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# Research on the Analysis and Evaluation of Risk Factors for Gas and Coal Spontaneous Combustion in Large-Scale Goaf Areas

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## ABSTRACT

In response to the potential hazards of spontaneous combustion and gas in large-scale goaf areas, the risk factors such as coal spontaneous combustion status, gas status, and ventilation status in goaf are analyzed. And simulation software is used to simulate the internal flow field of large-scale goaf, and the distribution law of its internal flow field is obtained. Then, the index evaluation method is used to conduct special evaluations of spontaneous combustion risk and gas risk in large-scale goaf areas. Finally, based on the determination of the warning indicators, levels, rules, and warning signals for large-scale goaf hazards, the results of the special evaluation of goaf hazards are transformed into corresponding warning signals for release, forming a set of large-scale goaf hazard analysis and evaluation technology system.

## KEYWORDS

Coal Mine; Large-Scale Goaf; Factor Analysis; Numerical Simulation; Hazard Assessment and Warning.

## 1. INTRODUCTION

In recent years, the loss of high-quality coal caused by spontaneous combustion of coal has continued to increase at a rate of 20~30 million tons per year, while the stagnant resource reserves caused by it exceed 200 million tons per year. Mine fires remain a major disaster for coal mine safety production and are the main factor restricting safety production [1-2]. Gas accidents are also extremely serious disasters that threaten coal mine safety production, easily causing a large number of casualties, destroying mine facilities, and secondary disasters [3-4]. The coupling of two types of disasters greatly increases the likelihood, danger, and severity of gas explosions and fires [5-7]. Gas accidents and fire accidents seriously restrict the safety production of coal mines in China. Studying and mastering the risk factors and evaluation techniques of gas and fire is of great significance for coal mine safety production.

In the study of the mechanism of coal spontaneous combustion, Li Zenghua proposed the theory of free radical action in coal spontaneous combustion, which believes that coal is broken under external forces, thereby generating a large amount of free radicals and creating conditions for coal spontaneous combustion oxidation. Martin studied the oxygen distribution on the surface of middling coal during low-temperature oxidation, and also supported the mechanism of free radical chain reaction. In the research of flow field in goaf, Li Zongxiang established a model for gas emission and air flow exchange in heterogeneous goaf based on the two-phase mixed gas seepage diffusion equation, and

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proposed a new method for calculating the air leakage in goaf. Based on the similarity theory of model experiments, Qin Yueping obtained the gas migration law of goaf in fully mechanized top coal caving mining and a reasonable gas discharge plan for goaf. Cao Shugang constructed a prediction and warning model for gas hazards in coal mining face based on LS-SVM technology. Scholars such as Li Zongxiang and Li jinglei used the mixed reading method of barometers to measure the ventilation resistance and ventilation equipotential map of the fully mechanized top coal caving mining area, and determined the air leakage velocity and amount of air leakage in the corner goaf of the fully mechanized top coal caving working face, as well as their distribution [8-10]. In the prevention and control of coal spontaneous combustion disasters in goaf areas, multiple integrated technologies have been developed, including water injection, grouting, inhibitor fire prevention and extinguishing, plugging, and colloid fire prevention and extinguishing. Each type of fire control technology has its own characteristics and is suitable for various environments, mainly reflected in its performance of "cooling, plugging, and blocking"[11-13].

Therefore, based on the extensive research work of many scholars, this article starts with the analysis of risk factors in large-scale goaf, and uses numerical simulation, risk assessment and other methods to study gas outburst and coal spontaneous combustion in goaf, forming a practical and feasible goaf risk assessment and early warning technology system.

## 2. ANALYSIS OF RISK FACTORS IN LARGE-SCALE GOAF

### 2.1. Project overview

The section level roadway of Tangkou Coal Industry Company adopts the goaf excavation method with narrow coal pillars, and the 2309 working face to be prepared for construction will also adopt small coal pillar mining. On the east side of the 2309 working face are the 2308 goaf and 2307 goaf, both of which are now sealed. The isolation coal pillars between them are also small coal pillars, which are often compressed and lose their isolation function during or after the mining process, thus forming large-scale goaf. The coal seam mined in the 2309 working face is the three upper coal mine of Shanxi Formation. The sedimentation of the three upper coal seam in the working face is relatively stable, with a coal seam thickness of 2.0~4.5m and an average of 3.5m, all of which can be mined. The three upper coal is black in color, with brownish black streaks, blocky, mainly composed of bright coal, followed by dark coal, with a small amount of vitrinite and silk charcoal bands. The internal cracks are developed, with a glassy luster and stepped fracture surfaces. There are local gangue inclusions. The lithology is claystone, with a thickness of about 0.1m. This coal seam belongs to gas coal. The test result of the spontaneous combustion period of this coal is: the range of spontaneous combustion period is 54~118 days. The distribution of partially mined out areas in mining area 230 is shown in Figure 1.

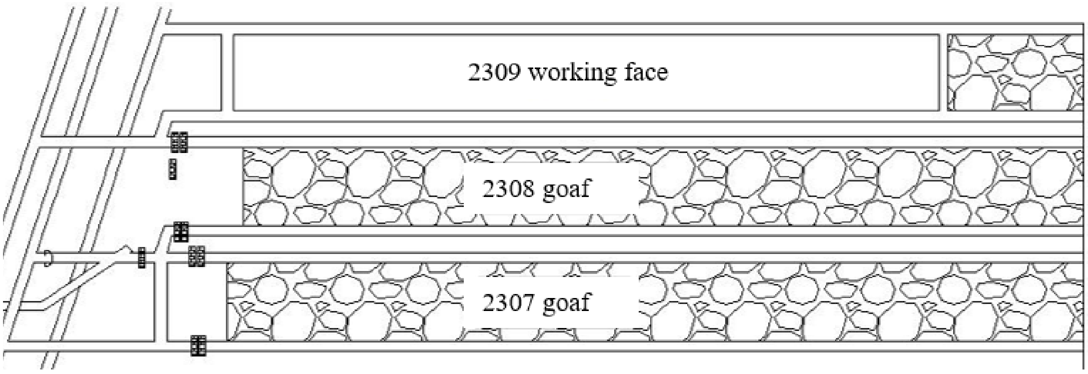



**Figure 1** Goaf schematic diagram of 230 mining area

## 2.2. Analysis of abnormal gas outburst in large-scale goaf

### 2.2.1. The impact of roof collapse on gas outburst in large-scale goaf

The process of large-scale collapse of the old roof causes a rapid gas outburst in the goaf of the working face. The main reasons are: ①The fracture, collapse, and expansion of the roof rock reduce the spatial volume of the goaf, increase the gas pressure inside the goaf, and create a pressure difference with the outside world, causing the accumulated gas in the goaf to gush out. ②As the roof collapses, adjacent layers release gas pressure and rush towards the goaf, causing gas to gush out of the goaf. ③When the suspended old roof collapses as a whole, dynamic pressure is formed, squeezing the gas in the goaf and creating a high-pressure gas flow that rushes towards the mining space, causing the gas in the working face to suddenly surge out and then exceed the limit. It has been a year since the completion of mining at the 2308 working face, and the roof span has tended to stabilize. The roof activity has basically ended, and the roof is basically in a stable state. The isolation coal pillar between the 2308 and 2309 working faces is a small coal pillar, which is often compressed and loses its isolation function during or after the mining process. The connectivity between the two goaf areas is strong. Therefore, the roof collapse of the 2309 goaf has a certain impact on the 2308 goaf.

### 2.2.2. The impact of air leakage and adjacent layer gas on gas outburst in large-scale goaf

Air leakage in goaf and gas outburst from adjacent layers are also reasons for gas outburst in 2308 goaf. Due to the constant volume of the goaf space, if there is external air leakage or adjacent gas sources continuously replenishing gas to the goaf, the pressure of the gas in the goaf will continue to increase, causing gas to gush out to the outside. However, the amount of gas left in the goaf is limited and cannot be infinitely released outward.

### 2.2.3. The impact of atmospheric pressure changes on gas outburst in large-scale goaf areas

In the absence of other external forces, the pressure acting on the large-scale goaf is only negative ventilation pressure and atmospheric pressure. And the negative pressure of ventilation will not change significantly, so the goaf and its vicinity are only affected by changes in atmospheric pressure. Due to the fact that the 2309 working face is connected to the ground through tunnels, small changes in atmospheric pressure can be quickly transmitted and act on the sealed surface. The goaf is connected to the outside world through surface fissures and limited underground air leakage fissures, and the space inside the goaf is relatively large. Therefore, when atmospheric pressure changes, the rate of gas pressure change in the goaf is extremely small, and it can be approximately assumed that the gas pressure in the goaf is not affected by atmospheric pressure. When there is a drastic change in atmospheric pressure, the pressure of the sealed air leakage flow will also undergo a drastic change, thereby affecting the gas emission from the 2308 goaf to the 2309 working face and the 2309 track roadway.

## 2.3. Analysis of spontaneous combustion in large-scale goaf

The occurrence and development of coal spontaneous combustion is essentially the spontaneous generation and gradual accumulation of heat, which heats up the coal seam and ultimately causes ignition and combustion. Coal spontaneous combustion requires the following four conditions simultaneously: coal has a tendency towards spontaneous combustion, continuous air leakage and oxygen supply conditions, an objective environment where heat is easily accumulated, and the presence of these three conditions in the same space for a sufficient amount of time.

The tendency of coal spontaneous combustion is determined by the internal characteristics of coal, which depend on the coal forming substances and conditions, indicating the ability of coal to interact with oxygen. The spontaneous combustion tendency of coal mainly depends on the degree of coalification, degree of coal seam weathering, coal seam moisture, coal rock composition, coal seam sulfur content, coal seam particle size, and coal seam gas content.

The conditions for air leakage and oxygen supply are mainly affected by the following factors: air leakage rate, air leakage form, coal seam thickness, coal fragmentation, sealing quality of goaf, geological structure and roof lithology, and coal seam dip angle. The conditions for heat storage and dissipation are mainly influenced by the following factors: air leakage intensity, thickness of residual coal in goaf, temperature of surrounding rock in the area, and burial depth of coal seam.

In terms of ventilation and thermal balance, there is always an area in the goaf that meets the conditions for spontaneous combustion, with appropriate air leakage and good conditions for spontaneous combustion. The oxidation heat generation is greater than the external heat dissipation, and there is heat accumulation. If there is a lot of residual coal in this area and the duration of existence is longer than the natural combustion period, spontaneous combustion is highly likely to occur, and this area becomes the spontaneous combustion zone. Generally, the longer the duration of heat leakage, the higher the risk of spontaneous combustion. Leakage time greater than the natural ignition period is prone to spontaneous combustion, while leakage time less than the natural ignition period may lead to spontaneous combustion.

# 3. LARGE SCALE GOAF STATE MONITORING AND NUMERICAL SIMULATION

Within the goaf, due to the fragmentation of the remaining coal and collapsed rock layers, there are numerous interconnected pores between them. Therefore, large-scale goaf can be regarded as a porous medium composed of a mixture of loose coal and fractured rock layers. Porous media possess properties such as porosity, specific surface area, permeability, and compressibility. The hindering effect of the solid skeleton in porous media causes a pressure loss in the fluid system passing through. Fluent's porous media model adds a source term representing momentum consumption to the momentum equation.

## 3.1. Simulation conditions and settings

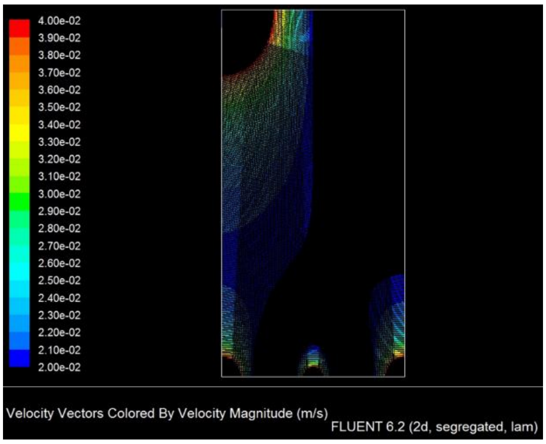
Large scale goaf can be regarded as a porous medium composed of a mixture of loose coal and fractured rock layers, so the flow field in it can be modeled using a porous medium seepage model. To solve nonlinear and complex problems, the assumed conditions for the leakage flow field in goaf are as follows: (1) the solid skeleton in goaf is incompressible, and the permeability in goaf remains unchanged. (2) The permeability of goaf is isotropic. (3) The air leakage velocity in the goaf is very small, and the overall flow of gas conforms to Darcy's law. (4) The fluid viscosity coefficient is the same in all parts of the goaf. (5) The flow field in the goaf is considered as a two-dimensional flow field. (6) Assumption of constant temperature in goaf. Based on the actual situation of the large-scale goaf of Tangkou Coal Industry Company, a simulation calculation area with a width of 400m and lengths of 800m, 600m, and 400m is established. Based on the actual conditions of the mine, Fluent software was used to simulate and study the large-scale goaf leakage flow field. The boundary conditions and basic parameters of the simulation were calculated and shown in Table 1.

**Table 1** Basic parameter table of boundary conditions

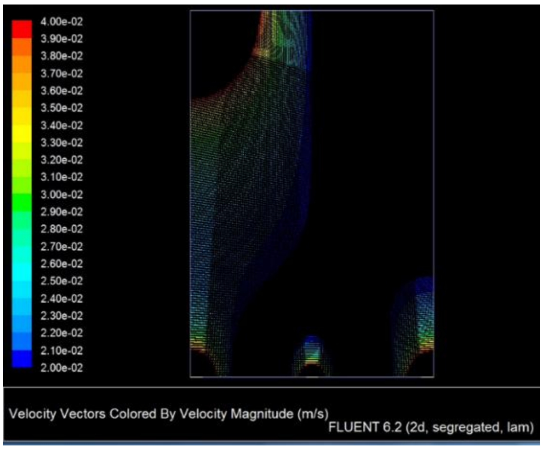
| Name | Parameter values |
|---|---|
| Entrance boundary type | Velocity-Inlet |
| Entrance speed(m/s) | 0.2 |
| Export boundary type | Outflow |
| Boundary types of goaf walls | Wall |
| Permeability of goaf(m2) | 1.6e-9 |
| Porosity of goaf | 0.1 |

### 3.2. Simulation results and analysis

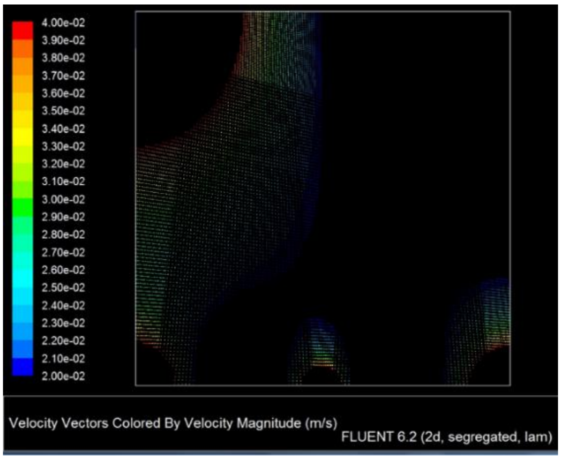
Enter the divided grid and boundary conditions into Fluent for calculation, and the result is shown in Figure 2. The flow velocity and volume of air leakage in the empty area often play a dominant role in spontaneous combustion. When the wind speed is too low, there is insufficient oxygen supply, and the heat generated by oxidation is very small, so it is easy to dissipate and not easy to accumulate heat. When the wind speed is too high, more heat is generated by oxidation, but the heat is carried away by the high wind speed, which also cannot form heat accumulation. Neither of the above two situations will cause coal spontaneous combustion. From this, it can be seen that coal spontaneous combustion occurs only when there are relatively reliable and sufficient oxygen supply conditions, and the heat generated by oxidation will not be carried away by the airflow in large quantities, resulting in the accumulation of heat. Based on the above analysis, combined with simulation results and the actual situation of the large-scale goaf of Tangkou Coal Industry Company, the following conclusion can be drawn: the areas with natural combustion in the large-scale goaf are mainly concentrated on one side of the 2308 goaf, and the widest point of the spontaneous combustion zone is about 100m away from the working face, extending about 200m into the goaf. The area of air leakage near the stopping line is relatively large within the range of 0.02~0.04m/s, indicating a high risk of spontaneous combustion.




(a) Goaf length 800 meters




(b) Goaf length 600 meters




(c) Goaf length 400 meters

**Figure 2** Contour map of air leakage field in goaf

# 4. RISK ASSESSMENT AND WARNING TECHNOLOGY FOR LARGE-SCALE GOAF

## 4.1. Gas hazard assessment of large-scale goaf

The risk assessment method for coal spontaneous combustion in goaf adopts the index method (scoring method) [14-15]. A risk assessment table is prepared for coal spontaneous combustion accidents in goaf, and the evaluation indicators are checked and evaluated based on the risk assessment table. Input the evaluation results into the computer, which calculates the risk level of coal spontaneous combustion in the goaf and conducts daily evaluation and warning work.

In the special evaluation of the risk of coal spontaneous combustion in large-scale goaf, the calculation of the risk index is carried out through the following formula:

$$F_f = 10 \bullet \sum_{i=1}^{4} Q_i F_i \tag{1}$$

Where, $F_f$ is Calculation value of coal spontaneous combustion risk index in large-scale goaf, $Q_i$ is Weight of evaluation indicator i, $F_i$ is Score of evaluation indicator i.

A special evaluation was conducted on the gas hazard in large-scale goaf areas, and the evaluation table prepared is shown in Table 2.

**Table 2** Gas hazards' special assessment tab of big goaf

| | Indicator | Inspection content |
|---|---|---|
| 1 | Gas concentration in goaf (%) | 1.1 The gas concentration in the goaf is between [4,17] |
| | | 1.2 The gas concentration in the goaf is between [3,4) or (17,20] |
| | | 1.3 The gas concentration in the goaf is higher than 20 |
| | | 1.4 The gas concentration in the goaf is lower than 3 |
| 2 | Temperature in goaf(°) | 2.1 The temperature in the goaf is greater than 300° |
| | | 2.2 The temperature in the goaf is between 200° and 300° |
| | | 2.3 The temperature in the goaf is between 60° and 200° |
| | | 2.4 he temperature in the goaf is below 60 ° |
| 3 | CO concentration in goaf (ppm) | 3.1 CO concentration in goaf >2280 |
| | | 3.2 CO concentration in goaf≥360 |
| | | 3.3 CO concentration in goaf≥67 |
| | | 3.4 CO concentration in goaf <67 |
| 4 | O2 concentration in goaf (%) | 4.1 The O2 concentration in the goaf is greater than 12 |
| | | 4.2 The O2 concentration in the goaf is between [6,12) |
| | | 4.3 The O2 concentration in the goaf is between [2,6) |
| | | 4.4 The O2 concentration in the goaf is lower than 2 |

Similar to the special evaluation of coal spontaneous combustion risk in goaf mentioned above, the weight values of gas risk evaluation indicators in goaf were calculated using the Analytic Hierarchy Process, as shown in Table 3. The classification standards for gas hazard levels in goaf are shown in Table 4.

**Table 3** Gas hazards' assessment index weight of goaf

| **Serial number** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Evaluating indicator | Gas concentration in goaf | Temperature in goaf | CO concentration in goaf | O2 concentration in goaf |
| Qi | 0.3 | 0.25 | 0.15 | 0.3 |

**Table 4** Gas hazards' classification standard of goaf

| **Hazard level** | **I** | **II** | **III** | **IV** |
|---|---|---|---|---|
| Hazard index | $F_f \geq 75$ | $55 \leq F_f < 75$ | $35 \leq F_f < 55$ | $F_f < 35$ |
| Evaluation significance | Very dangerous | Dangerous | Commonly | Safety |

## 4.2. Large scale goaf gas and spontaneous combustion warning

### 4.2.1. Indicators and levels of warning

The indicators used for warning the danger of large-scale goaf are the special evaluation results of coal spontaneous combustion danger in goaf and the special evaluation results of gas danger in goaf. Here, the classification method of hazard level in the special evaluation process is used to divide the hazard level, as shown in Table 5.

**Table 5** Early-warning index hazards' classification

| **Evaluating indicator** | | **IV** | **III** | **II** | **I** |
|---|---|---|---|---|---|
| Risk of spontaneous combustion | Temperature in goaf | <60 | [60, 200) | (200, 300] | >300 |
| | CO concentration in goaf (ppm) | <67 | [67, 360] | (360, 2280] | >2280 |
| | Ethylene concentration in goaf (ppm) | 0 | (0, 1) | [1, 9] | >9 |
| | Spontaneous combustion hazard index | $F_f < 35$ | $35 \le F_f < 55$ | $55 \le F_f < 75$ | $F_f \ge 75$ |
| | Countermeasure | Take general preventive measures | Detect high temperature points and carry out special treatment | Take comprehensive measures immediately to address the risk of spontaneous | Stop production and take fire extinguishing measures |
| Gas hazard | Gas concentration in goaf (%) | <3.0 | >20 | [3.0, 4.0)/(17,20] | [4,17] |
| | Gas hazard index | $F_e < 35$ | $35 \le F_e < 55$ | $55 \le F_e < 75$ | $F_e \ge 75$ |
| | Countermeasure | Normal work | Strengthen monitoring | Strengthen monitoring to prevent air leakage | Close monitoring to prevent ignition and air leakage |

### 4.2.2. Determination and release of warning signals

Divide the risk warning level of goaf accidents into 4 levels, and use blue, yellow, orange, and red to indicate the escalation of accident risk in sequence. The relationship between warning levels and warning signals is shown in Table 6.

**Table 6** Warning signal and level warning cross-references

| Warning level | Early warning signal | Preventive measures |
|---|---|---|
| I | Red | Handle immediately |
| II | Orange | Deadline processing |
| III | Yellow | Request processing |
| IV | Blue | Pay attention to monitoring |

The issuance of warning signals is mainly carried out automatically through computer networks, and is also issued through telephone with auxiliary prompts. For certain specific risk information such as veto indicators, if the staff discovers serious problems at the first time, they should immediately report to the Inoue duty room via telephone. The duty room should issue warning signals through telephone and computer networks based on the situation of the problem. For risk information such as disaster hazard assessment results, manual and computer analysis are required to obtain warning levels, and these warning signals are mainly released through computer networks. The warning signal issued over the phone should then be disseminated through computer networks to make it more standardized and have a wider coverage.

## 5. CONCLUSION

(1) Through investigation and analysis, the characteristics and laws of spontaneous combustion and gas hazards in large-scale goaf were analyzed in detail, providing a basis for the special evaluation of the danger of goaf.

(2) A mathematical model of large-scale goaf flow field was established, and numerical simulation software was used to simulate the leakage flow field inside the goaf. The distribution law of the flow field inside the goaf was given, and the simulation results were basically consistent with the actual situation, providing a theoretical basis for disaster prevention and control in the goaf.

(3) Based on the actual situation on site, feasible and effective hazard assessment methods were selected, and the risks of spontaneous combustion and gas were evaluated and analyzed separately. Finally, the warning index system, warning level, and warning release of gas and spontaneous combustion in large-scale goaf were studied.

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