown in Fig.2.

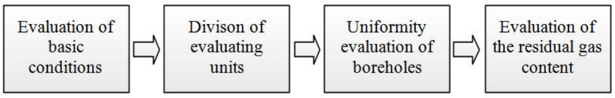


Fig. 2. Logical process of the standardized evaluation method

3.2 Functional analysis of the evaluation software

Managing a set of basic data, including coal seam parameters, working face parameters, and original gas parameters, is necessary to conduct the evaluation. The construction parameters of boreholes should be saved and maintained during the drilling construction process. After the completion of drilling, the boreholes are immediately sealed and connected to the extraction pipeline. Then, a series of parameters is recorded for the gas extraction. The related data on gas emissions should also be recorded. These data are related to the location of sensors and are usually recorded once per work shift.

According to the previous analysis, the software must have some core functions, including the evaluation of basic conditions, the division of evaluating units, the uniformity evaluation of boreholes, and the evaluation of residual gas content.

A graphical module was designed to enhance the display. This module was driven by data and shows the working face synchronously. When the difference coefficient of pre-extraction time was calculated, gradient colors were used to represent it. The shorter the time is, the darker the color is; the longer the time is, the brighter the color is.

The design of functional use cases is shown in Fig.3.

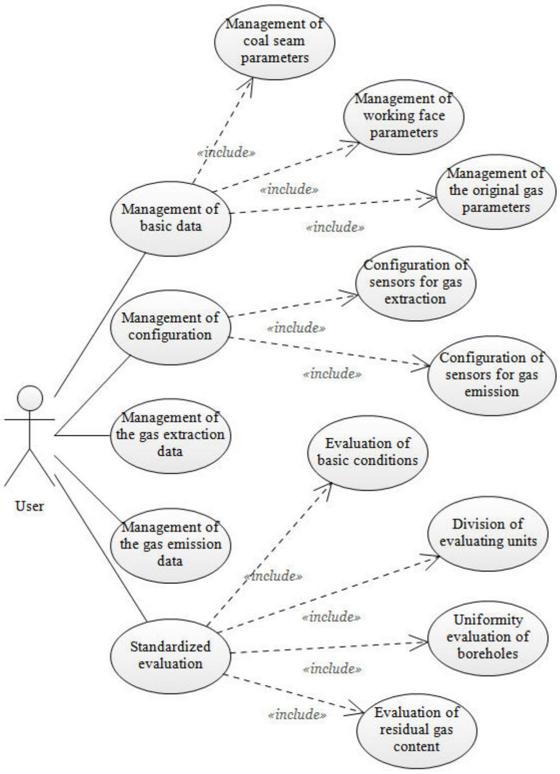


Fig. 3. Design of functional use cases

3.3 Analysis of data models

The basic data mainly include coal seam parameters, working face parameters, and original gas parameters. Coal seam parameters include ID, name, average thickness, dip angle, and bulk density. The working face parameters include ID, name, mine type, strike length, dip length, and coal reserves. The original gas parameters include the nondesorbable gas content, original gas content, original gas pressure, original gas reserves, and extraction radius.

The ID of the working face is selected as the primary key to simplify the data model, and the three parts are merged. Then, the E-R(Entity-Relation) diagram is designed, as shown in Fig.4.

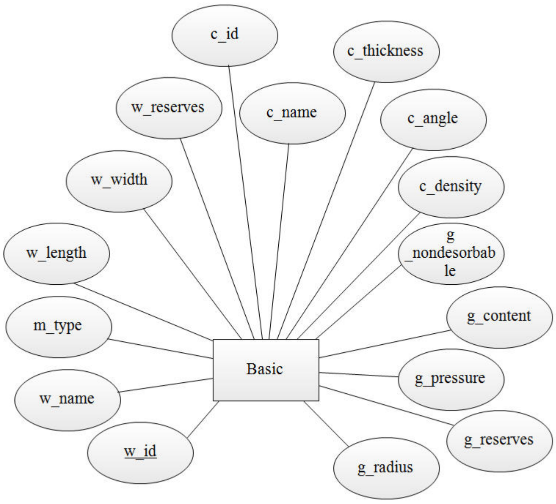


Fig. 4. E-R diagram of basic data

Furthermore, the relationship model of Basic can be described as follows:

- Basic (w_id, w_name, m_type, w_length, w_width, w_reserves, c_id, c_name, c_thickness, c_angle, c_density, g_nondesorbable, g_content, g_pressure, g_reserves, g_radius)

Similarly, the other data models, including sensor configuration, borehole construction, gas extraction, gas emission, evaluation of basic conditions, supporting documents, and evaluating units, can be designed. The primary key is marked by the underline, and the foreign key is marked in bold, as follows:

- Sensor (id, type, location)
- Borehole (**w_id**, roadway, id, open, height, azimuth, inclination, diameter, length, **u_id**)
- Extraction (**w_id**, id, **s_id**, date, shift, time, orifice, CH4, temperature, pressure, mixed, purity)
- Emission (**w_id**, id, **s_id**, date, shift, time, CH4, CO2, mixed, purity)
- Evaluation (**w_id**, id, content)
- Document (**w_id**, id, sn, name, type, size, path)
- Unit (**w_id**, id, begin, end, uniformity, coefficient, residual)

In the data models, the Basic entity is the starting point. It stores the primitive data that are widely referenced by other models. The Sensor entity stores the location data indicating where the sensors are installed. It is associated with different roadways to monitor ventilation, flow rate, gas concentration, and other data. The Borehole entity stores the construction parameters of boreholes. Given that multiple boreholes are constructed in one working face, the relationship between Basic and Borehole is 1:n. The entities of Extraction and Emission store the parameters of gas extraction and emission by work shift. Thus, they are associated with Basic and Sensor through a 1:n relationship. The Basic entity stores eight items for the evaluation of basic conditions, and their supporting documents are stored in the Document entity. Thus, their relationship is 1:n, and the relationship between Basic and Evaluation is 1:n. The Unit entity is the key to the storage of evaluating data. It saves calculated results such as the uniformity conclusion of borehole distribution, the difference coefficient of pre-extraction time, and residual gas content. Given the possibility of multiple evaluations for each working face and multiple evaluation units, a 1:n correlation exists between Basic and Unit.

Therefore, the data models and their relationship are designed, as shown in Fig.5.

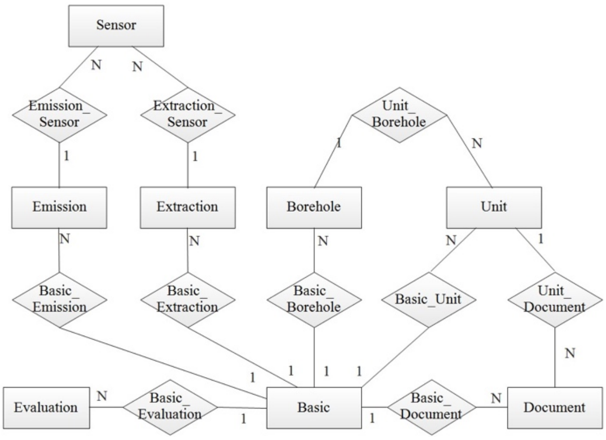


Fig. 5. E-R diagram

3.4 Algorithm design

Evaluation modules include four steps in sequence, namely, "evaluation of basic conditions," "division of evaluating units," "uniformity evaluation of boreholes," and "evaluation of residual gas content." Evaluation modules must obtain data from other modules, which are "basic data," "sensor configuration," "parameters of gas extraction," and "parameters of gas emission," and generate the conclusion, as shown in Fig.6.

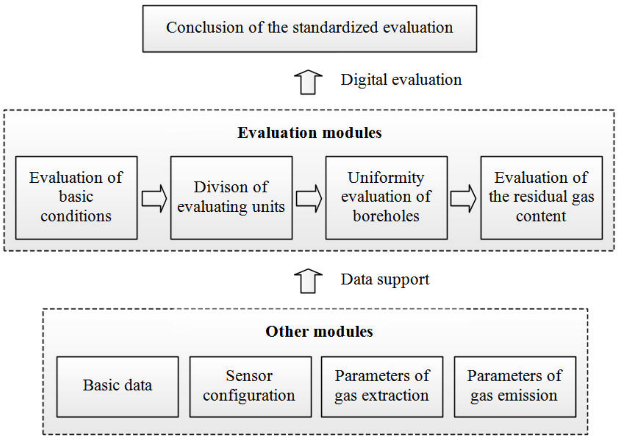


Fig.6. Standardized evaluation process

3.4.1 Evaluation of basic conditions

The evaluation of basic conditions is qualitative, which is generally concluded by the reviews of multiple experts. This evaluation contains eight items according to the requirements of the "Provisional Regulations on Coal Mine

Gas Extraction Standards" of China. Describing these items and providing the supporting documents are necessary. The eight items are as follows:

(1) Has the system of gas extraction been established as required, and is it operating normally and continuously? The supporting documents include "Design of the Gas Extraction System" and "Acceptance of the Gas Extraction System."

(2) Does the plan of gas extraction exist as required? The supporting documents include "Gas Extraction Standard," "Gas Extraction Volume," "Gas Extraction Equipment and Facilities," "Funding Plan," "Production Plan," and "Replacement of the Mining Face."

(3) Does the solution of gas extraction exist? The supporting documents include "Solution of the Gas Extraction" and "Design of the Construction of Gas Extraction."

(4) Do the data of completion and acceptance for the projects of gas extraction exist, and are the data authentic? The supporting documents include "Completion Drawing of the Projects of Gas Extraction" and "Parameters of the Projects of Gas Extraction."

(5) Have the self-evaluation standards and the management rules of gas extraction been established to meet relevant standards? The supporting documents include "Self-evaluation Standards of Gas Extraction" and "Management Rules of Gas Extraction."

(6) Does the capacity of the pump station for gas extraction, the capacity of the backup pump, and the capacity of the pipeline network meet the requirements? The supporting documents include "Information of the Pump Station of Gas Extraction" and "Calculation of the Pipeline Capacity."

(7) Have sufficient measurement points been arranged in the system of gas extraction? Do the measuring instruments comply with relevant standards, and can they be regularly inspected to ensure accuracy? The supporting documents include "Measuring Instruments" and "Measuring Points."

(8) Do the relevant conditions for gas testing meet the standards? The supporting documents include "Conditions for Gas Pressure Testing" and "Conditions for Gas Content Testing."

The other steps can continue only after passing the evaluation of basic conditions. Otherwise, relevant measures must be taken to rectify until the evaluation is passed.

3.4.2 Division algorithm for evaluating units

According to the standards, the difference coefficient of gas pre-extraction of each evaluation unit cannot exceed 30%. After the necessary parameters are input, the algorithm analyzes the difference coefficient for all boreholes. When it is not more than 30%, the boreholes are divided into one evaluating unit. Otherwise, they are divided into multiple evaluating units with 30% as the boundary, as the following description:

(1) Setting the control range, auxiliary parameters, and basic parameters

In the vector diagram, the left button of the mouse is dragged to delineate the control range of the coal seam to be evaluated in the working face. At the same time, auxiliary parameters, including deadline, coal quality, daily production, and the exposure time of the roadway, are input to calculate the equivalent width of gas predischarge.

Some other necessary parameters, including the nondesorbable gas content, extraction radius, coal bulk density, average thickness of the coal seam, original gas content, strike length, and dip length of the working face, do not need input and can be extracted from the basic data.

(2) Looping through all the boreholes along the seam to generate evaluating units

The boreholes along the seam are usually constructed from the haulage way, airway, or crosscut toward the coal body. Therefore, the boreholes are traversed along the strike direction of the working face.

Step 1) Initialize the loop variable $i=1$, $j=1$ and initialize the threshold of the difference coefficient of pre-extraction time $\theta=30\%$;

Step 2) Initialize the evaluating unit E_i, and set its difference coefficient of pre-extraction time $\eta_i=0\%$;

Step 3) Add the first borehole d_j into E_i, and set it as the beginning boundary;

Step 4) Try to add the subsequent borehole d_{j+1} into E_i, and then try to calculate the difference coefficient of pre-extraction time as $\eta_i^{'}$;

Step 5) When $\eta_i^{'}\le\theta$, complete the addition of borehole d_{j+1} into E_i, and update η_i as $\eta_i^{'}$;

Step 6) When $\eta_i^{'}>\theta$, set $i=i+1$, and jump to **Step 2)**;

Step 7) When d_{j+1} is not the last borehole, set $j=j+1$, and jump to **Step 4)**;

Step 8) When d_{j+1} is the last borehole, output the evaluating units $E_i(i=1,2,3,...)$, and go to the end.

The division algorithm for evaluating units is summarized, as shown in Fig.7.

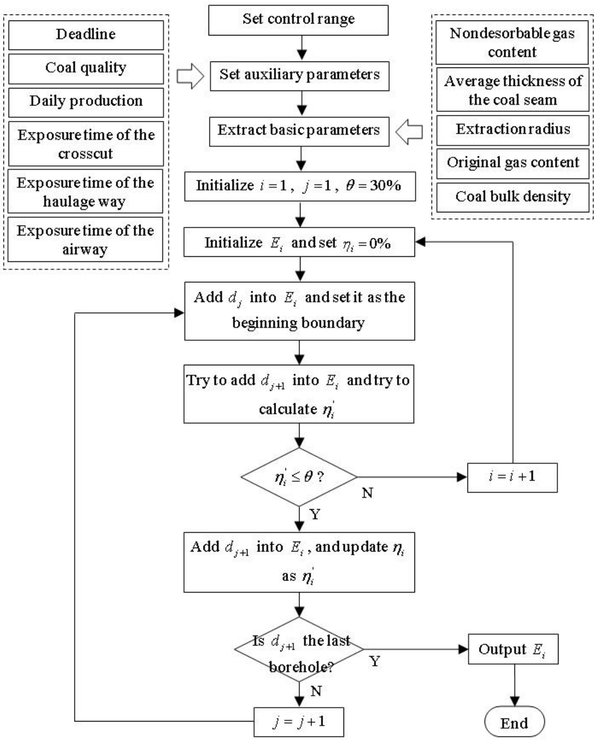


Fig.7. Division algorithm for evaluating units

3.4.3 Algorithm for evaluating the uniformity of boreholes

All evaluating units $E_i(i=1,2,3,...)$ are looped through in sequence; for each one, the following steps are executed:

Step 1) Extract the extraction radius R from basic data;

Step 2) Extract the set of all boreholes $D=\{d_i\}$ within E_i, where $i=m,m+1,...,n$, m is the ID of the first borehole within E_i, and n is the ID of the last borehole within E_i;
Step 3) Initialize the set of blank zones $Q=\{\}$;
Step 4) Initialize the loop variable $i=m$;
Step 5) When $d_i \neq n$, go to **Step 6)**; otherwise, jump to **Step 8)**;
Step 6) When the distance between d_i and d_{i+1} is greater than $0.707R$, add d_i into Q, set $i=i+1$, and jump to **Step 5)**;
Step 7) When the distance between d_i and d_{i+1} is less than or equal to $0.707R$, set $i=i+1$, and jump to **Step 5)**;
Step 8) Output the set of boreholes Q as the blank zones, and go to end.

The algorithm for evaluating the uniformity of boreholes is summarized, as shown in Fig.8.

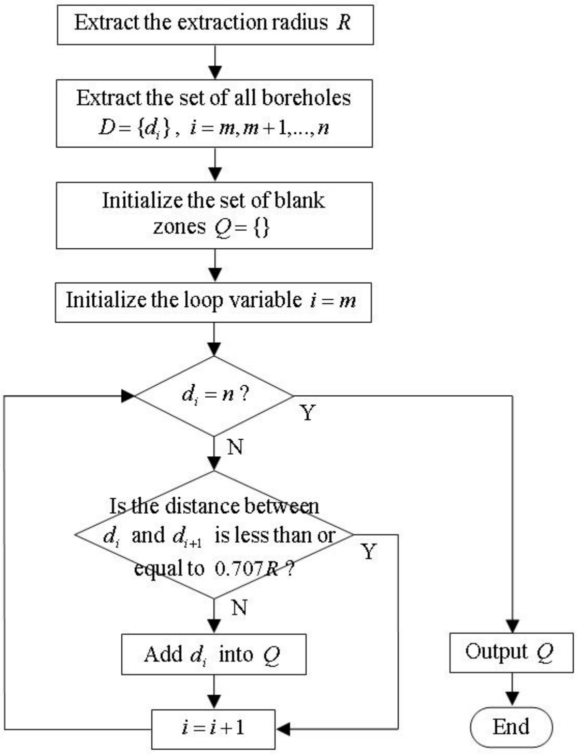


Fig. 8. Algorithm for evaluating the uniformity of boreholes

3.4.4 Algorithm for calculating the residual gas content

All evaluating units $E_i(i=1,2,3,...)$ are looped through in sequence; for each one, the following steps are executed:
Step 1) Calculate the total amount of the extraction gas and the emission gas of E_i;
Step 2) Extract the basic data, and calculate the coal reserves of E_i;
Step 3) Extract the basic data and the original gas content of E_i;
Step 4) Calculate the residual gas content of E_i, and then go to end.

The algorithm for calculating the residual gas content is summarized, as shown in Fig.9.

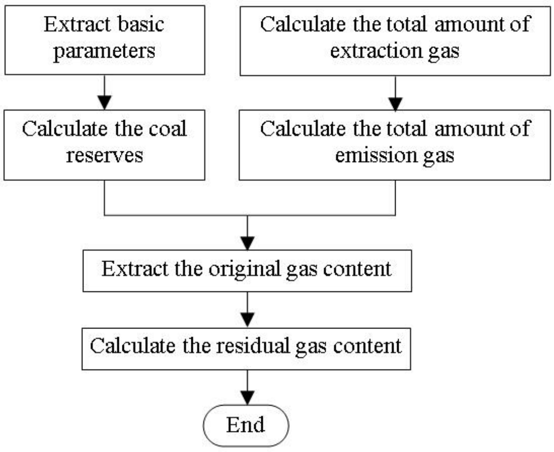


Fig. 9. Algorithm for calculating the residual gas content

4. Result Analysis and Discussion

4.1 Experimental area

The Qianhe coal mine in Gaoping City, Shanxi Province, China, has a production capacity of 1.2 million tons per year when mining the 3# coal seam. It has the maximum absolute gas emission of $23.10m^3/\min$ and the maximum relative gas emission of $9.15m^3/t$. The 3103 working face is arranged in the first mining area of the 3# coal seam and has an elevation of $+787m-+803m$ and a burial depth of $137-153m$. The 3# coal seam is anthracite. It has good coal quality and an average thickness of $5.3m$. Its average inclination angle, roughly in a north-south direction, is 2.7 degrees, with the east being higher and the west being lower. Its strike length is $900m$, the dip length is $150m$, and the coal bulk density is $1.45t/m^3$.

The layout of the 3103 working face is U-shaped. The method of gas pre-extraction by boreholes along the seam is adopted to prevent gas disasters and reduce the gas content of the coal seam. The boreholes are vertically arranged on one side of the 3103 airway, with a diameter of $75mm$. The spacing between each other is $3m$. The opening position is $1.5m$ away from the roadway bottom, and the length is $150m$, as shown in Fig.10.

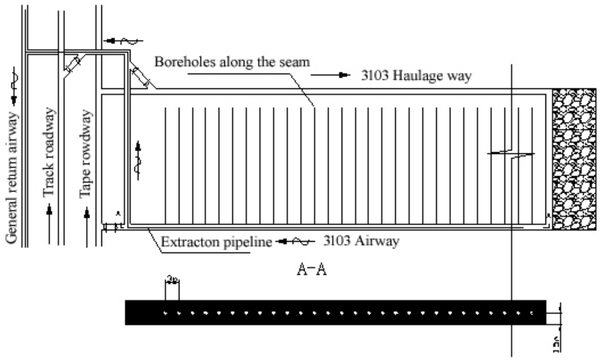


Fig. 10. Arrangement of boreholes along the seam in the 3103 working face

The area for the standardized evaluation of gas extraction is the $400m$ inner section, in which the coal reserve is $449819.66t$. The exposure time of the mind roadway and crosscut is approximately $152d$. Thus, the equivalent width of gas predischarge is $9m$, as shown in Fig.11.

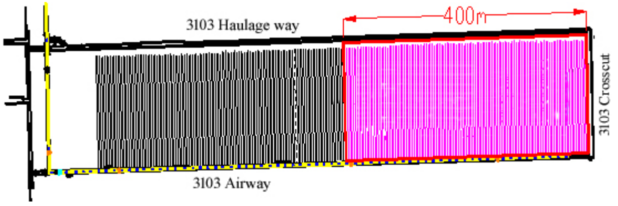


Fig. 11. Area for the standardized evaluation of gas extraction in the 3103 working face

4.2 Results of the standardized evaluation

The basic data of the 3103 working face were input into the software. These data include the type of coal mine, the name of the working face, strike length, dip length, average thickness of the coal seam, the name of the coal seam, the dip angle of the coal seam, the position of the working face, bulk density, nondesorbable gas content, original gas content, original gas pressure, and extraction radius. Then, the coal reserves were calculated automatically, as shown in Fig.12.

Type of coal mine	High Gas Mine	Bulk density (t/m3)	1.45
Name of working face	3103	Coal reserves (t)	1037475.00
Strike length (m)	900.0	Non-desorbable gas content (m3/t)	2.08
Dip length (m)	150.0	Gas content (m3/t)	4.10
Average thickness of coal seam (m)	5.30	Gas pressure (MPa)	0.14
Name of coal seam	3# Coal Seam	Extraction radius (m)	4.9
Dip angle (degree)	2.7	Original gas reserves (m3)	4253647.50
Position of working face	Left		

Fig. 12. Inputting the basic data

According to the design document, all boreholes were constructed and then connected to the extraction pipeline immediately. The parameters of gas extraction and emission were recorded and stored in the software. The daily average values of gas extraction and emission from the day beginning extraction to the deadline of evaluation are shown in Fig.13.

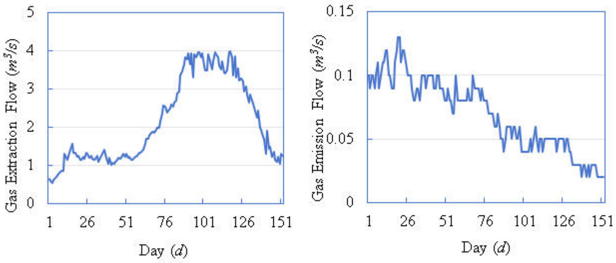
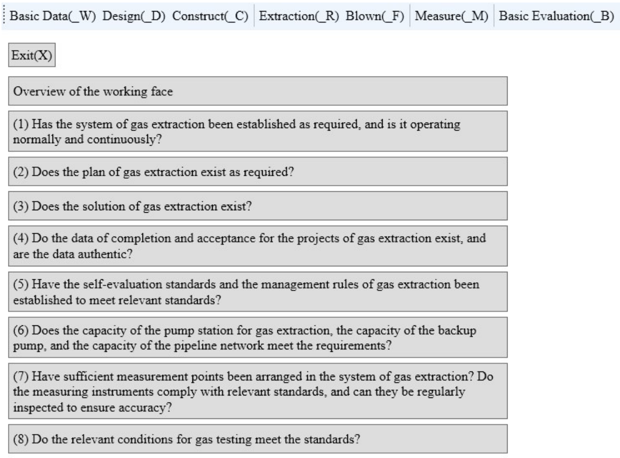


Fig. 13. Parameters of the gas extraction and emission

The evaluation of basic conditions is qualitative. In the software, it was accomplished by answering a series of designated questions and submitting corresponding supporting documents, as shown in Fig.14

The first item was taken as an example, namely, "Has the system of gas extraction been established as required, and is it operating normally and continuously?" The answer was provided in the box, and their two supporting documents were updated, as shown in Fig.15.



Overview of the working face

(1) Has the system of gas extraction been established as required, and is it operating normally and continuously?

(2) Does the plan of gas extraction exist as required?

(3) Does the solution of gas extraction exist?

(4) Do the data of completion and acceptance for the projects of gas extraction exist, and are the data authentic?

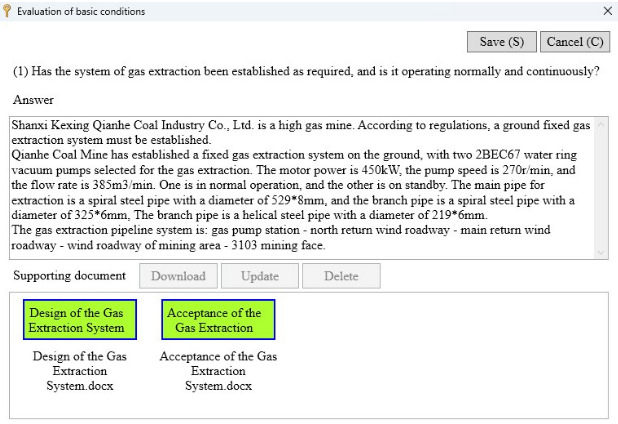
(5) Have the self-evaluation standards and the management rules of gas extraction been established to meet relevant standards?

(6) Does the capacity of the pump station for gas extraction, the capacity of the backup pump, and the capacity of the pipeline network meet the requirements?

(7) Have sufficient measurement points been arranged in the system of gas extraction? Do the measuring instruments comply with relevant standards, and can they be regularly inspected to ensure accuracy?

(8) Do the relevant conditions for gas testing meet the standards?

Fig.14. Main interface of the evaluation of basic conditions

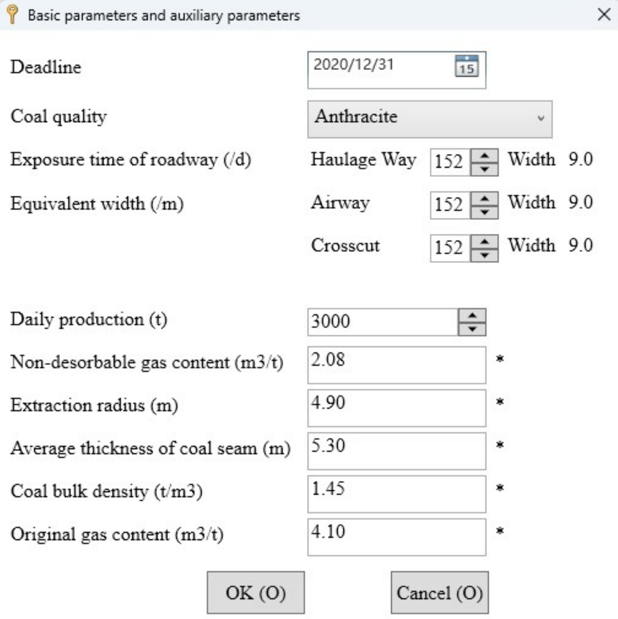


(1) Has the system of gas extraction been established as required, and is it operating normally and continuously?

Answer

Shanxi Kexing Qianhe Coal Industry Co., Ltd. is a high gas mine. According to regulations, a ground fixed gas extraction system must be established.
Qianhe Coal Mine has established a fixed gas extraction system on the ground, with two 2BEC67 water ring vacuum pumps selected for the gas extraction. The motor power is 450kW, the pump speed is 270r/min, and the flow rate is 385m3/min. One is in normal operation, and the other is on standby. The main pipe for extraction is a spiral steel pipe with a diameter of 529*8mm, and the branch pipe is a spiral steel pipe with a diameter of 325*6mm, The branch pipe is a helical steel pipe with a diameter of 219*6mm.
The gas extraction pipeline system is: gas pump station - north return wind roadway - main return wind roadway - wind roadway of mining area - 3103 mining face.

Fig. 15. An example of basic condition evaluation

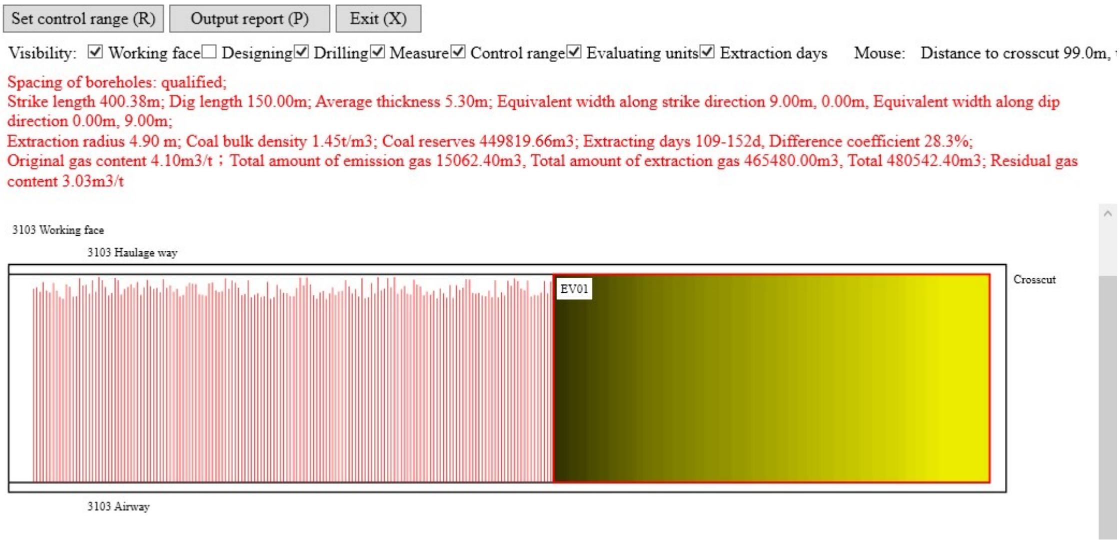


Deadline	2020/12/31		
Coal quality	Anthracite		
Exposure time of roadway (/d)	Haulage Way	152	Width 9.0
Equivalent width (/m)	Airway	152	Width 9.0
	Crosscut	152	Width 9.0
Daily production (t)	3000		
Non-desorbable gas content (m3/t)	2.08	*	
Extraction radius (m)	4.90	*	
Average thickness of coal seam (m)	5.30	*	
Coal bulk density (t/m3)	1.45	*	
Original gas content (m3/t)	4.10	*	

Fig.16. Extraction of basic parameters and input of auxiliary parameters

In the graphical display of the software, the 400 m inner range of the 3103 working face was selected through the left button of the mouse. Then, related basic parameters were extracted from the database, such as nondesorbable gas content, original gas content, extraction radius, and coal bulk density. Moreover, some auxiliary parameters, such as the deadline, coal quality, and daily production, were required, as shown in Fig.16.

After the extraction of basic parameters and the input of auxiliary parameters were completed, the software launched three algorithms in sequence, namely, the division algorithm for evaluating units, the evaluating algorithm for the uniformity of boreholes, and the calculating algorithm for the residual gas content. Finally, the results were presented in graphical form, as shown in Fig.17.



Spacing of boreholes: qualified;
Strike length 400.38m; Dig length 150.00m; Average thickness 5.30m; Equivalent width along strike direction 9.00m, 0.00m, Equivalent width along dip direction 0.00m, 9.00m;
Extraction radius 4.90 m; Coal bulk density 1.45t/m3; Coal reserves 449819.66m3; Extracting days 109-152d, Difference coefficient 28.3%;
Original gas content 4.10m3/t ; Total amount of emission gas 15062.40m3, Total amount of extraction gas 465480.00m3, Total 480542.40m3; Residual gas content 3.03m3/t

Fig.17. Display of the evaluation results

According to Figure 17, the results include the following:

(1) The coal body within the control range is divided into one evaluating unit and named "EV01."

(2) The strike length of "EV01" is $400.38m$, the dip length is $150.0m$, the thickness of the coal seam is $5.3m$, the equivalent width along strike direction is $(9m, 0m)$, the equivalent width along dip direction is $(0m, 9m)$, the extraction radius is $4.9m$, the coal bulk density is $1.45t/m^3$, and the coal reserves are $449819.66t$.

(3) The shortest days for gas pre-extraction of "EV01" are $109d$, and the longest days are $152d$, with a difference coefficient of 28.3%.

(4) The evaluation conclusion of the uniformity of boreholes is qualified.

(5) The evaluation conclusion of the residual gas content is as follows: the original gas content is $4.1m^3/\text{t}$, the total amount of emission gas is $15062.4m^3$, the total amount of extraction gas is $465480m^3$, and the residual gas content is $3.03m^3/t$.

4.3 Analysis of the results

(1) Analysis of the uniformity of drilling spacing

A total of 133 boreholes were constructed in the control range. The sequence of their spacing $\{\Delta d_i\}$ is shown in Fig.18.

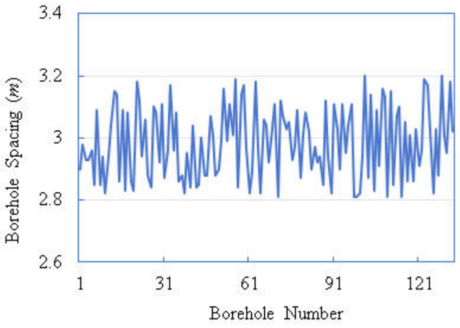


Fig.18. Spacing sequence of boreholes

The max spacing is $\max\{\Delta d_i\} = 3.2m$, and the extraction radius is $R = 4.9m$; thus,

$$\max\{\Delta d_i\} = 3.2m < 0.707R = 3.46m \tag{4}$$

Therefore, no blank zone exists, thereby meeting the requirement of uniformity. Moreover, the evaluation conclusion of the uniformity of boreholes is correct.

(2) Analysis of the difference coefficient of extraction days

The sequence of extraction days of boreholes $\{e_i\}(i = 1,2,...,133)$ is shown in Fig.19.

In Fig. 19, $\min\{e_i\} = 109d$, and $\max\{e_i\} = 152d$. Thus, the difference coefficient of extraction time is

$$\begin{aligned} \eta &= \frac{T_{\max} - T_{\min}}{T_{\max}} \times 100\% \\ &= \frac{\max\{e_i\} - \min\{e_i\}}{\max\{e_i\}} \times 100\% \\ &= 28.3\% < 30\% \end{aligned} \tag{5}$$

Therefore, the difference coefficient of extraction time is less than the required threshold of 30%, and the division of evaluating units is correct.

(3) Analysis of the residual gas content

In the evaluating unit "EV01", the strike length is $L = 400.38m$, the dip length is $l = 150m$, the equivalent width along the strike direction is $H_1 = 9m$, $H_2 = 0m$, the equivalent width along the dip direction is $h_1 = 0m$, $h_2 = 9.0m$, the extraction radius is $R = 4.9m$, the average thickness of coal seam is $m = 5.3m$, and the coal bulk density is $\gamma = 1.45t/m^3$. Thus, the coal reserves can be calculated as follows:

$$\begin{aligned} G &= (L - H_1 - H_2 + 2R)(l - h_1 - h_2 + R)m\gamma \\ &= 449819.66m \end{aligned} \tag{6}$$

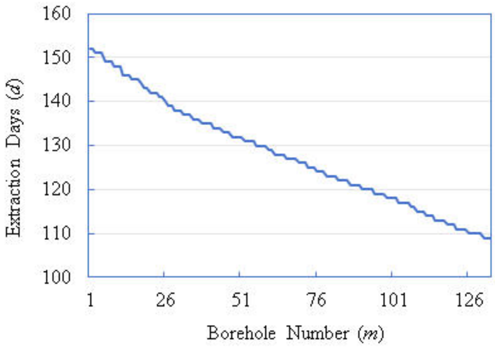


Fig. 19. Extraction day sequence of boreholes

The total amount of gas extraction is

$$Q_1 = \sum_{i=1}^{152} 1440 q_{1i} = 465480 m^3 \tag{7}$$

The total amount of gas emissions is

$$Q_2 = \sum_{i=1}^{152} 1440 q_{2i} = 15062.4 m^3 \tag{8}$$

The original gas content is $W_0 = 4.10 m^3/t$. Thus, the residual gas content can be calculated as

$$W_{CY} = \frac{W_0 G - Q_1 - Q_2}{G} = 3.03 m^3/t \tag{9}$$

Therefore, the evaluation conclusion for the residual gas content is correct.

Experts from the China University of Mining and Technology conducted on-site measurements of the residual gas content in the control range to verify the correctness of the evaluation conclusion. Their results are shown in Table 2.

Table 2. Measurements of the residual gas content in the 3103 working face

Location	**Desorbable gas content** (m^3/t)			**Nondesorbable gas content** (m^3/t)	**Gas content** (m^3/t)
3103 working face	Loss amount (m^3/t)	0.01	0.94	2.08	3.02
	Underground desorbable amount (m^3/t)	0.02			
	Degass amount before crushing (m^3/t)	0.28			
	Degass amount after crushing (m^3/t)	0.63			

The residual gas content obtained by the two methods is approximately equal, indicating that the evaluation conclusion of the residual gas content is accurate.

5. Conclusions

In response to the problems of large amounts of data, complex calculation, and poor real-time performance in the standardized evaluation for the pre-extraction of coal seam gas by boreholes along the seam, this study adopted a digital technology to design a series of algorithms, which are implemented in the software. The following conclusions can be drawn:

(1) The eight criteria for the evaluation of basic conditions are achieved by answering questions item by item and submitting supporting documents.

(2) The data models for the standardized evaluation are designed, including basic data, evaluation of basic conditions, supporting documents, sensors configuration, gas extraction, gas emission, boreholes, and evaluating units and their relationships.

(3) Three algorithms are designed and implemented, including the division algorithm for evaluating units, the algorithm for the uniformity evaluation of boreholes, and the algorithm for calculating the residual gas content.

(4) In the developed software, three algorithms are launched automatically one by one when the control range and related auxiliary parameters are input. Then, the evaluation conclusions are generated, in which the difference coefficient of pre-extraction time should be less than 30%, and the spacing between boreholes should be less than or equal to $0.707R$. The final results of the evaluation are presented in graphical form.

(5) The on-site experiment was conducted at the 3103 working face of the Qianhe coal mine in Gaoping City, Shanxi Province, China. The residual gas content obtained by the evaluation software is $3.03 m^3/t$, and the on-site measured data are $3.02 m^3/t$. Two results are approximately equal, verifying the accuracy of the digital standardized evaluation technology.

This study combined digital technology with the standardized evaluation method for the pre-extraction of coal seam gas by boreholes along the seam, and a series of data models and three important algorithms are designed. The algorithms were suitable for the on-site application and simplified the standardized evaluation process of gas extraction considerably. However, the generalization ability of this method remains insufficient and needs to be validated and optimized in other applications because of the limited number of experiments.

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