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# Characteristics and Evolution Mechanism of Coal and Gas Outburst Disasters

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## Abstract

**Coal and gas outburst is a destructive dynamic hazard in coal mining, which seriously threatens the safety of miners' lives and properties and the safety of coal mine production. In order to explore the characteristics and evolution mechanism of coal and gas outburst behavior in depth, this article systematically analyzes the formation mechanism of coal and gas outburst. Through the specific case analysis of coal and gas outburst disasters in a certain mine in Gansu, the key features of outburst behavior are identified. By analyzing the outburst dynamics model and the evolutionary process of outburst, the evolution mechanism of coal and gas outburst is explored. The research results show that coal and gas outburst is a sudden gas dynamic behavior caused by various factors such as geological conditions, strata characteristics, and mining technology. The superposition of tectonic stress concentration zones and gas enrichment zones is prone to trigger dynamic behavior. The research results have important theoretical and practical value for guiding actual production safety.**

## Keywords

**Gas Outburst; Disaster Characteristics; Evolution Mechanism; Dynamic Model; Case Study.**

## 1. Introduction

Coal and gas outburst is a major disaster in the process of coal mining, which often leads to casualties and property losses. The behavioral characteristics of coal and gas outbursts mainly manifest as the frequency of outbursts, the intensity of outburst phenomena, and their scope of influence. The intensity of outbursts can be quantified by parameters such as the volume of gas outburst, outburst time, and instantaneous change rate, usually expressed in cubic meters per minute ($m^3$/min). In some cases, the gas outburst volume of individual outbursts can even reach several thousand cubic meters per minute, posing a great threat to the safe production of mines.

The evolution mechanism of coal and gas outbursts is closely related to the geological structure, stress state, and physical and chemical properties of coal-rock mass. Generally, strata vibration and stress concentration are the main causes of coal and gas outbursts. According to the theory of stress-strain, after the surrounding rock of the mine encounters failure, local stress concentration can trigger the expansion of coal bed fractures and gas release. Under stress overload conditions, coal density, porosity, and gas content significantly affect the occurrence of outbursts. Many scholars have conducted related research. Y.J. Li[3] analyzed the current research status of the mechanism of coal and gas outbursts, explained the methods and key technologies for monitoring and early warning of outbursts, summarized the measures for preventing outbursts and enhancing gas permeability, and proposed research prospects. C.J. Wang[4], based on the mechanical background triggered by typical outburst accidents, started from the dynamic response law of coal body mechanical damage during mining, revealed the expansion characteristics of damaged gas-containing coal body during multi-variable mechanical behaviors, clarified the mutual feedback response law between mining stress and gas pressure, elucidated the main control mechanism of initial damage of coal body during outburst, and then proposed the mechanism of expansion and mutation of coal and gas outbursts. X.L. Yang[5] developed an outburst simulation experiment system that considers the gas supply effect of coal mass around the outburst hole in the unloading zone based on the similarity theory, and determined the key parameters of the gas supply device through strict calculation based on the outburst model and gas seepage theory. The experiment system mainly includes four modules: outburst hole dynamic system, outburst excitation device, roadway simulation system, and data acquisition and control center, which can simulate the formation and propagation of outburst shock waves in the roadway, the migration of coal-gas two-phase flow during outburst, and the backflow of gas, among other dynamic phenomena. A simulation experiment of outburst catastrophe with gas pressure of 0.8 MPa was carried out, and the formation process of outburst shock wave was directly observed using a high-speed camera. L.C. Wang[6] used a self-built coal and gas outburst simulation system to study the characteristics of coal dust transportation selection after outburst and the evolution law of impact pressure of coal and gas two-phase flow. C.L. Zhang[7] conducted outburst simulation experiments of coal and gas under different gas pressure conditions using a self-developed multifunctional coal and gas outburst simulation test system, and monitored the temperature of coal seam and roadway throughout the outburst process. These research results analyze the process and evolution of coal and gas outbursts from different perspectives. However, coal and gas outbursts are a disaster caused by the coupled effects of multiple factors, and the characteristics and evolution mechanism of their dynamic behavior are crucial for preventing disasters. Therefore, it is necessary to carry out related research on the formation conditions, behavior characteristics identification, and evolution mechanism of disasters.

## 2. Conditions for the Formation of Coal and Gas Outbursts

The formation conditions of coal and gas outbursts mainly involve geological conditions, rock strata characteristics, and mining techniques. Firstly, the burial depth of the coal seam is a key factor, with the risk of coal and gas outbursts significantly increasing when the depth is generally over 300 meters. The magnitude of gas pressure directly affects the occurrence of outburst events. Usually, when the gas pressure exceeds the bearing capacity of the coal seam, it is generally considered that an outburst may occur when the gas pressure reaches 0.74 MPa. In addition, the gas content and gas permeability of the coal seam are also determining parameters. When the gas content is above 30 $m^3/t$ and the permeability increases, the risk of outbursts significantly rises.

The complexity of rock structures, especially the degree of jointing and faulting, significantly influences the stability of coal seams. Developed fault or joint systems may become high-pressure gas zones, increasing the likelihood of coal seam outbursts. Meanwhile, the physical and chemical properties of coal, such as density, strength, and mineral composition, also affect its safety. High-strength coal seams are less likely to experience outbursts, while soft coal seams pose higher risks. Additionally, the depositional environment has an important impact on the composition and structure of coal seams, with underwater sedimentary coal seams typically rich in gas, increasing the likelihood of outbursts.

In terms of mining technology, mining methods and speed also directly affect the occurrence of outburst events. When advancing rapidly, it is necessary to control gas emission by measures such as water injection and ventilation to reduce the risk of outbursts. When concentrating on mining or conducting large-scale mining, attention should be paid to the changes in local mine pressure to avoid sudden situations caused by the too rapid removal of support. By using gas extraction technology and continuously monitoring the flow and pressure changes of coal seam gas, outbursts can be effectively monitored and warned. Currently, seismic exploration and microseismic monitoring are commonly used technical means for identifying the risk of coal and gas outbursts.

## 3. Analysis of Prominent Behavioral Characteristics

### 3.1. Disaster Cases

The field of a mine in Gansu is a relatively wide and gentle folded structure composed of the main 1st anticline, 2nd syncline, 3rd anticline, and 4th syncline, extending from west to east from Baoji Mountain. The southern side of the field is affected by the $F_{1-2}$ fault group, which causes severe damage to the southwestern wing coal seam, resulting in a complex structural zone in the shallow part of the southwestern wing. The characteristics of the damaged coal seam are powdery, loamy, and flaky, with microfolds and fractures visible. In July 14, 1977, water suddenly rushed into the drift, submerging 18m of the inclined shaft. After pumping out the water, on August 9, 1977, coal and rocks were suddenly ejected accompanied by gas outbursts, blocking the drift for 23m along the inclined shaft from bottom to top, with 168$m^3$ of coal and 65$m^3$ of rocks cleared. Prior to the incident, the lower part of the coal seam (crushed mudstone and siltstone) had started to collapse. As the falling rocks were cleared, the falls increased, leading to a large amount of coal and rocks being ejected, along with water from the fractures. During the cleanup process, a gas explosion occurred due to the failure of an electrical switch, resulting in one fatality. After resuming work, the remaining coal and rocks were cleared. When reaching 4m from the face, on October 22, another coal and rock ejection occurred, blocking the drift along the inclined shaft for 43.7m from bottom to top, burying a temporary water tank 1307m horizontally away and 15m deep. After 24 hours, the methane concentration in the return air remained at 1.2%, with water and foam on the surface of the debris and gas bubbles rising from the water. A total of 479.8$m^3$ of coal and rock were cleared.

### 3.2. Highlighted Causes Analysis

Based on the dynamic phenomenon that occurred in a certain mine in Gansu Province, combined with the geological structure of the well field, the occurrence and structural properties of coal, and the characteristics of dynamic phenomena, the reasons can mainly be attributed to the following aspects.

(1)Due to the influence of the Longxi rotational tectonic movement, the geological structures in a certain minefield in Gansu Province have undergone compressive and shear stress, resulting in the development of faults and folds. Some of these structures are still active, leading to high geostress. Under the geostress, there is a significant amount of elastic potential in the surrounding rocks and coal seams, providing the energy source for dynamic events to occur.

(2)The minimum depth where dynamic phenomena occur is 355.6m, reaching a maximum of 530.4m. Due to the high ground stress and gas pressure in coal seams, the measured gas pressure can reach 1.88MPa, which also creates favorable conditions for the occurrence of dynamic phenomena.

(3)The locations where dynamic phenomena occur are distributed in the structural damage zone north of the $F_{1-2}$ fault group and south of the $F_3$ and $F_{48}$ faults. The damaged coal is in powder, paste, and flake shapes, with low mechanical strength, and the types of damage range from Class III to Class V.

(4)The roof and floor of the coal seam are mostly composed of siltstone and mudstone, with poor permeability, which is conducive to the preservation of coal seam gas. Moreover, the main faults in the mining area are mostly reverse thrust or reverse fault with good sealing performance. Therefore, once the coal seam is exposed to release pressure, the amount of gas outburst is high.

### 3.3. Recognition of Power Behavior Characteristics

The key basis for revealing the evolution mechanism and formulating prevention and control measures of coal and gas outburst disasters lies in the characteristics of outburst behaviors. The core indicator of disaster severity is the outburst intensity, and its dynamic response characteristics are significantly affected by the geostress level. The increase in geostress level leads to a significant increase in the strength and initial velocity of coal outburst, and during the outburst process, geostress changes and gas pressure release are mainly concentrated in the unloading area and the support stress area, while the release of elastic strain energy is mainly reflected in the support stress area. The dynamic changes of geostress, gas pressure, elastic strain energy, and other physical parameters play a decisive role in the outburst behavior. In addition, the physical properties of the outburst material also reflect the mechanical characteristics of the disaster. For example, the electromagnetic radiation characteristics exhibited by coal under uniaxial compression conditions can provide a basis for predicting the danger of outbursts, and the abnormal changes in electromagnetic radiation parameters are often directly related to energy release during the coal damage process.

To accurately identify the characteristics of coal and gas outburst behavior, a behavior feature recognition framework based on multi-source data is constructed. Machine learning algorithms, such as Support Vector Machine (SVM) and Random Forest (RF), are used to analyze the impact of factors such as geological structure, engineering geology, and coal seam gas pressure on the outburst behavior. K-fold cross-validation is used to ensure the robustness of the models, with each model being trained and validated through at least 100 iterations to reduce the influence of data fluctuations on the results, ensuring the reliability and representativeness of the analysis results.

Highlight energy calculation is one of the core parameters of highlighting new services, consistent with the physical relationship between mass and velocity. In addition, the model integrates multidimensional data on the chain carriers of coal and gas outburst disasters and reflects the laws, effectively revealing the correlation between highlighting energy and premonitory signs of outbursts. However, although energy calculation provides quantification of the potential for outbursts, it still needs to be combined with actual measured geological data to comprehensively reflect the formation of outburst behavior and the chain development process of disasters.The energy calculation formula is highlighted:

$$E=\frac{1}{2}mv^2$$

## 4. Highlighted Evolution Mechanism

### 4.1. Highlighting the Basic Theory of Evolution

The evolution mechanism of coal and gas outburst disasters involves complex dynamic processes under the coupling effects of multiple factors, and its evolutionary laws follow the sudden change theory framework from quantitative change to qualitative change. The safety rheology-catastrophe theory points out that the outburst process of coal and gas is the evolution process of the system safety state from stability to criticality and then to catastrophe, providing an important basis for revealing its evolution mechanism. According to this theory, the evolution of the outburst system can be divided into stable rheology stage, critical rheology

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stage, and catastrophe stage. In the stable rheology stage, the geostress and gas pressure gradually accumulate, the coal mass is in a state of elastic deformation, and the system is in a relatively safe state; with the continuous increase of stress and gas pressure, the coal mass enters the critical rheology stage, its internal damage gradually expands, local areas experience microfractures, and the system is in an unstable critical state; when external disturbances or internal damage reach the critical threshold, the system will undergo a catastrophe, a large amount of gas and coal suddenly release, resulting in an outburst disaster.

The driving factors of the evolution process mainly include geological structural stress, high-pressure gas enrichment, and coal body structural fragility. The occurrence conditions of coal seams (such as dip angle, depth), the physical and mechanical properties of coal bodies (such as strength coefficients, permeability), and the characteristics of gas occurrence (such as adsorption capacity, desorption rate) jointly determine the sensitivity and hazard of outburst. With the increase of mining depth, the horizontal stress significantly increases, while the gas pressure also increases. Under the combined action of high stress and high-pressure gas, the coal body gradually accumulates internal damage, eventually leading to structural failure.

The energy evolution highlighted in the process is the core of its dynamic characteristics. The prominent energy mainly comes from the release of coal body elastic deformation energy and gas potential energy, with the sudden release of gas pressure being the key driving force for coal ejection. During the evolution of rupture, micro-cracks inside the coal body gradually expand and intersect, forming high-speed gas flow channels, accompanied by rapid energy release. High-speed camera observations show that during the outburst process, coal body rupture exhibits a multi-level expansion mode, with initial micro-cracks forming in stress concentration areas, then expanding along coal seam weak planes or fracture networks, ultimately leading to massive destruction and material ejection.

## 4.2. Highlight Dynamics Model

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Input: Parameters related to coal and gas outburst disasters
Output: Evolutionary mechanism analysis results
1. Initialize model parameters based on the characteristics of coal and gas outburst disasters
2. Define the dynamic process variables of gas outburst
3. Parallel calculation of gas pressure and coal stress in each working face
   For each working face in parallel execution
      Calculate gas pressure
      Calculate coal stress
   end for
4. Summarize the calculation results of each working face
5. Simulate the evolution process using dynamic equations
6. The while evolution process has not reached stability
      update parameters
      Re simulate the evolutionary process
   end while
7. Analyze the model output to determine prominent disaster behavior characteristics
8. Return the analysis results of the evolutionary mechanism
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**Figure 1**. Pseudocode of the dynamic model

Based on the fundamental dynamics equation $F(x) = ma$, a complex model is built to describe the interaction between gas and coal. This model couples the mechanical behavior of coal with the flow behavior of gas, forming a set of dynamic equations that can reflect the evolution process of gas outburst. The model parameters are determined by field monitoring data and laboratory experimental results, ensuring the practicality and accuracy of the model.

In order to achieve scientific computing of the model, "pseudo code for dynamic model" was designed. This algorithm optimizes the calculation process, improves the efficiency of calculations, especially in parallel computing of coal stress and gas pressure, the algorithm can effectively reduce the consumption of computational resources. By simulating the evolution process of various types of working faces under different conditions extensively, a systematic understanding of the evolution laws is achieved. In the process of model simulation, parameters and simulation environments are constantly updated to approach the dynamic changes of real coal mine operations, thereby improving the reliability of the prediction results. Pseudocode of the dynamic model see Figure 1.

Based on the actual geological conditions, coal seam structure characteristics, and gas occurrence status, a series of key data are comprehensively collected to establish the initial conditions and boundary conditions of coal and gas outburst models. Detailed simulation parameters are set, such as coal strength, gas pressure, stress distribution, etc., providing a solid foundation for the accurate evolution of outburst disasters during the simulation process.

The process simulation flowchart clearly defines the whole process from defining the model to analyzing simulation results, strictly ensuring that each step can be executed accurately. This process reflects the scientific and rationality of the research method, making the study reproducible. In the simulation of the evolutionary process, we first establish the theoretical model of the evolutionary mechanism, then cross-validate with the software we independently developed and model data, and finally conduct comprehensive simulation experiments using integrated models and software tools. The evolution process simulation flowchart see Figure 2.

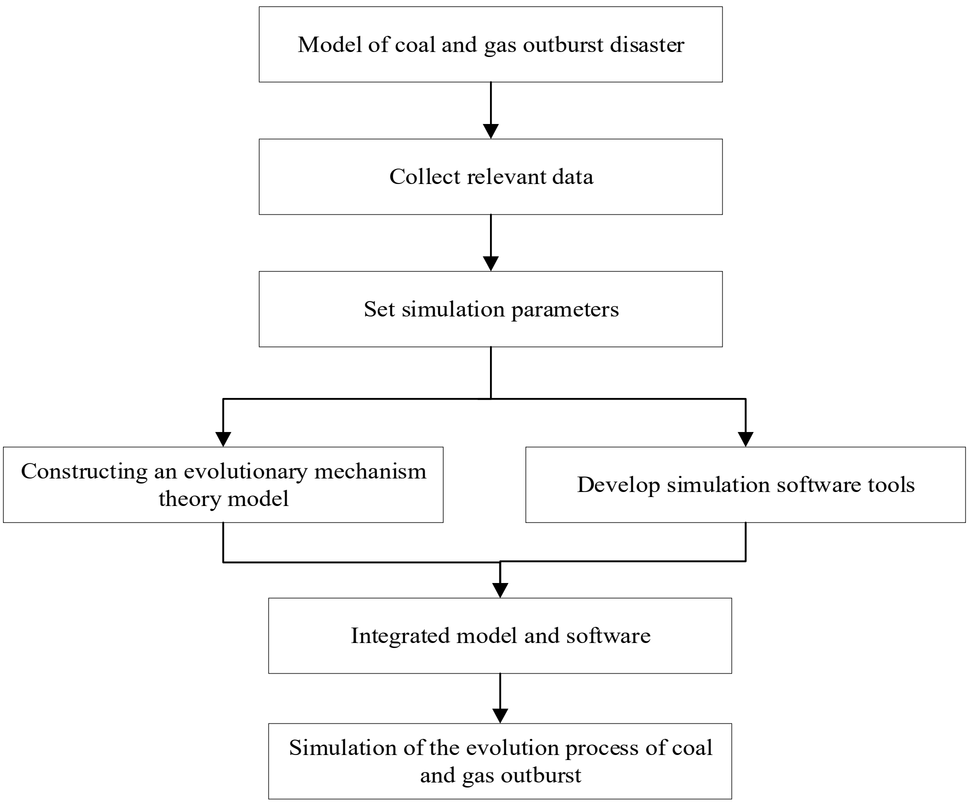


**Figure 2.** The evolution process simulation flowchart

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## 5. Conclusion.

Coal and gas outburst is a nonlinear dynamic phenomenon driven by the coupling of multiple fields. Its disaster evolution process shows obvious staged characteristics, and is a disaster formed by the coupling of the geostress field, gas pressure field, and coal damage field. Internal coal undergoes microfracture due to the interaction of stress field and gas field, accompanied by abnormal gas flow and coal plastic deformation. Outburst eruption manifests as high-energy release, and the outburst strength is power-law related to coal fragmentation. The ejection distance of outburst material is significantly positively correlated with gas pressure.

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