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Invited Review
Mechanism investigation on coal and gas outburst: An overview

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Abstract: Coal and gas outburst is a frequent dynamic disaster during underground coal mining activities. After about 150 years of exploration, the mechanisms of outbursts remain unclear to date. Studies on outburst mechanisms worldwide focused on the physicochemical and mechanical properties of outburst-prone coal, laboratory-scale outburst experiments and numerical modeling, mine-site investigations, and doctrines of outburst mechanisms. Outburst mechanisms are divided into two categories: single-factor and multi-factor mechanisms. The multi-factor mechanism is widely accepted, but all statistical phenomena during a single outburst cannot be explained using present knowledge. Additional topics about outburst mechanisms are proposed by summarizing the phenomena that need precise explanation. The most appealing research is the microscopic process of the interaction between coal and gas. Modern physical-chemical methods can help characterize the natural properties of outburst-prone coal. Outburst experiments can compensate for the deficiency of first-hand observation at the scene. Restoring the original outburst scene by constructing a geomechanical model or numerical model and reproducing the entire outburst process based on mining environment conditions, including stratigraphic distribution, gas occurrence, and geological structure, are important. Future studies can explore outburst mechanisms at the microscale.

Keywords: coal and gas outburst; outburst mechanism; outburst model; outburst simulation; microscopic pore structure

1. Introduction

Coal and gas outburst (hereinafter referred to as outburst) is a frequent dynamic disaster during underground coal mining activities [1–2]. A concise definition is provided by the Australian regulations: “Outburst—the sudden release of gas and material from the working place that can vary in magnitude and intensity” [3]. The ejected coal with a high kinetic energy and the emitted methane with explosive risk may cause high fatality and equipment damage.

More than 40000 outbursts (up to 2007) had been reported around the world since the first documented outburst in France in 1834 [4–5]. An outburst is a major mine hazard with exploitation of coal resources, and about 22 countries, including former Soviet Union, America, China, England, Germany, France, Poland, Australia, South Africa, Japan, India, and Mexico, have experienced outburst disasters. The huge economic loss and casualties had caused a considerable social influence. The largest outburst in the world occurred at Gagarin coal mine in Union of Soviet Socialist Republics (USSR) on 13th July 1969, with 14000 tons coal ejection and 2500000 m³ methane emission [6]. Fig. 1 shows the number of total mine accidents and outburst accidents in China from 2007 to 2018. Total mine accidents were reduced annually with the development of the coal industry, and at least three outburst accidents occurred per year. Fig. 2 shows the fatalities of total mine accidents and outburst accidents in China from 2007 to 2018. Outbursts are mostly the serious accidents with a high fatality rate, accounting for 16%–38% of the total accident fatalities.

On the basis of a long-term statistical analysis about physical phenomena during outbursts, features of outbursts are summarized as follows: (1) outburst risk increases with the mining depth [7–8]. Yu [7] defined the threshold depth of outburst as the minimum depth where the outburst may occur under the existing geological conditions; (2) a large outburst risk covers the geological structure region [9–10], and the regional distribution of outburst proneness appears during mining. Researchers [11–12] considered that outbursts are correlated with soft coal, faults, and/or dykes; (3) out-
bursts mostly occur during tunneling in coal seam, and uncovering coal in cross-cut is intense [8]; (4) the operating induction, such as drilling, cutting, and blasting, is usually discovered before outbursts [8, 13]; (5) some signs, such as sounds, coal spalling, temperature variation, and drill pipe sticking, are observed before a sudden outburst; (6) temporal characteristic is described as the delay occurrence of an outburst; He et al. [6] illustrated outburst occurrence as the result of the rheological behavior of coal; (7) outburst coal, presented as coal lump, granular, and powder, is expelled with a distance from a few meters to thousands of meters, and a cavity in coal seam is formed. The working opening or heading space may be strewn with broken materials.

Significant progress has been made on outburst mechanisms in the past 150 years. Data on coal properties, outburst regularity, hypotheses, and models were obtained through statistical analysis, logic deduction, laboratory experiments, or numerical modeling. However, the mechanism of outbursts remains unclear because none of the theories can explain all statistical phenomena and features during an outburst [14–16]. To present the current progress, we provide an overview of outburst mechanisms from four novel aspects: physicochemical and mechanical properties of outburst-prone coal, laboratory outburst experiment and numerical modeling, mine-site investigations, and doctrines of outburst mechanisms.

2. Physicochemical and mechanical properties of outburst-prone coal

2.1. Chemical components

Coal is a typical organic rock with a complex macromolecular network. The molecular building blocks are linked by covalent and noncovalent bonds of different sizes [17–18]. The mechanical and chemical properties of coal can be influenced by small soluble organic compounds existing in the coal matrix or macromolecular network structure. These small soluble organic compounds make up 10wt%–23wt% and sometimes 30wt% of coal organic matter [17–20]. Cao et al. [10] found that outburst-prone coal contains more soluble organic matter than none outburst-prone coal. Zhang et al. [21] reported that the chloroform extraction of soluble compounds can serve as an index of outburst risk. Extracting organic micromolecules from coal can increase the proportion of meso-/macro-pores and reduce the resistance of gas flow [22]. Similarly, Yang et al. [23] concluded that the soluble organic matter can lower the strength of coal and promote coal and gas outburst.
Chemical composition varies with coal types or depends on the geological environment \cite{18,24–26}. Tectonic stress affects the original physical structure and chemical properties of coal. Ulyanova et al. \cite{27} found one more subcomponent in coal before underground outburst but only two subcomponents after the outburst on the basis of the Raman spectra of fat coal. Dong et al. \cite{28} proved that mechanical force can cause the degradation and chain scission of polymers. Tectonically, the chemical structure of coals can be changed by deforming chemical bonds, which can lead to bond breakage or gas generation \cite{29}. The metamorphism of geologic structure and the dynamic failure of coal can cause changes in chemical composition, which indicates the intrinsic relations between mechanic and chemistry.

### 2.2. Microscopic pore structure

The microscopic pore structure of coal seriously impacts gas adsorption, desorption, diffusion, or even flow \cite{30–31}. A single technology test cannot reveal complete information of the physicochemical structure of coal because of the heterogeneity of this material. The use of different methods, including scanning electron microscopy (SEM) \cite{32–34}, transmission electron microscopy \cite{35–36}, low-pressure nitrogen gas adsorption (LP-N$_2$GA) \cite{32,37}, low-pressure carbon dioxide gas adsorption (LP-CO$_2$GA) \cite{38}, small-angle X-ray scattering \cite{39–40}, small-angle neutron scattering \cite{41}, nuclear magnetic resonance (NMR) \cite{42–43}, and atomic force microscopy (AFM) \cite{44–45}, can provide insights into the physicochemical properties of natural coal.

#### 2.2.1. Porosity types and morphology

De Boer \cite{46} identified certain types of hysteresis loops associated with various pore shapes. Nie et al. \cite{34} performed SEM and LP-N$_2$GA to investigate the pore structure of coal with different ranks. The pores of samples were characterized by four pore shapes according to the hysteresis loops and SEM images, as shown in Fig. 3. The pore shape in coal can impact the behavior of gas emission. For example, the hysteresis effect of gas adsorption and desorption occurs more in bottleneck pores because of their poor interconnectivity compared with cylindrical, slit, and wedge-shaped pores. Researchers \cite{42,47} employed NMR wide line spectroscopy to verify the existence of open and closed porosity and provided a definition of closed pores. Closed-pore volumes increase the outburst proneness of coal. Jiang et al. \cite{48} proposed that bottle- and slit-type pores in granulitic and mylonitic coal contribute to outbursts.

Cao et al. \cite{9} observed microstructurally altered coal with crushing-type microstructure via SEM. Outburst-prone coal has a greater degree of deformation and microstructure alteration in reverse fault footwalls. Tectonic deformation causes micropores collapse and enhances mesopore specific surface area and volumes \cite{38}. Pan et al. \cite{45} characterized the pore morphology of ductile and brittle deformation of coal through AFM and found that the predominant pore morphology of tectonic deformed coal is flat micropores.

#### 2.2.2. Pore size distribution and adsorption behavior

Several scholars recognized the close relation between pore size distribution and adsorption. An et al. \cite{49} investigated the effect of micropores on the adsorption behavior of coal in different ranks. Li et al. \cite{50} concluded that the desorption characteristics of tectonic coal at the initial stage are determined by the proportion of microporous and transitional pores. Sun et al. \cite{51} found that the fractal dimensions of coal pore surfaces are related to adsorption capacity and that higher irregularity means rougher surfaces and more micropores. Yang et al. \cite{52} proposed a fractal-thermodynamic model to understand the correlations between pore structure and gas sorption behavior.

These findings are valuable to understand gas storage and migration in coal, which also contribute to the regularity of outbursts. However, the closed-pore structure distribution, pore distribution in three-dimensional (3D) space, and connectivity of coal microstructure remain to be clarified.

### 2.3. Mechanical characteristics of gas-bearing coal

#### 2.3.1. Coal strain induced by gas adsorption

Cubical dilatation of coal occurs when gas is adsorbed, and coal matrix shrinks but maintains a residual deformation while gas is desorbed \cite{53–55}. He et al. \cite{6} indicated that gas adsorption decreases the surface energy of coal, leading to solid-phase dilatation. The definition of gas “erosion” was developed to describe the effect of coal strength weakened by gas \cite{56}.

Models of adsorption swelling were developed to describe the mechanical behavior of gas-bearing coal. Wu and Zhao \cite{57} considered that adsorption-induced swelling stress is the major contributor to effective stress. Associated with adsorption swelling, gas erosion, original damage, and failure of coal skeleton, a dual pore damage constitutive model was established by researchers \cite{58–59}. Hol et al. \cite{60} developed a thermodynamic model combining with poroelasticity to describe the competitive relation between adsorption swelling and compression. Nie et al. \cite{61} introduced a particle tracking method with computerized tomography (CT) scanning to calculate the coal matrix strain induced by gas adsorption (Fig. 4). The spatial–temporal distribution of coal mesoscopic deformation is inhomogeneous during gas adsorption. Some parts of coal swell and other parts shrink, but the mineral phase and porosity undergo swelling deformation.

#### 2.3.2. Constitutive relation of gas-bearing coal

The mechanical behavior of gas-bearing coal is described mostly based on the framework of effective stress, influenced by adsorption gas and free gas. The elasto-plastic model is widely employed to illustrate the stress path, elastic deformation, and failure behavior of gas-bearing coal.
The yield criteria, including Mohr–Coulomb, Drucker–Prager, Griffith, and maximum tensile stress theory, are applied to describe the plastic flow of gas-bearing coal. Visco-elasto-plasticity can represent the time-dependent behavior of gas-bearing coal. He et al. [6] adopted the classical Nishihara model to characterize the rheological behavior of gas-bearing coal. Researchers proposed an extended Nishihara model [65–66] to describe the creep of gas-bearing coal. Danesh et al. [67] adopted an extended stress–strain model of anisotropic media to investigate the impact of creep strains on coal permeability. Results show that the time-dependent strain in coal should be considered when predicting the interaction between gas transport and coal deformation.

2.3.3. Gas seepage in coal

Coal seams show considerable difference in gas storage mode and permeability characteristics compared with normal porous gas reservoirs [68]. Harpalani and Chen [55] found an 80% increase in coal cleat porosity due to matrix shrinkage induced by gas desorption. Li et al. [69] reported that the adsorption-induced strain of coal matrix increases with increasing gas pressure and leads to poor porosity and permeability.

The evolution of permeability of gas transport in coal seams is complex, concurrent with varied stress conditions, coal properties, and gas occurrence. Wang et al. [70] proposed a multi-scale model of coal–gas coupling. Wang et al. [71] and Xue et al. [72] studied the mechanical behavior of coal–rock combination body. Wang et al. [73] and Espinoza et al. [74] investigated the desorption-induced failure of coal. Researchers [75–78] studied the gas–solid coupling properties of gas-bearing coal, including creep regularity, seepage rule, and Klinkenberg effect, and geomechanical characteristics under loading axial stress and unloading confining.

Fig. 3. SEM images of coal in different ranks: (a) anthracite of Peigou; (b) anthracite of Zhenxing; (c) low-volatile bituminous of Runhong; (d) low-volatile bituminous of Guandi; (e) low-volatile bituminous of Changcun; (f) low-volatile bituminous of Ximing; (g) medium-volatile bituminous of Zhenchengdi; (h) medium-volatile bituminous of Malan; (i) high-volatile bituminous of Donghuatu; (j) high-volatile bituminous of Xin’an; (k) lignitic coal of Malan. Reprinted from Fuel, 158, B.S. Nie, X.F. Liu, L.L. Yang, J.Q. Meng, and X.C. Li, Pore structure characterization of different rank coals using gas adsorption and scanning electron microscopy, 908-917, Copyright 2015, with the permission from Elsevier.
They considered that a sudden enhancement of permeability in coal wall or even outbursts might be easily triggered by the combined effect of ground stress, gas pressure, and temperature.

Quantitative analysis of coal failure to predict outburst has not been achieved, and current studies on the fragile characteristics of coal are insufficient. The mechanical behavior of coal is complicated because of its complex microstructure and chemical composition. With consideration of gas–solid coupling, explorations must focus on the failure process of gas-bearing coal to elucidate the mechanisms of outburst hazard.

3. Laboratory-scale outburst experiment and numerical modeling

3.1. Outburst experiment

Laboratory experiment studies provide opportunities to test the relation between outbursts and various factors by controlling experimental conditions. Moreover, it is a feasible way to verify hypothesis or explore outburst mechanisms. On the basis of the scale of experimental apparatus, outburst experiments were classified into two categories: simple and modern scale.

3.1.1. Simple scale

Researchers [79–81] used a shock tube to simulate coal fragmentation. An outburst pipe designed by Polish Academy of Sciences was used to investigate the influence of sorption on the outburst occurrence and outburst risk of coal with different strengths [82–84]. Alexeev et al. [85] used a true triaxial loading apparatus to reproduce artificial outburst-type fracture mode. Scholars [86–87] developed a one-dimensional (1D) outburst simulation apparatus and applied it to investigate outburst in condition of uncovering coal in cross-cut. Cai [88] designed a three-dimensional (3D) outburst simulation apparatus based on the principle of elasticity similarity.

3.1.2. Modern scale

With the improvement of experiment instruments and methods, experimental platforms tend to be large scale in specimen size, multifunctional in experimental research, and mass data in model response. Table 1 shows the modern-scale experiment platforms developed by China institutions. Using a triaxial outburst simulation system, Tu et al. [16] studied the initiation energy of outbursts at the gas-rich region. Yin et al. [15] developed an experimental apparatus with non-uniform distribution of loadings, and Peng et al. [89] investigated the influence of gas seepage on outbursts.
Wang et al. [90] performed multi-factor orthogonal experiments by using the outburst simulation system based on the CSIRO (Commonwealth Scientific and Industrial Research Organization) model.Nie et al. [91] developed a middle-scale simulation system of outburst with a specimen size of 1.5 m × 0.6 m × 1.0 m, which can simulate the coal seam sandwiched by roof and floor. Zhou et al. [92] and Zhang et al. [93] designed a test system for the visualization of dynamic disasters, including a power system and a simulated roadway system. The evolution of spatiotemporal characteristics of pressure, temperature, and impact force was obtained in an outburst simulation. Li et al. [94] developed a large-scale 3D outburst quantitative physical modeling system with a specimen size of 1.5 m × 1.5 m × 3.0 m, maximum gas pressure of 3 MPa, maximum load capacity of 60 MPa, and maximum acquisition frequency of 500 kHz. A tunnel micro-TBM unit was equipped to simulate the effect of mining disturbance. The system provided a quantitative simulation platform for researching outburst occurrence conditions.

<table>
<thead>
<tr>
<th>Experimental platform</th>
<th>Dimension size of specimen</th>
<th>Loading conditions</th>
<th>Geologic setting</th>
<th>Gas pressure / MPa</th>
<th>Data acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A triaxial outburst simulation system (Tu et al. 2016) [16]</td>
<td>0.25 m × 0.25 m × 0.25 m</td>
<td>Triaxial and uniform loading</td>
<td>Coal seam</td>
<td>≤10</td>
<td>—</td>
</tr>
<tr>
<td>An experimental apparatus for outburst simulation (Yin et al. 2016) [15]</td>
<td>0.57 m × 0.32 m × 0.385 m</td>
<td>Biaxial and non-uniform loading</td>
<td>Coal seam</td>
<td>≤2</td>
<td>—</td>
</tr>
<tr>
<td>Outburst simulation system based on the CSIRO model (Wang et al. 2015) [90]</td>
<td>0.2 m × 0.6 m</td>
<td>Axial and uniform loading</td>
<td>Coal seam</td>
<td>≤3</td>
<td>Gas pressure and high-speed photography</td>
</tr>
<tr>
<td>Middle scale simulation system of outburst (Nie et al. 2019) [91]</td>
<td>1.5 m × 0.6 m × 1.0 m</td>
<td>Axial and non-uniform loading</td>
<td>Coal seam, roof and floor, and geologic structure</td>
<td>≤2</td>
<td>48-channel data acquisition system, collected data including stress, displacement, gas pressure, temperature, and high-speed photography</td>
</tr>
<tr>
<td>Test system for the visualization of dynamic disasters (Zhou et al. 2019; Zhang et al. 2019) [92–93]</td>
<td>0.41 m × 0.41 m × 1.0 m</td>
<td>Triaxial and non-uniform loading</td>
<td>Coal seam and road system</td>
<td>≤10</td>
<td>64-channel data acquisition system, collected data including stress, displacement, gas pressure, temperature, concentration, and impact force</td>
</tr>
<tr>
<td>A large-scale 3D outburst quantitative physical modeling system (Li et al. 2018) [94]</td>
<td>1.5 m × 1.5 m × 3.0 m</td>
<td>Triaxial and non-uniform loading</td>
<td>Coal seam, roof and floor, geologic structure, and mining disturbance</td>
<td>≤3</td>
<td>500 kHz of maximum acquisition frequency, collected data including strain, stress, gas pressure, and temperature</td>
</tr>
</tbody>
</table>

Some environmental factors, such as mining disturbance, geologic structure, and coal original state, are simplified in the design of experimental platforms. These simplifications are necessary to create ideal experimental conditions. Outburst experimental results obtained with large-size specimens are close to reality because the process of outburst is complicated and covers preparation, triggering, development, and end stages. Experimental platforms meeting complex conditions, such as coal seam sandwiched by roof and floor, geologic structure, and mining disturbance, are preferred but entail huge economic cost. Current experimental researchers mostly focus on the factors influencing outbursts. An outburst simulation that can realistically represent the disasters at work face is important to further study.

3.2. Numerical modeling

With the rapid advance of computer science, numerical modeling has achieved great development from the derivation of solutions with simplified geometry and boundary conditions to a global-scale modeling of multiple physical processes. Quantitative analysis of outbursts can provide useful insights into their mechanisms. Current studies on outburst modeling only provided one- or two-stage description and focused on outburst preparation, development, and preparation and triggering.

3.2.1. Modeling of outburst preparation

Chen [62] adopted a hybrid computation scheme to model the outburst process and implemented parametric studies.
Paterson [95] proposed a model of structural failure and used tensile strength as a criterion of coal failure. Valliappan and Zhang [96] adopted the finite element method (FEM) to calculate the variation of elastic energy of coal and rock. Barron and Kullmann used a boundary element code to model a non-coal outburst [97–98]. Tao et al. [99] developed a THM (thermo–hydro–mechanical) coupling model of gas-bearing coal to analyze outburst occurrence. An et al. [64] established a numerical model for gas and coal coupling, incorporating adsorption-induced swelling and desorption-induced shrinkage. With a coupling model, Liu et al. [100] investigated the evolutions of stress and gas pressure during uncovering coal in cross-cut.

3.2.2. Modeling of outburst development

Otuonye and Sheng [101] formulated a two-dimensional (2D) mathematical model for solving gas flow and propagation of a shock wave in roadway. Zhou et al. [102] adopted the finite volume method (FVM) to simulate the propagation of outburst shock waves and gas flow numerically within underground roadways.

3.2.3. Modeling of outburst preparation and triggering

Chio and Wold [103] developed a coupled geomechanical-reservoir model to analyze the proneness and post-initiation of outbursts. Xu et al. [104] developed the RFPA (Realistic Failure Process Analysis) 2D—GasFlow code to simulate the process of outburst, incorporating gas seepage in porous media, damage deformation, and instantaneous failure. Wold et al. [105] used a stochastic model based on the Monte Carlo technique to simulate the spatial distribution of permeability and strength. Xue et al. [63] developed a simulator by coupling FLAC 3D and COMET3 to simulate outburst initiation. In addition, Xue et al. [106] and Wang and Xue [107] proposed a model coupling the DEM (Discrete Element Method) and LBM (Lattice Boltzmann Method) to simulate outburst initiation and development. The particle motion, gas concentration, and fluid velocity can present the process of coal fracturing. The fractured coal is ejected under the exertion force of fluid, and an outburst cavity is formed inside the coal wall.

The outburst process is complicated, including phase transformation, gas flow, solid deformation, and breakage, and an entire outburst description is valuable. Gas-bearing coal is characterized by the large deformation and two-phase flow during an outburst. Conventional methods, such as FEM and FVM, cannot illustrate both features. Therefore, the development of new numerical methods for the entire process of an outburst, describing large deformation of solid and coal–gas movement, is indispensable for further study.

4. Mine site investigations

4.1. Red international trade union colliery in USSR

Yu reported field observations of the outburst process, conducted by Red international trade union colliery, at Mining Safety and Environmental Protection in 1980 [108]. The Jielezovsky coal seam with the mining level of +537 to +640 m was selected as the test zone. A roadway 10 m below coal seam was excavated as the observing site, ahead of coal face about 90 m long. Gas pressure was recorded by drilling 56 boreholes from the observation site to the coal seam and by

![Fig. 5. Field observations of coal and gas outburst in Red international trade union colliery, USSR: (a) roadway layout in test area of coal seam, Red international colliery; (b) variation of pressure difference in test zone [108].](image-url)
installing pressure gauges. The observation site and design of boreholes are shown in Fig. 5(a).

The original gas pressure of the test zone ranging 0 to 70 m along the tunneling direction was 2.6–3.0 MPa. The coefficient of gas filtration varying along the coal seam was \((4.6–220) \times 10^{-5} \text{m}^2/(\text{MPa} \cdot \text{d})\), and that in the damaged zone registered a larger value. Pressure differences between pre-outburst and post-outburst varying along the tunneling direction are shown in Fig. 5(b). One blasting induction with non-outburst was accompanied with significant changes in gas pressure. However, gas pressure difference was not immediately observed when an outburst was induced by blasting. Significant changes in gas pressure were present after the outburst. Thus, the immediate pressure change induced by blasting means the release of gas energy. The coal seam ahead of coal face was divided into three zones: breakage zone with the length of 5–8 m, low stress, low gas pressure, and high coefficient of gas filtration; compression zone with the length of 2–12 m, stress concentration, higher gas pressure, and low coefficient of gas filtration; original zone approaching the undisturbed region of coal seam.

### 4.2. Zhongliangshang colliery in China

An outburst with 817 tons coal and rock ejection, 38540 m³ gas emission, and 39 s duration was observed at Zhongliangshan colliery in Chongqing, southwest of China, on 4th November, 1977 [8,109]. The observation site and records of gas pressure, gas flow, temperature, gas concentration and sounds are shown in Fig. 6. No. 1 and No. 2 boreholes were employed to monitor the variation in gas pressure, No. 3 borehole gas flow, and No. 4 temperature and gas concentration. Gas pressure in No. 1 and No. 2 boreholes dropped during the outburst, but the response of No. 2 was earlier because it was closer to the coal face. A small pressure increase in No. 2 borehole was shown at 9 s with gas flow increasing in No. 3 borehole. This result indicated that the gas releasing rate was faster than the coal damage rate and that the plugging coal led to a slight recovery of pressure. The gas flow in No. 3 borehole reached the maximum at 10 s after outburst triggering, and this phenomenon could be recognized as outburst development. The gas concentration in No. 4 borehole increased rapidly, whereas the gas flow in No. 3 borehole increased rapidly, whereas the gas flow...
borehole increased again from 18 to 21 s. This result can be ascribed to the fact that the coal mass close to No. 4 borehole participated in outburst and the adsorbed gas was released. The outburst terminated with gas flow dropping to the minimum. The loud crash and strong wind blowing noises produced during impact fracturing and gas emission, respectively, were monitored during the outburst.

Although a large quantity of statistical data and experiences about outburst have been accumulated, field observation of the entire process of outbursts is rare. An outburst is highly destructive, and its real-time monitoring can be challenging. Choosing the appropriate project location, arranging the engineering site, and equipping the monitoring system consume numerous human and material resources. Field observation provides first-hand data and is the most valuable for research. Laboratory outburst experiments or numerical modeling can be an alternative for the study of outburst mechanisms.

5. Outburst mechanism

In recent decades, a series of hypotheses or conjectures based on field testing, statistics, and laboratory experiments has been proposed for outburst mechanisms. These theories are established from the viewpoint of a driven force of an outburst. Based on different dominant factors leading to an outburst, these theories can be divided into two categories: single-factor and multi-factor mechanisms. The former mainly includes gas-dominant and stress-dominant theories. The latter is also known as combination-effect theories of multiple factors, believing that factors, including gas, stress, and coal property-related factors, can influence the occurrence of outbursts.

5.1. Single-factor mechanism

5.1.1. Gas dominant theories

Scholars first focused on the close relationship between outburst and sudden gas emission [110]. Gas dominant theories hold that high pressure methane stored in coal is the main contributor to an outburst. Another presentation is that the most common and direct factor initiating an outburst is the free gas present in the coal seam.

The well-known gas dominant theories include cavity theory [2], gas pocket [111], pressure fall theory [112–113], body force theory [95], and phase transformation theory [114–115]. The role of pressure gradients in coal was highlighted by pressure-fall theory and body force theory. The phase transformation model held that a rarefaction shock wave is induced by a jump-like change in stress state and that a phase transformation destroys the medium and initiates an outburst.

5.1.2. Stress dominant theories

Stress dominant theories believe that stress is the main contributor and energy source to an outburst, while gas release in the process of crushing coal comes only second. Two aspects about the source of stress during outbursts are considered: tectonic stress of crustal movement and load of overlying strata on coal seam; stress concentration ahead of coal face is induced by mining activities.

Along this strand of research, Singh’s mechanism [116], dynamic theory [117–118], crushing wave theory [119–120], and united instability theory [121] were known by researchers. Mining factors were emphasized by Singh’s mechanism and dynamic theory, and natural tectonic and induced stress were both considered by crushing wave theory. United instability theory [121] held that the stability of coal/rock depends on its equilibrium of the deformation system. Several researchers have associated outbursts and rockbursts as a single phenomenon with the difference that gas may be absent [121–122].

5.2. Multi-factor mechanism

The formation of multi-factor mechanism was marked with USSR scholar Nekrasovski’s theory in 1950s, based on experiences of on-site outbursts and theories of his predecessors. Nekrasovski held that outburst results from the combination of multiple factors, including the role of gas in coal, mechanical and physical properties, microstructure, macrostructure, geological structure, and gravity of coal [6,123].

An energy theory of outbursts proposed by Hodot [124] held that the coal mass near the coal face is crushed by the sudden release of strain energy and gas energy, and emitting gas suspends the coal pieces to form coal–gas flow. On the basis of investigations on coal properties and outburst experiments, “energy theory” enriches the multi-factor mechanism.

Considering that the major factors contributing to outbursts include gas, geostress, mechanical and physical properties of coal, and their time-dependent properties, researchers [6,125] proposed a rheological mechanism of outburst. Experimentally, failure of gas-bearing coal is characterized by three time-dependent phases, namely, attenuation distortion, uniform deformation, and accelerated distortion. Outburst is the rapid process of coal rheology behavior, in which the former two phases are the preparation of outburst initiation, and the later phase is the outburst initiation and development. Four regions ahead of coal face, relaxation region, intensive rheological region, weak rheological region, and original region, were divided on the basis of stress distribution on the mining panel, as shown in Fig. 7. With time running out, rheological failure of coal body occurs at the work face. The mitigation of stress concentration, decrease in lateral stress, and depletion of gas pressure show time-related characteristics. This theory describes the outburst regularity from the spatiotemporal viewpoint and has some progress in the quantitative analysis of outburst initiation.

Choi and Wold [126] proposed the CSIRO model and be-
lieved that outburst is the combined effect of multiple factors, including geostress and its dynamic distribution, gas and its dynamic distribution, and mechanic physic properties of coal and its dynamic distribution. Accompanied by extraction activities, gas, stress, and strength mutually interact with each other and produce a comprehensive effect.

Hu et al. [127] described the breakage process of coal among four stages of an outburst, including preparation, trigger, development, and termination stages. Evolution of outburst cavity was illustrated by analyzing the coal failure modes induced by geostress and gas pressure, as shown in Fig. 8. The damaged surface around the outburst cavity goes deep into the internal side of the coal seam continuously during an outburst. The outburst process is summarized as an intermittent and multiple destruction and impulsive ejection.

![Diagram of outburst process](http://example.com/diagram)

**Fig. 7.** Rheological regions around the tunnel opening ($t_1, t_2,$ and $t_3$ are the time of rheological behavior, $t_1 < t_2 < t_3$).

**Fig. 8.** Entire process of coal and gas outburst. Reprinted from *Int. J. Coal Geol.*, 194, K. Jin, Y.P. Cheng, T. Ren, W. Zhao, Q.Y. Tu, J. Dong, Z.Y. Wang, and B. Hu, Experimental investigation on the formation and transport mechanism of outburst coal–gas flow: Implications for the role of gas desorption in the development stage of outburst, 45-58, Copyright 2018, with the permission from Elsevier.

Other multi-factor mechanisms of outbursts include the steady advance model [79–80], spherical shell losing stability model [86,128], magma fragmentation mechanism [81], a stick-slip mechanism [129–130], and an instantaneous outburst model [131].

The multi-factor mechanism, incorporating the mining-induced disturbance, effective stress, gas flow, and physico-chemical and mechanical properties, is built up through the long-term exploration of outburst occurrence. Several researchers [123–131] concurred that coal failure is affected by the variation of effective stress and that the broken coal is ejected by the rapid desorbing gas. On the basis of multi-factor mechanism, some outburst realities, such as the rapid desorbing rate of coal, abnormal geological structures, and
depth of outburst location, can be considered as the factors that increase effective stresses or reduce coal strength. These factors increase the outburst proneness of coal seam but are not sufficient causes of outburst initiation. So far, no one single theory can explain the entire process of an outburst. In consideration that the nature of outburst-prone coal is not completely understood, the theories of multi-factor mechanism can be constantly improved with the updated knowledge of coal properties.

6. Outlook

6.1. Research issues

Outburst process is complicated and involves physics, chemistry, mechanics, and geology. Present knowledge of physicochemical and mechanical properties of outburst-prone coal is insufficient to explain all statistical phenomena during an outburst. A precise explanation should be made for the phenomenon. Some of the important topics for further study are listed as follows.

(1) Excess coalbed methane in coal seam. The volume of emitting gas during an outburst is usually greater than the measured gas content in coal seam [132]. For example, an outburst in Dashucun coal mine on 19th April 2007 produced 1270 t coal ejection and $9.3 \times 10^3$ m$^3$ gas emission. The gas content of outburst coal is about $73.2 \text{ m}^3/\text{t}$, which is considerably greater than gas content of coal seam. Many scholars have noticed the existence of excess coalbed methane and conducted related investigations, such as closed porosity [47], gas hydrate [133], cluster structure of supercritical CH$_4$ [134], and excess adsorption amount of supercritical CO$_2$ [135]. Thus, the key point is the gas occurrence and migration in natural coal structure.

(2) Low-threshold outburst phenomenon. The critical values of 0.74 MPa gas pressure and 8 m$^3$/t gas content are specified as the identification indicators in China (AQ 1024–2006, specification for identification of coal and gas outburst-prone mines). However, some outbursts are triggered with the indicator of gas pressure or gas content lower than 0.74 MPa or 8 m$^3$/t on the spots. For example, statistics of outburst accidents in the Xinmi mining area of China from November 1989 to 2011 showed that 57% of outbursts were with gas content of less than 8 m$^3$/t and 75% were with gas pressure of less than 0.74 MPa [136]. The failure process of gas-bearing coal is extremely complicated because the influence of gas adsorption and pore structure on effective stress is difficult to predict [137–138]. Therefore, a feasible criterion describing gas-bearing coal failure can enable the assessment of the outburst proneness of coal seam.

(3) The highest probability of inducing operations for an outburst is blasting at coal face, compared with drilling, supporting, and cutting coal [8,13,130,139]. Blasting operation can eliminate the stress concentration and facilitate the crack development. Nie and Li [140] studied the influences of vibration acting on gas desorption or coal structure. Researching on the process of an outburst induced by blasting is meaningful to elucidate outburst mechanisms [139–142].

(4) Outburst coal presents sorted behavior, of which minimum particle size is less than 0.1 mm. Table 2 shows the size distribution of coal particles from four outbursts in Chinese coal mines. Coal powder with size less than 1 mm takes up a high proportion in outburst coal. Coal particles below the millimeter level have a greater relevance with tension of high-pressure gas [58,143–145]. Nie and He [146] paid attention to the phenomenon that nanopore damage or destruction is followed by gas release during an outburst. “Gas microburst” is employed to illustrate the process that gas inflation under a pressure gradient causes the breakage of coal pores. While numerous or countless gas microbursts are gathering and releasing huge amounts of gas, coal is disintegrated and contributes to outburst. On the basis of the nanoscale mechanical properties of gas-bearing coal, investigations on the microscale mechanism of the interaction between coal and gas will help reveal outburst mechanisms.

Table 2. Coal size distribution of four outbursts in China [8]

<table>
<thead>
<tr>
<th>No.</th>
<th>Diameter / mm</th>
<th>Outburst location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;0.1</td>
<td>K2 coal seam at +280 m elevation in Zhongliangshan coal mine, China</td>
</tr>
<tr>
<td>2</td>
<td>0.1–1.0</td>
<td>27.5% 26.7% 10.0% 20.0%</td>
</tr>
<tr>
<td>3</td>
<td>1.0–5.0</td>
<td>31.0% 17.6% 9.8%</td>
</tr>
<tr>
<td>4</td>
<td>5.0–10.0</td>
<td>23.9% 23.5% 39.5%</td>
</tr>
<tr>
<td>5</td>
<td>&gt;10.0</td>
<td>26.0% 20.0%</td>
</tr>
</tbody>
</table>

(5) Compound dynamic disasters. As the mining depth increases, two dynamic disasters, outburst and rockburst, can coexist, interact, and deteriorate the safety environment mutually. Pan and other researchers [147–148] introduced the concept of compound dynamic disaster of outburst and rockburst and established the unified criterion of instability. Gao et al. [149] and Zhang et al. [150] studied the influence of gas on coal burst tendency and believed that the evaluation on rockburst risk of gas-bearing coal seams should consider the influence of gas. Thus, a future requirement for mechanism exploration is to conduct an integrated study by unifying outburst and rockburst.

6.2. Research techniques

The updated research techniques can facilitate a deep understanding of the nature of coal, which provides new
sights into outburst mechanisms [34–45,89–94,100–107]. Microscopic investigation on coal materials by using detection methods of modern physics can help reveal the physicochemical properties of coal. Imagining microstructure of porous media has opened up the possibility to image the microspace of coal materials. Further development and application of the imaging technology would greatly promote the research of the nanoscale properties of coal. Focused ion beam nanotomography (FIB-nt) enables 3D high-resolution imaging at the sub-100-nm scale, and the results can directly be applied to analyze porosity and permeability [151]. Focused ion beam scanning electron microscopy and focused ion beam helium ion microscopy were used to characterize shale gas reservoir [152]. X-ray tomography can deliver the 3D internal structure of entire samples as well as coal matrix or microparticles. Nano-CT, a new generation of laboratory-based X-ray computed tomography, provides 3D images that can be processed and analyzed to obtain morphological information of pore network at the nanoscale resolution (50–100 nm). Zhao et al. utilized synchrotron-based nano-CT [153] to characterize pore shapes, sizes, connectivity, and tortuosity. Ptychographic X-ray computed tomography (ptychographic tomography), using a ptychographic coherent imaging approach to record tomographic data sets, can image large fields of view at high resolution [154]. A superior performance of ptychographic tomography reaches an isotropic 3D resolution of 16 nm [155]. In addition, nanomechanical testing methods, such as AFM and nanoindentation, can obtain microscale stiffness, rigidity, resistance to breakage, and adhesive properties [156–159]. Characterization of mechanical behavior at the microscale would help explore the breakage mechanism of coal during an outburst. Exploration of the interaction between coal and gas at the microscale can reveal the outburst mechanism at the microscale, which can be a trend for further study. Laboratory outburst experiments cannot be substituted because the first-hand observation data on the scene are rare. Such experiments can not only meet the requirements of exploring and verifying outburst mechanisms but also represent a true outburst disaster case to discuss the catastrophic process. Numerical modeling can show great flexibilities while dealing with on-site problems and provide a practical point of view.

7. Conclusions

The outburst mechanism is overviewed according to priority: physicochemical and mechanical properties of outburst-prone coal, laboratory outburst experiment and numerical modeling, mine-site investigations, and doctrines of outburst mechanism. Some conclusions are obtained as follows.

1) Multi-method characterization about the microscopic morphology and pore structure can gain insights into the properties of natural coal materials. With consideration of gas–solid coupling, researching on the failure process of gas-bearing coal can be an important idea to explore the mechanism of outburst hazard.

2) Laboratory outburst experiments, reproducing the outburst process and making up for data deficiency in the scene, are important. A consistent numerical simulation of the entire process of outburst with a suitable numerical method, describing the large deformation of gas-bearing coal and gas–solid movement, can be indispensable to further research.

3) Multi-factor mechanism is widely accepted, but the theories of multi-factor mechanism can be constantly improved with the updated knowledge of coal properties. A further improvement, analyzing the outburst process at the microscale, is important in understanding the mechanism.

4) Further studies can be carried out through a methodology framework. On the basis of the new insights on the physicochemical and mechanical properties of coal materials, an extended numerical model of describing the entire outburst process might be established to predict and assess outburst risks and verified by experiments restoring outburst on the scene.

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