Studies on the Influencing Factors of Gas Emission in a Steeply Inclined and Ultrathick Coal Seam Working Face

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Cite This: ACS Omega 2022, 7, 38322−38336

ABSTRACT: To determine the factors affecting the gas emission in the working face during the horizontal sublevel mining of steeply inclined and ultrathick coal seams (SIUTCSs), the gas emission sources were identified and evaluated using the analytic hierarchy process (AHP), and the gas emission quantity was calculated using a prediction model. Sobol sensitivity analysis was then conducted on the influencing factors involved in the model to determine their influences on the working face gas emission. The AHP analysis found that the pressure relief area in the lower section is the main gas emission source of the working face, and the adjacent coal seams, old goaf, and rear goaf are not. The gas emission prediction model exhibits good accuracy. The calculation results suggest that the gas released from the lower section coal body accounts for 44.16−50.44% of the total gas emission quantity of the working face, and thus, it is the main gas emission source. The Sobol sensitivity analysis reveals that the dip angle of the coal seam has the greatest influence on the absolute gas emission quantity of the working face with a significantly larger sensitivity than those of other factors. The comprehensive sensitivity data analysis also suggests that the lower section coal body is the major contributor to the gas emission of the working face. Our work further puts forward a technical system of ultrahigh pressure hydraulic “drilling−slitting−pressing−draining” integrated antireflection enlarged gas extraction for controlling the gas emission from the coal body at the bottom of the SIUTCS. The engineering test demonstrates that this system can increase the permeability of the coal body and significantly improve the gas extraction efficiency of the coal body in the study area.

1. INTRODUCTION

Due to their special occurrence modes, the mining method and hazard characteristics of steeply inclined coal seams are different from those of horizontal coal seams. Horizontally sectioned, fully mechanized caving mining is the most widely used mining method of the steeply inclined and ultrathick coal seams (SIUTCSs) containing gas, yet the working face of the mine is often subject to the gas transfinite problem. Therefore, it is very important to determine and analyze the factors affecting the gas emission of the working face.

The gas emission of coal mining has been extensively studied. Hu et al. believed that the advance support pressure affected the coal seam gas emission by affecting the permeability coefficient of the coal seam. They reported that the permeability coefficient of the coal seam decreased, and thus, the gas emission decreased with the increase of the support pressure. The research results of Wang et al. showed that the instantaneous pressure generated by roof breaking was also a main factor causing abnormal gas emissions. Taking the working face in the Tashan Coal Mine as the research object, they further proposed the mechanism of the abnormal gas emissions caused by roof breaking. Whittles et al. analyzed the influences of geotechnical factors on the gas flow in the working face by numerical simulation, which provided a new method to identify the gas emission sources of the working face. Zhai et al. concluded by studying 153 coal and gas outburst accidents in which mining depth, coal seam thickness, and the lithologies of the roof and floor were the main factors affecting gas outburst. Ou et al. characterized the functional groups of coal samples by infrared spectroscopy and evaluated the effects of oxygen-containing functional groups on the gas emission of the coal seam. Jiang et al. studied the effects of faults on the pore structure of coal and its resultant change on the gas emission.

Many scholars also attempted to predict the gas emission quantity during mining by analyzing the corresponding influencing factors. Chen et al. constructed a dynamic gas...
emission prediction model by comprehensively considering the parameters affecting the gas emission quantity. Chen et al.\textsuperscript{12} established a gas emission zone on the basis of the evolution law of stress and permeability and obtained a gas emission prediction model by the numerical simulation and field measurement of the gas emission zone. The accuracy of the prediction model was verified with a relative error of 1.3\textendash1.6\%.

Wang et al.\textsuperscript{13} analyzed the gas flow of the fallen coals and coal wall using the sphere diffusion equation of the coal particle gas and radial unsteady flow equations of the coal seam gas and established a dynamic prediction model of gas emission including key factors. Their research results are of great significance in practical gas prevention and control of the tunneling working face. Zhao et al.\textsuperscript{14} developed a coal and gas outburst prediction model from the perspective of coal and gas outburst. Wang et al.\textsuperscript{15} proposed a gray Markov prediction model on the basis of the gray system theory and Markov chain theory to predict the gas emission quantity in mines and verified the model using the historical data. For the steeply inclined coal seams, Huang et al.\textsuperscript{16} developed a different-source gas emission prediction model that exhibited good accuracies in practical applications. Wang et al.\textsuperscript{17} reviewed the prediction methods of coal seam gas emission in China and expounded the development direction of gas emission prediction models in the future.

Although the gas emission influencing factors and the gas emission quantity prediction of the coal mine working face have been extensively studied and great progresses have been made,\textsuperscript{18\textendash20} the gas emission in SIUTCSs has rarely been involved. In general, SIUTCSs are mined by horizontally sectioned, fully mechanized caving, which usually causes different gas emission modes compared to those in horizontal and slightly inclined coal seams. Because the gas emission sources of the SIUTCSs are unclear and the study on the gas emission control measures remains underdeveloped, their mining usually causes gas transfinite on the working face. Therefore, the determination of the gas emission sources and the influencing factors during the horizontally sectioned, fully mechanized caving mining is critical for the safe mining of steeply inclined coal seams (Figure 1).

**Figure 1.** Gas emission problems in the mining of steeply inclined coal seams.

**Figure 2.** Occurrence conditions of a steeply inclined coal seam.
In the present study, the gas emission sources of the fully mechanized, horizontal sublevel mining of SIUTCSs were analyzed and each source was evaluated by the analytic hierarchy process (AHP) for its contribution to the gas emission quantity of the working face. A gas emission quantity prediction model of the horizontally sectioned, fully mechanized caving face in SIUTCSs was used to predict the gas emission quantity of the working face at the horizontal level of +575 m in the 45# coal seam of the Wudong Coal Mine, and the accuracy of the prediction model was verified. The sensitivity of each influencing factor in the prediction model was examined by Sobol sensitivity analysis to understand its influence on the gas emission quantity of the working face.

2. GAS EMISSION SOURCES OF THE HORIZONTAL SUBLEVEL CAVING FACE IN SIUTCSs

2.1. Horizontally Sectioned Fully Mechanized Caving Mining of SIUTCSs. Steeply inclined coal seam refers to a coal seam with a dip angle greater than 45°. Because the occurrence conditions of steeply inclined coal seam are quite different from those of horizontal and slightly inclined coal seams, their mining methods are also different from each other. Figure 2 shows the occurrence conditions of a typical, steeply inclined coal seam. Many mining methods have been developed for steeply inclined coal seams, such as horizontal sublevel fully mechanized

Figure 3. Schematic diagram for the horizontally sectioned, fully mechanized top coal caving mining of the SIUTCSs.

Figure 4. Schematic diagram for the gas emission sources of the horizontally sectioned, fully mechanized caving mining of the steeply inclined coal seam.
caving, stepped coal mining, flexible shielding support mining, roadway mining with sublevel caving, fully mechanized caving, and so on. Horizontally sectioned, fully mechanized top coal caving is usually adopted for the mining of SIUTCSs. Figure 3 shows the sectional diagram of the roadway design for mining. Briefly, the coal seam is subdivided into the horizontal sections of 20–30 m in the vertical direction. On the same elevations, the airways and roadways are constructed along the roof and floor of the section, respectively. Blastholes are drilled at the ends of the two roadways in the strike direction for the fully mechanized top coal caving. The mining height is 3.5–4.5 m, and the maximum top coal caving height is 15–20 m. To improve the unit yield of the working face and reduce the excavation rate per 10,000 tons, the horizontal section height tends to increase, and the coal recovery rate can reach up to 80–85%.

### 2.2. Gas Emission Sources of the Working Face in SIUTCSs

Due to the technical characteristics of the horizontally sectioned, fully mechanized caving mining, large amounts of gas can be released into the working face of a SIUTCS containing gas from many sources. As shown in Figure 4, the coal body is continuously slit by the fully mechanized mining machine and falls on the transport belt below. The gas carried in the mined coal body is desorbed and emitted to the working face. The top coal is broken by loosening the blasting and transported out of the working face by the scraper conveyor. The gas desorbed from this part of the coal during the mining will also be emitted to the working face.

With the advancement of the working face, the stress distribution balance of the original rock in the coal seam is broken, and three stress areas are formed in front of the working face, e.g., pressure relief area, stress concentration area, and in situ stress area. The gas in the pressure relief area in front of the working face migrates via the pores and fissures in the coal body into the working face. Meanwhile, three stress areas including the pressure relief area, stress concentration area, and in situ stress area are also formed in the lower coal seam as shown in Figure 5. The goafs generate additional stress on the coal seam and surrounding rocks. When the additional stress becomes larger than the yield strength limit of the coal seam, the coal seam may be deformed and damaged. The gas in the lower coal seam then emits into the work surface.

Some residual top coals after the caving may fall together with the overlying rock on the upper of the working face, forming an upper old goaf. There is a small amount of gas in the fallen coal as well as in the upper old goaf, which is emitted into the working face. There are also some residual coals in the rear goaf, and the gas carried by the residual coals will also be released into the working face. The gas in the coal body under the goaf will also migrate into the goaf and eventually reach the working face. In addition, the gas in the adjacent coal seams can also migrate into the working face, which should also be taken into consideration.

To sum up, there are seven gas emission sources in the horizontally sectioned, fully mechanized caving face in the SIUTCS:

1. Gas emission from the pressure relief area in front of the working face
2. Gas emission from the fallen coals
3. Gas emission from the top coal
4. Gas emission from the pressure relief area
5. Gas emission from the lower coal seam
6. Gas emission from the old goaf
7. Gas emission from the adjacent coal seams

### 3. Qualitative Evaluation of Gas Emission Sources of the Working Face by AHP

#### 3.1. Principle of AHP

AHP first classifies the elements related to the decision problem into several layers, such as the...
Table 1. Nine Importance Levels and Their Assigned Values out of a 1/9 Scale Model

| factor i over factor j | quantitative values |
|------------------------|---------------------|
| as important           | 1                   |
| a little important     | 3                   |
| more important         | 5                   |
| highly important       | 7                   |
| extremely important    | 9                   |
| the intermediate value of two adjacent judgments | 2, 4, 6, 8 |

Table 2. Pairwise Comparison of $A_1$

| $A_1$ | $v_1$ | $v_2$ | $v_3$ | $v_4$ | $v_5$ | $v_6$ | $v_7$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| $v_1$ | 1     | 1/5   | 1/5   | 1/7   | 1/7   | 1/7   | 1/9   |
| $v_2$ | 1     | 1/3   | 1/3   | 1/7   | 1/7   | 1/7   |       |
| $v_3$ | 5/3   | 1     | 1     | 1/7   | 1/7   | 1/7   |       |
| $v_4$ | 5     | 3     | 1     | 1     | 1/5   | 1/5   | 1/7   |
| $v_5$ | 7     | 7/5   | 7     | 5     | 1     | 1/3   | 1/3   |
| $v_6$ | 7     | 7     | 7     | 5     | 1     | 1/3   | 1/3   |
| $v_7$ | 7     | 7     | 7     | 3     | 3     | 3     | 3     |

Table 3. Pairwise Comparison of $A_2$

| $A_2$ | $v_1$ | $v_2$ | $v_3$ | $v_4$ | $v_5$ | $v_6$ | $v_7$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| $v_1$ | 1/5   | 1/3   | 1/2   | 1/8   | 1/7   | 1/9   |       |
| $v_2$ | 5     | 1     | 2     | 3     | 1/5   | 1/2   | 1/4   |
| $v_3$ | 1      | 2/3   | 2/3   | 2/3   | 1/7   | 1/6   | 1/8   |
| $v_4$ | 5/3    | 2/3   | 2/3   | 2/3   | 1/7   | 1/6   | 1/8   |
| $v_5$ | 7     | 7     | 7     | 5     | 1     | 3     | 1/2   |
| $v_6$ | 7     | 2     | 3     | 6     | 1/3   | 1     | 1/3   |
| $v_7$ | 9     | 4     | 5     | 8     | 2     | 3     | 1     |

Table 4. Pairwise comparison of $A_3$

| $A_3$ | $v_1$ | $v_2$ | $v_3$ | $v_4$ | $v_5$ | $v_6$ | $v_7$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| $v_1$ | 1     | 4     | 2     | 1/5   | 1/6   | 1     | 1/5   |
| $v_2$ | 1/4   | 1     | 1     | 1/7   | 1/8   | 1/5   | 1/8   |
| $v_3$ | 1/2   | 1     | 1     | 1/6   | 1/7   | 1/2   | 1/7   |
| $v_4$ | 5     | 7     | 6     | 1     | 1/2   | 4     | 1/3   |
| $v_5$ | 6     | 8     | 7     | 2     | 1     | 5     | 1/2   |
| $v_6$ | 1     | 5     | 2     | 1/4   | 1/5   | 1     | 1/4   |
| $v_7$ | 5     | 8     | 7     | 3     | 2     | 4     | 1     |

Values are given in Table 1. The judgment matrix satisfies: $v_{ij} = 1/v_{ji}$.

The comparison needs to be conducted by professionals. In general, multiple professionals are invited and each gives a judgment matrix. The judgment results of the different professionals are integrated to improve the accuracy of the evaluation. In our work, the judgment matrices given by 4 researchers of our research group are adopted, and their comparison data tables are as shown in Tables 2–5.

The data in the comparison tables can be converted into the corresponding matrices. For example, Table 2 can be converted into matrix $A_1$.

$$
A_1 = \begin{bmatrix}
1 & 1/5 & 1/5 & 1/7 & 1/7 & 1/7 & 1/9 \\
1 & 1/3 & 1/3 & 1/7 & 1/7 & 1/7 & \\
1 & 1/2 & 1/2 & 1 & 1/7 & 1/6 & 1/8 \\
2 & 1/3 & 1/2 & 1 & 1/7 & 1/6 & 1/8 \\
1 & 1/2 & 1 & 1 & 1/7 & 1/7 & 1/7 \\
1 & 1 & 1/2 & 1/2 & 1 & 1/3 & 1/3 \\
1 & 1 & 1/2 & 1 & 1/3 & 1/3 & 1/3 \\
1 & 1/2 & 1/2 & 1/2 & 1/2 & 1/2 & 1/2 \\
1 & 1/3 & 1/3 & 1/3 & 1/3 & 1/3 & 1/3 \\
1 & 1/4 & 1/4 & 1/4 & 1/4 & 1/4 & 1/4 \\
1 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \\
1 & 1/7 & 1/7 & 1/7 & 1/7 & 1/7 & 1/7 \\
1 & 1/8 & 1/8 & 1/8 & 1/8 & 1/8 & 1/8 \\
1 & 1/9 & 1/9 & 1/9 & 1/9 & 1/9 & 1/9
\end{bmatrix}
$$

(1)

The weight vectors are calculated by the “normalization method”, and the judgment matrix $A_1$ is normalized by column into

$$
\begin{bmatrix}
0.0303 & 0.0345 & 0.0085 & 0.0102 & 0.0187 & 0.0288 & 0.0638 \\
0.0303 & 0.0345 & 0.0142 & 0.0171 & 0.0187 & 0.0288 & 0.0638 \\
0.1515 & 0.1034 & 0.0425 & 0.0512 & 0.0187 & 0.0288 & 0.0638 \\
0.1515 & 0.1034 & 0.0425 & 0.0512 & 0.0262 & 0.0403 & 0.0638 \\
0.2121 & 0.2414 & 0.2975 & 0.2560 & 0.1311 & 0.0672 & 0.1489 \\
0.2121 & 0.2414 & 0.2975 & 0.2560 & 0.3933 & 0.2015 & 0.1489 \\
0.2121 & 0.2414 & 0.2975 & 0.3584 & 0.3933 & 0.6046 & 0.4468
\end{bmatrix}
$$

(2)

The rows of the column-normalized matrix are averaged to obtain a weight matrix of the gas emission sources:

$$
W_l = \begin{bmatrix}
0.0278 \\
0.0296 \\
0.0657 \\
0.0684 \\
0.1934 \\
0.2501 \\
0.3649
\end{bmatrix}
$$

(3)

The weights of $v_1$–$v_7$ are determined to be 0.0278, 0.0296, 0.0657, 0.0684, 0.1934, 0.2501, and 0.3649, respectively. The maximum characteristic root ($\lambda_{max}$) is then obtained with eq 4.
Figure 8. Weights of the sources of the gas emission of the working face.

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} [AW_{i}] = \frac{1}{7} \begin{pmatrix} 1 & 0.1997 \\ 1 & 0.2176 \\ 1 & 0.4774 \\ 1 & 0.5027 \\ 1 & 1.6021 \\ 1 & 2.1556 \\ 1 & 3.0359 \end{pmatrix} = \begin{pmatrix} 0.0278 \\ 0.0296 \\ 0.0657 \\ 0.0684 \\ 1.6021 \\ 2.1556 \\ 3.0359 \end{pmatrix}
\]

(4)

where

\[
[AW_{i}] = \begin{pmatrix} 1 & 1/5 & 1/5 & 1/7 & 1/7 & 1/7 \\ 1 & 1/3 & 1/3 & 1/7 & 1/7 & 1/7 \\ 5 & 3 & 1 & 1/7 & 1/7 & 1/7 \\ 5 & 3 & 1 & 1/5 & 1/5 & 1/7 \\ 7 & 7 & 7 & 5 & 1 & 1/3 & 1/3 \\ 7 & 7 & 7 & 5 & 3 & 1 & 1/3 \\ 7 & 7 & 7 & 7 & 3 & 3 & 1 \end{pmatrix}
\]

(5)

The result is then examined by the consistency test, and the consistency index (CI) is calculated as

\[
\text{CI} = \frac{\lambda_{\text{max}} - n}{n - 1} = \frac{0.1279}{7} = 0.0969 < 0.1
\]

(7)

If \( n = 7 \), the random consistency index (RI) = 1.32 and the consistency ratio is

\[
\text{CRI} = \frac{\text{CI}}{\text{RI}} = \frac{0.1279}{1.32} = 0.0969 < 0.1
\]

(8)

The consistency ratio is less than 0.1, suggesting that the judgment matrix is acceptable, and the weights are valid.

The remaining three judgment matrices are processed by the same method. The weights of each factor in the matrices are obtained and examined by the consistency test. Figure 8 shows the weights of the 7 gas emission sources in the four matrices.

All evaluations given by the four researchers reveal that the gas emission of the pressure relief area in the lower coal seam occupies the largest weight, and thus, it is the main gas emission source of the working face. The evaluation results of No. 1 and No. 4 researchers suggest that the gas emission of the fallen coal is the second largest source, and those of No. 2 and No. 3 researchers show that the second largest source is from the gas...
emission from the pressure relief area in front of the working face. Yet, the evaluation results of all researchers are in good agreement that the gas emissions of the adjacent coal seam, old goaf, and rear goaf occupy relatively small weights, so they are not the main gas emission sources of the working face. All researchers, except for No. 3, agree that the gas emission of the top coal is not the main gas emission source of the working face.

4. SOBOL SENSITIVITY ANALYSIS OF GAS EMISSION INFLUENCING FACTORS

4.1. Gas Emission Prediction Model of a Horizontally Sectioned, Fully Mechanized Caving Face in SIUTCSs.

The gas emission quantity prediction methods of the coal mine working face can be roughly divided into the mine statistics method and the source-based prediction method, and the latter is the most widely used and effective method. For the source-based prediction, the gas emission sources are analyzed first, and the emission quantities of the sources are summed up to give the gas emission quantity of the working face. The relative gas emission quantity of the horizontally sectioned, fully mechanized caving face in the SIUTCS can be calculated with eq 9.

\[ q_j = q_1 + q_2 + q_3 + q_4 \]  

where \( q_1, q_2, q_3 \) and \( q_4 \) are the relative gas emission quantities of the working face, the horizontal section being mined, the adjacent coal seam, the pressure relief area in the lower coal seam, and the old goaf, respectively, in \( \text{m}^3/\text{t} \).

The relative gas emission quantity of the section being mined can be obtained using eq 10.

\[ q_j = K_i K_s \frac{m}{m_0} (X_{0i} - X_{IC}) \]  

where \( K_i \) is the gas discharge coefficient of the surrounding rock; \( K_s = 1.20 \) if the roof is managed by the full collapse method; \( K_s \) is the gas emission coefficient of waste coals on the working face, \( \text{m}^3/\text{t} \); \( X_{0i} \) is the gas content of the original lower coal seam, \( \text{m}^3/\text{t} \); \( X_{IC} \) is the gas content of the residual coal seam, \( \text{m}^3/\text{t} \); \( m \) is the thickness of the coal seam, \( \text{m} \); \( m_0 \) is the mining height of the coal seam, \( \text{m} \).

The relative gas emission quantity of the adjacent coal seams is calculated with the equation below:

\[ q_2 = \sum_{i=1}^{n} \frac{m_i}{m_0} \zeta_i (X_{0i} - X_{IC}) \]  

where \( m_i \) is the thickness of the \( i^{th} \) adjacent coal seam, \( \text{m} \); \( \zeta_i \) is the gas emission rate of the \( i^{th} \) adjacent coal seam affected by the mining, \%; \( X_{0i} \) is the gas content of the original \( i^{th} \) adjacent coal seam, \( \text{m}^3/\text{t} \); \( X_{IC} \) is the gas content in the residual \( i^{th} \) adjacent coal seam, \( \text{m}^3/\text{t} \).

The relative gas emission quantity of the pressure relief area in the lower coal seam is calculated using the equation:

\[ q_3 = \frac{1}{m_0 \sin \alpha} \left( \frac{(X_{0i} - X_{IC})}{2} h_i + \frac{X_{IL} h_i}{6} \right) \]  

where \( \alpha \) is the dip angle of the coal seam, degree; \( X_{0i} \) is the gas content of the original lower coal seam, \( \text{m}^3/\text{t} \); \( X_{IC} \) is the gas content of the residual lower coal seam, \( \text{m}^3/\text{t} \); \( h_i \) is the mining-induced damage depth, \( \text{m} \); \( X_{IL} \) is the gas content gradient, \( \text{m}^3/\text{t} \cdot \text{m}^{-1} \).

The relative gas emission quantity of the upper old goaf is calculated using eq 13.

\[ q_4 = K'(q_1 + q_2 + q_3) \]  

where \( K' \) is the gas emission coefficient of the old goaf, and it is 0.15 here.

The absolute gas emission quantity of the working face is then obtained using eq 14.

\[ q_{ij} = q_{ij} \frac{A}{1440} \]  

where \( q_{ij} \) is the absolute gas emission quantity of the working face, \( \text{m}^3/\text{min} \); \( q_{ij} \) is the relative gas emission quantity of the working face, \( \text{m}^3/\text{t} \); \( A \) is the daily output of the working face, \( \text{t/d} \).

4.2. Working Face Gas Emission Quantity Prediction.

The gas emission prediction model established above is then used to predict the gas emission quantity of the working face at the horizontal level of +575 m in the 45# coal seam in the Wudong Coal Mine. The values of the model parameters are shown in Tables 6–8.

### Table 5. Pairwise comparison of \( A_k \)

| \( A_k \) | \( v_1 \) | \( v_2 \) | \( v_3 \) | \( v_4 \) | \( v_5 \) | \( v_6 \) | \( v_7 \) |
|-------|--------|--------|--------|--------|--------|--------|--------|
| \( v_1 \) | 1      | 1      | 5      | 3      | 1/2    | 1/3    | 1/5    |
| \( v_2 \) | 1      | 1      | 3      | 2      | 1/4    | 1/5    | 1/7    |
| \( v_3 \) | 1/5    | 1/3    | 1      | 1      | 1/7    | 1/8    | 1/9    |
| \( v_4 \) | 2      | 4      | 7      | 5      | 1      | 1      | 1/3    |
| \( v_5 \) | 3      | 5      | 8      | 6      | 1      | 1      | 1/2    |
| \( v_6 \) | 5      | 7      | 9      | 8      | 3      | 2      | 1      |

The parameter values in Tables 6–8 are brought into the prediction models to calculate the gas emission quantities of the working face for 5 days. As can be seen from Figure 9, the relative...
errors between the predicted and measured values are in the range of 3.05−12.45% with an average value of 7.21%, which meets the requirements of engineering practices. Therefore, the prediction model is valid.

Figure 10 shows the relative gas emission volume rates and proportions of each gas emission source on different days. The gas emission rate of the pressure relief area in the lower coal seam is the largest, accounting for 44.16−50.44% with an average value of 46.99% of the total gas emission, suggesting that it is the main source of the gas emission of the working face.

4.3. Principle of the Sobol Sensitivity Analysis. Sobol sensitivity analysis was conducted on each influencing factor in the prediction model to examine its influence on the gas emission of the working face. Sobol sensitivity analysis decomposes the model \( f(\mathbf{x}) \) into a combination of single-parameter and multiparameter functions and determines the impacts of parameter changes on the model response by calculating the influences of the sampling variances of the parameters on the total variance of the model response. The Sobol sensitivity analysis process can be summarized as follows.

When \( \Omega = \{x|0 \leq x_i \leq 1; i = 1, 2, ..., n\} \) is defined as the value range of the input parameter \( x_i \), \( Y = f(\mathbf{x}) \) can be decomposed into a combination of single-parameter functions and multi-parameter functions as

\[
\begin{align*}
 f(\mathbf{x}) &= f_0 + \sum_{i=1}^{n} f_i(x_i) + \sum_{1 \leq i \leq j \leq n} f_{ij}(x_i, x_j) + \ldots + f_{1,2,...,n}(x_1, x_2, ..., x_n) \\
 &= D + \sum_{1 \leq i \leq n} S_i + \sum_{1 \leq i < j \leq n} S_{ij} + \ldots + S_{1,2,...,n}.
\end{align*}
\]  

(15)

where \( f_0 \) is a constant and the integrals of the other terms over any of the parameters included are zero, e.g.,

\[
\int_{\Omega} f_{i_1,i_2,...,i_k}(x_{i_1}, x_{i_2}, ..., x_{i_k}) \, dx_{i_k} = 0, \quad 1 \leq k \leq s.
\]

Equation 15 is first squared and then integrated in the entire computational domain, which is combined with eqs 16 and 18 to give

\[
D = \sum_{i=1}^{n} D_i + \sum_{1 \leq i < j \leq n} D_{ij} + \ldots + D_{1,2,...,n}
\]

(19)

When one defines \( S_1, S_2, ..., S_n = D_1, D_2, ..., D_n / D \), it can be obtained from eqs 18 and 19 that

\[
\sum_{i=1}^{n} S_i + \sum_{1 \leq i < j \leq n} S_{ij} + \ldots + S_{1,2,...,n} = 1
\]

(20)

where \( S_i \) is the first-order sensitivity of parameter \( x_i \) which reflects the main influence of \( x_i \) on the output (the influence of \( x_i \) on \( f(\mathbf{x}) \)); \( S_{ij} (i \neq j) \) is the second-order sensitivity of parameters \( x_i \) and \( x_j \) which reflects the cross influence of the two parameters; \( S_{ii} \) is the total sensitivity of the parameter \( x_i \) which is the sum of the sensitivities of the parameter at all orders and \( S_{ii} = 1 - S_0 \) where \( S_0 \) is the total sensitivity of all other parameters than the parameter \( x_i \) to the model response.

4.4. Sensitivity Analysis of Gas Emission Influencing Factors. Sensitivity analysis was then conducted on the 17 influencing factors involved in the gas emission prediction model of the working face, which are the gas discharge coefficient of the surrounding rock (\( K_r \)), the gas emission coefficient of the waste coals on the working face (\( K_{w} \)), the gas content of the original coal seam (\( X_{0i} \)), the gas content of the residual coal seam (\( X_{c,i} \)), the thickness of the coal seam (\( m_i \)), the mining height of the coal seam (\( m_{ij} \)), the thickness of the \( i^{th} \) adjacent coal seam (\( m_i \)), the gas emission rate of the adjacent coal seam affected by mining (\( \bar{z} \)), the gas content of the original \( i^{th} \) adjacent coal seam (\( X_{0i} \)), the gas content of the residual \( i^{th} \) adjacent coal seam (\( X_{ci} \)), the gas emission rate of the residual lower coal seam (\( X_{ci} \)), the gas content of the residual lower coal seam (\( X_{ci} \)), the mining-induced damage depth (\( h_i \)), the gas content gradient (\( X_i \)), the gas emission coefficient of the old goaf (\( K' \)), and the daily output of the working face (\( A \)). The value range of each parameter is listed in Table 9.

The sensitivity analysis starts with the gas emission influencing factors of the section being mined, the adjacent coal seam, and the lower coal seam. The parameters in eqs 10, 11, and 12 are, respectively, analyzed for their influences on the relative gas emission quantity of the corresponding emission sources to further evaluate their influences on the absolute gas emission quantity of the working face. Because the results of the Sobol sensitivity analysis greatly depend on the sample size and the analyses with small sample sizes may not accurately reflect the real influences of the parameter changes on the model output, the sensitivity of each factor is calculated with different sample sizes. The calculation is terminated when the result tends to be stable with the increase of sample size, and the final value is considered as the calculated result.

Figure 11 shows the changes in the first-order sensitivities of the factors affecting the gas emission from the section being...
mined with the increase of sample size. As can be seen, the sensitivities of all influencing factors become stable as the sample size exceeds 6000. Therefore, the sensitivities obtained with the sample sizes over 6000 are averaged for each factor and plotted in the spider chart to compare their influences on the relative gas emission quantity of the section being mined. As shown in Figure 12, the sensitivity of the gas content of the original coal seam (0.6710) is significantly higher than those of other five factors, suggesting that it has the greatest impact on the relative gas emission quantity of the section. The thickness of the coal seam is the second most important influencing factor with a sensitivity of 0.1359. The gas content of the residual coal seam and the gas emission coefficient of waste coals on the working face show much lower sensitivities of 0.0750 and 0.0163, respectively, indicating that they have little effects on the gas emission of the section. The sensitivities of the thickness of the coal seam and the gas emission coefficient of the surrounding rock are only 0.0015 and 0.0027, respectively, and thus, they are the least important factors affecting the gas emission quantity of the section.

Figure 13 shows the changes in the first-order sensitivities of the factors affecting the relative gas emission of the adjacent coal seams with the increase of sample size. The sensitivities of all influencing factors gradually become stable as the sample size increases to over 8000. Therefore, the sensitivities obtained with the sample sizes over 8000 are averaged for each influencing factor and compared as shown in Figure 14. The sensitivity of the gas content of the original adjacent coal seams (0.2960) is the highest, followed by those of the thickness (0.1774) and the gas emission rate affected by mining (0.1806) of the adjacent coal seams. The thickness of the coal seam shows the least effect with a sensitivity of 0.0009. The sensitivity of the gas content of

Figure 10. Relative gas emission volume rates and proportions of each gas emission source of the working face on different days.
the residual adjacent coal seams is only 0.0331, suggesting that it also has little influence on the gas emission.

The changes in the first-order sensitivities of the factors affecting the relative gas emission quantity of the lower coal seam with the increase of sample size are presented in Figure 15. Similarly, the sensitivities of all influencing factors gradually become stable as the sample size increased to over 8000. The sensitivities of each influencing factor obtained with the sample sizes over 8000 are averaged and compared with those of other factors as shown in Figure 16 to evaluate its influence on the gas emission of the lower coal seam. The comparison suggests that the dip angle of the coal seam has the greatest influence with the highest sensitivity of 0.4672, followed by the gas content of the original lower coal seam and the mining-induced damage depth that show the sensitivities of 0.0604 and 0.0341, respectively. The mining height of the coal seam and the gas content gradient and the gas content of the residual lower coal seam show the low sensitivities of 0.0002, −0.0001, and 0.0080, respectively, suggesting that they have very little influences on the gas emission of the lower coal seam.

The influences of all of the 17 influencing factors on the absolute gas emission quantity of the working face are then evaluated by the Sobol sensitivity analysis. The sensitivities of all influencing factors become stable as the sample size increases to over 8000 (Figure 17). Therefore, the sensitivities of each influencing factor obtained with sample sizes over 8000 are averaged and compared. As shown in Figure 18, the sensitivity of the dip angle of the coal seam (0.3285) is the highest, followed by the daily output of the working face that displays the sensitivity of 0.1259. The sensitivity of the gas content of the original coal seam is 0.1008, and those of other

Table 9. Parameter Value Ranges for Sensitivity Analysis

| parameter # | parameter | value |
|-------------|-----------|-------|
| 1           | gas discharge coefficient of the surrounding rock, $K_1$ | 1.1−1.3 |
| 2           | gas emission coefficient of the waste coals on the working face, $K_2$ | 1.67−2.50 |
| 3           | gas content of the original coal seam, $X_{d0}$ (m$^3$/t) | 1−10 |
| 4           | gas content of the residual coal seam, $X_{dC}$ (m$^3$/t) | 0.5−3.5 |
| 5           | thickness of the coal seam, $m$ (m) | 8−30 |
| 6           | mining height of the coal seam, $m_0$ (m) | 22−25 |
| 7           | thickness of the $i$th adjacent coal seam, $m_i$ (m) | 0−30 |
| 8           | gas emission rate of the adjacent coal seam affected by mining, $\zeta_i$ (%) | 0−100 |
| 9           | gas content of the original $i$th adjacent coal seam, $X_{i0}$ (m$^3$/t) | 1−10 |
| 10          | gas content of the residual $i$th adjacent coal seam, $X_{iC}$ (m$^3$/t) | 0.5−3.5 |
| 11          | dip angle of the coal seam, $\alpha$ (deg) | 1−89 |
| 12          | gas content of the original lower coal seam, $X_{d0}$ (m$^3$/t) | 1−10 |
| 13          | gas content of the residual lower coal seam, $X_{dC}$ (m$^3$/t) | 0.5−3.5 |
| 14          | mining-induced damage depth, $h_p$ (m) | 3.5−38 |
| 15          | gas content gradient, $X_t$ (m$^3$/t·m$^{-1}$) | 0.012−0.048 |
| 16          | gas emission coefficient of old goaf, $K'$ | 0.15−0.25 |
| 17          | daily output of working face, $A$ (t/d) | 500−3000 |

Figure 11. Evolutions of the first-order sensitivities of the gas emission influencing factors of the section being mined.

Figure 12. Comparison of the first-order sensitivities of the gas emission influencing factors of the section being mined.

Figure 13. Evolutions of the first-order sensitivities of the gas emission influencing factors of the adjacent coal seams.

original lower coal seam and the mining-induced damage depth that show the sensitivities of 0.0604 and 0.0341, respectively. The mining height of the coal seam and the gas content gradient and the gas content of the residual lower coal seam show the low sensitivities of 0.0002, −0.0001, and 0.0080, respectively, suggesting that they have very little influences on the gas emission of the lower coal seam.

The influences of all of the 17 influencing factors on the absolute gas emission quantity of the working face are then evaluated by the Sobol sensitivity analysis. The sensitivities of all influencing factors become stable as the sample size increases to over 8000 (Figure 17). Therefore, the sensitivities of each influencing factor obtained with sample sizes over 8000 are averaged and compared. As shown in Figure 18, the sensitivity of the dip angle of the coal seam (0.3285) is the highest, followed by the daily output of the working face that displays the sensitivity of 0.1259. The sensitivity of the gas content of the original coal seam is 0.1008, and those of other influencing factors are lower.
factors are less than 0.1000, suggesting their minor influences. In particular, the gas emission coefficient of the old goaf and the gas content gradient show the lowest sensitivities of 0.0001 and 0.0000, respectively, suggesting that they are the least important influencing factors. The sensitivities of the gas emission coefficient of the surrounding rock, the gas content of the original adjacent coal seam, and the gas content of the residual adjacent coal seam are 0.0006, 0.0003 and 0.0002, respectively, all less than 0.001. The sensitivities of the gas emission coefficient of the waste coals on the working face (0.0030), the mining height of the coal seam (0.0011), the thickness of the adjacent coal seams (0.0024), the gas emission rate of the adjacent coal seams affected by mining (0.0016), and the gas content of the residual lower coal seam (0.0047) are in the range of 0.001−0.01. The sensitivities of coal seam thickness (0.0255), gas content of the residual coal seam (0.0123), gas content of the original lower coal seam (0.0538), and the mining-induced damage depth (0.0260) are in the range of 0.01−0.1. In all, the sensitivities follow the order of dip angle of the coal seam (\( \alpha \)) > daily output of the working face (\( A \)) > gas content of the original coal seam (\( X_{00} \)) > gas content of the original lower coal seam (\( X_{d0} \)) > mining-induced damage depth (\( h_p \)) > coal seam thickness (\( m \)) > gas content of the residual coal seam (\( X_{kC} \)) > residual lower coal seam (\( X_{dC} \)) > gas emission coefficient of waste coals on the working face (\( K_2 \)) > thickness of the adjacent coal seam (\( m_i \)) > gas emission rate of the adjacent coal seam affected by mining (\( \zeta_i \)) > mining height of the coal seam (\( m_0 \)) > gas emission coefficient of the surrounding rock (\( K_1 \)) > gas content of the original adjacent coal seam (\( X_{i0} \)) > gas content of the residual adjacent coal seams (\( X_{iC} \)) > gas emission coefficient of the old goaf (\( K' \)) > gas content gradient (\( X_t \)) (Figure 19).
The sensitivity of the dip angle of the coal seam is much larger than those of other factors, indicating that it is the major influencing factor of the absolute gas emission quantity of the working face. In addition to the coal seam dip angle, two of the six influencing factors with sensitivities greater than 0.01, e.g., the gas content of the original lower coal seam \((X_{d0})\) and the mining-induced damage depth \((h_p)\), are involved in the calculation of the gas emission quantity of the lower coal seam, further implying that the lower coal seam is the greatest contributor to the gas emission of the working face.

5. DISCUSSION

Both the AHP and Sobol sensitivity analyses indicate that the lower coal seam is the main gas emission source of the horizontally sectioned, fully mechanized caving face in the SIUTCSs. The model calculations reveal that the gas emission from the pressure relief area in the lower coal seam accounts for 44.16−50.44\% with an average value of 46.99\% of the total gas emission, which confirms the prediction results.

To solve the gas transfinite problem in the horizontally sectioned, fully mechanized caving face in the SIUTCSs, we have proposed a lower coal seam gas emission control method, that is, the ultrahigh pressure hydraulic “drilling−slitting−pressing−draining” integrated antireflection enlarged gas extraction technology as shown in Figure 20. First, the gas control roadway is constructed along the coal seam at the bottom of the section being mined. The hydraulic fracturing holes and gas drainage holes are designed along the strike direction in the gas control roadway, and the bedding holes are drilled upward along the coal seam dip direction. After the drilling reaches the predetermined position, the drill pipe is withdrawn backward. During the withdrawal process, hydraulic slitting is conducted with the high-pressure water jet ejected by the drill bit at the preset intervals until the drill pipe is completely withdrawn. The holes are sealed with a rapid capsule hole sealing device and high-pressure water is injected into the holes for hydraulic fracturing. At the same time, the gas in the lower coal body is drained via the drainage holes to reduce gas emission to the upper working face and thus control the gas emission.

To evaluate the effectiveness of this technology for the coal seam gas emission control, relevant engineering tests were conducted.
carried out in the south lane of the east wing of the 45# coal seam at the +500 level of the Wudong Coal Mine at 40−400 m and the upper layer. The representative drilling holes were selected to analyze the antireflection effect. For the 1# borehole, only gas extraction was carried out, not any antipermeability measures. Only slitting and gas extraction were conducted on 3# borehole. The 4#, 6#, and 8# boreholes were subjected to slitting and hydraulic fracturing at 20, 30, and 40 MPa, respectively. The gas concentrations and gas flow rates in the drilling holes were monitored for 30 days for statistical analysis.

As shown in Figure 21, the gas extraction concentration and amount of the 1# borehole with no antireflection measures adopted are low. The average gas extraction concentration and amount for 30 days are only 17.35% and 0.011 m$^3$/min, respectively. The slitting process significantly increase both the average gas concentration and extraction amount of the 3# borehole to 39.09% and 0.021 m$^3$/min, respectively, 2.25 and 1.91 times of those of the 1# borehole. The average gas extraction concentration and amount of the 4# borehole subjected to slitting and hydraulic fracturing are 53.57% and 0.047 m$^3$/min, respectively, 3.08 and 4.27 times of those of the 1# borehole. Increasing the fracturing pressure to 30 MPa increases the average gas extraction concentration and amount of the 6# borehole to 56.96% and 0.066 m$^3$/min, respectively, which are 3.28 and 6 times of those of the 1# borehole. The average gas extraction concentration and amount of the 8# borehole are 60.77% and 0.069 m$^3$/min, respectively, which are 3.5 and 6.27 times those of the 1# borehole. The comparison of the results of the 8# and 3# borehole suggests that the fracturing increases the average gas extraction concentration and amount by 1.45 and 5.54 times. These results suggest that the ultrahigh pressure hydraulic “drilling−slitting−pressing−draining” integrated antireflection enlarged gas extraction technology has increased the permeability and significantly improved the gas extraction efficiency of the coal body in the south lane of the east wing of the 45# coal seam at the +500 level in the Wudong Coal Mine and the upper layer.
6. CONCLUSION

In summary, the working face gas emission sources have been identified and evaluated by an analytic hierarchy process (AHP). The gas emission quantity of the coal seam working face was calculated using a gas emission prediction model, and the influencing factors in the model were subjected to Sobol sensitivity analysis to determine their influences on the working face gas emission. On the basis of the results, a gas emission prediction model was proposed and evaluated. The following conclusions are drawn.

1. The AHP analysis indicates that the pressure relief area in the lower coal body is the main gas emission source of the working face, and the adjacent coal seams, old goaf, and rear goaf are not. The evaluation results of two researchers indicate that the fallen coal is the second largest gas emission source, while the other two researchers believe that it is the pressure relief area in front of the working face.

2. The relative errors between the predicted and measured gas emission quantities of the working face are in the range of 3.05–12.45% with an average value of 7.21%, which meets the requirements of practical engineering applications, and thus, the model is valid. The prediction results reveal that the gas emission from the pressure relief area in the lower coal seam accounts for 44.16–50.44% with the average value of 46.99% of the total gas emission quantity, further confirming that it is the main gas emission source of the working face.

3. The Sobol sensitivity analysis suggests that the dip angle of the coal seam has the greatest influence on the absolute gas emission quantity of the working face with a significantly higher sensitivity than those of the other influencing factors. In addition to the dip angle of the coal seam, two of the six influencing factors with sensitivities over 0.01, e.g., the gas content of the original lower coal body and the mining-induced damage depth, are involved in the gas emission calculation model of the lower coal seam, further indicating that the lower coal seam affects the gas emission of the working face most significantly.

4. Aiming at the problem of the large gas emission quantity of the coal body at the bottom of SIUTCSs, this paper puts forward a technical system for controlling the gas emission, e.g., the ultrahigh pressure hydraulic “drilling—slitting—pressing—draining” integrated antireflection enlarged gas extraction. The application of the technique to the south lane of the east wing of the 45# coal seam at the +500 level in the Wudong Coal Mine and the upper layer suggests it can increase the permeability and significantly improve the gas extraction efficiency of the coal body.

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https://doi.org/10.1021/acsomega.2c02917

ACS Omega 2022, 7, 38322–38336

38335
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c02917

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Project Nos. 51974176; 52174194; 51934004), the Shandong Province Natural Science Foundation of Outstanding Youth Fund (ZR2020JQ22), and the Shandong Province Colleges and Universities Youth Innovation and Technology Support Program (2019KJH006).

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