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Numerical Simulation Study on the Multi-Physical Field Response to Underground Coal and Gas Outburst under High Geo-Stress Conditions

Bo Zhao ^{1,2,*}, Guangcai Wen¹, Jun Nian¹, Qianwei Ma³, Chaojun Fan⁴, Xiaobo Lv¹ and Chunsheng Deng¹

- ¹ School of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China; wgc139@126.com (G.W.); njmkws@163.com (J.N.); lxb257@163.com (X.L.); dengchunsheng@tyut.edu.cn (C.D.)
- ² Coal Science and Industry Group Chongqing Research Institute, Chongqing 400037, China
- ³ Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH 43210, USA; ma.1914@osu.edu
- ⁴ School of Mining, Liaoning Technical University, Fuxin 123008, China; chaojunfan@139.com
 - Correspondence: zhaobo91@cqu.edu.cn; Tel.: +86-18375861815

Abstract: Based on thermal–fluid–solid coupling law in coal and gas outburst, a multi-physical field numerical analysis model is built for the whole outburst process. The response laws of stress, gas pressure, temperature, and seepage in different areas and different time nodes around coal and rock mass in the coal and gas outburst under high stress condition are discussed. Research results show: Firstly, the stress response law of the coal and rock mass around the burst hole is initial vibration–sudden attenuation–late stability. Secondly, the gas pressure response law in different areas is that the gas pressure response rate decreases gradually with the increase of the distance from the outburst. Thirdly, the adsorbed gas contained in the broken coal near the outburst port is desorbed rapidly and expands to do work, and the temperature changes dramatically after outburst occurs. In contrast, with the increase of stress, the proportion of elastic potential in total coal and gas outburst energy increases, and the proportion of coal and gas outburst decreases with the increase of stress. The critical gas pressure under the energy condition of coal and gas outburst decreases with the increase of stress. It illustrates that the lower gas pressure can also meet the energy condition of coal and gas outburst under high stress.

Keywords: deep mining; coal and gas outburst; multi-physical field; energy condition

1. Introduction

With the depletion of coal resources in shallow mines and the increasing instability of world energy, mining operations inevitably develop gradually from shallow mining to deep mining [1–5]. Many mining areas in the world have entered deep mining. Taking the central and eastern regions of China (Huainan and Huaibei mining areas, etc.) as an example, the mining depth generally reaches 700–800 m [6–10]. The mining depth of more than 70 coal mines reached 1000 m in 2020 [11,12]. Moreover, with the increase of mining depth, the stress, gas pressure and content, and ground temperature rise continuously, the coupling law of stress, gas, coal, and rock becomes more complex, and various disasters and accidents become more serious [13–17]. In the case of gas extraction up to standard, coal and gas outburst accidents still occur frequently under deep high stress condition, which has seriously restricted the safety of coal mining [18]. Therefore, it is of great significance to study stress, gas and coal coupling mechanism, and coal and gas outburst theory under high stress in deep mining [19–26].

Coal and gas outburst is a dynamic phenomenon in which a large amount of coal rock carrying a large amount of gas is suddenly released into the mining space [27]. Burst coal-gas can sometimes travel several or even thousands of meters against the wind in



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the tunnel, and the burst coal can sometimes fill the entire tunnel [28,29]. When the coal-gas mixture meets a fire source in a roadway, it may cause a gas, coal dust, or gas coal dust explosion, among others, which seriously endanger mine worker safety and cause a huge economic loss. The coal and gas outburst mechanism has been studied extensively in major coal producing countries by means of theoretical analysis, laboratory tests, numerical simulation, and field tests [30–33]. A series of hypotheses on coal and gas outburst mechanism are established [34-38]: "gas-dominated hypothesis", "stress dominated hypothesis", "comprehensive hypothesis", "chemical nature hypothesis", etc. Currently, research on coal and gas outbursts is based mainly on the comprehensive hypothesis. The theory that the in situ stress and gas pressure provide an energy source for the occurrence and development of coal and gas outbursts is generally believed [39-42]. The physical and mechanical properties of coal and rock reflect the ability of coal and rock to resist damage. Furthermore, Wang et al. proposed that the coal and gas outburst intensity increases with the increase of mining depth and coal seam thickness [37]. Xu et al. used RFPA2D-Gasflow software to conduct numerical tests on the basic mechanical properties, and studied the mechanical properties and seepage evolution law of coal and rock under different stress conditions [43,44]. Koltun et al.state diffusion in heterogeneous media and sorption–desorption processes [45]. Overall, there are few research results on the multi-physical field parameter response of coal and gas outburst under different stress conditions. Therefore, based on thermo-fluid-solid coupling in the whole coal and gas outburst process, a numerical model is established to study the multi-field coupling relationship. Taking the outburst accident in Dingji Coal Mine as the prototype, numerical simulation was used to study multiple physical field response parameters in the whole coal and gas outburst process, thus providing a reference for the prediction and prevention of deep coal and gas outburst.

2. Multi-Physics Coupling in the Coal and Gas Outburst Based on Fractal Analysis 2.1. *Stress Equation*

Based on fluid–structure coupling theory [46], the matrix stress of gas-bearing coal rock can be expressed as:

$$\sigma' = \sigma - \alpha p \delta_{ij} \tag{1}$$

where α is the Biot coefficient, which reflects the relationship between effective volume stress and gas pressure in coal matrix; δ_{ij} is the Kroneker coefficient; and p is the gas pressure, MPa.

The stress balance equation of the coal body can be expressed as:

$$\sigma'_{ij,j} + f_i = 0 \tag{2}$$

Substituting Equation (2) into Equation (1) gives:

$$\sigma_{ij,i}' - (\alpha p \delta_{ij})_i + f_i = 0 \tag{3}$$

Therefore, the stress–strain relationship of gas-bearing coal in the stress zone of original rock at the elastic stage can be expressed as:

$$\begin{cases} \sigma'_{ij} = 2G\varepsilon_{ij} + \frac{2G\mu}{1-2\mu}\varepsilon_v\delta_{ij} - K\varepsilon_v\delta_{ij} \\ \sigma'_{ij} = \sigma_{ij} - \beta\delta_{ij}p \\ \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \end{cases}$$
(4)

where ε_{ij} is the strain component (i, j = x, y, z), %; *G* is shear modulus, MPa; ε_v is bulk strain, %; and $u_{i,j}$ is the displacement component.

The yield failure criterion of coal conforms to the Drucker–Prager criterion (D–P criterion), combined with Mohr–Coulomb criterion gives:

$$F = \sqrt{J_2 + \alpha_{DP}I_1 - k_{DP}} \tag{5}$$

According to fracture mechanics, the mechanical criterion of tensile failure conforms to the maximum tensile stress criterion:

$$K_I \ge K_{IC} \tag{6}$$

$$K_I = \sigma \sqrt{2\pi r} \tag{7}$$

The condition of crack propagation is that the gas pressure gradient inside the crack and on the exposed surface is greater than the tensile strength of the coal body. Therefore, the cracks in the coal body expand along the direction perpendicular to the maximum gas pressure gradient, making the cracks expand and causing lamellar cracks.

$$p_1 - p_0 \ge \sigma_t \tag{8}$$

where p_1 is gas pressure in coal crack, MPa, and p_0 is atmospheric pressure, MPa.

2.2. Fluid Migration Equation

Dual pore structure is a widely accepted model to describe gas migration in coal. The coal is cut into matrix units by fractures in the coal seam, and adsorbed gas in the coal matrix migrates to the fracture system through desorption and matrix diffusion, and then to the seepage movement in the fracture system. The process of gas diffusion on coal matrix surfaces can be described by the following equation.

$$q = D\alpha_s V_1(c_1 - c_2) \tag{9}$$

where *q* is the diffusive mass flux; α_s is the shape factor; V_1 is the coal matrix volume, ml; c_1 is gas mass concentration in coal matrix, g/mL; and c_2 is gas mass concentration in the crack, g/mL.

It is difficult to determine the diffusion coefficient and shape factor in the diffusion formula, so adsorption time is often used to express the diffusion speed; the basic equation of gas diffusion to cracks in the matrix follows:

$$q = \frac{MV_1}{\tau RT} (p_1 - p_2)$$
(10)

The continuity equation of gas migration in coal seam follows:

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla(\rho v) = q \tag{11}$$

where ρ is the gas density, g/cm³; φ is the porosity; and *q* is the variation of gas flow in unit coal matrix, cm³.

According to the basic assumption, gas migration in the fracture conforms to Darcy's law:

$$v = \frac{k}{\mu} \nabla p \tag{12}$$

The gas content equation can be expressed as:

$$Q = \left(\frac{abp_1}{1+bp_1} + \frac{\phi_1 p_1}{\rho p_0}\right) \cdot \rho M \tag{13}$$

The volume of gas in coal with the temperature, gas pressure, and the relationship between each component is expressed as the equation of state of coal seam gas:

$$\rho_{\rm g} = \frac{Mp}{RTZ} = \frac{\rho_n p}{p_n Z} \tag{14}$$

According to the these basic assumptions, the gas flow in coal seam satisfies Darcy's law (12), the gas content equation satisfies Equation (13), and the gas state equation satisfies Equation (14). By substituting the three equations into the continuity relationship, Equation (11), the coupled seepage equation of coal containing gas can be obtained as follows:

$$\frac{\partial \left[\left(\frac{abcp}{1+bp} + \varphi \cdot \frac{p}{p_n} \right) \cdot \rho_n \right]}{\partial t} - \nabla \cdot \left(\frac{k}{\mu} \cdot \nabla p \cdot \frac{p}{p_n} \right) = I$$
(15)

$$2\alpha p \frac{\partial e}{\partial t} + \left[2\varphi + \frac{2(1-\varphi)}{K_s}p + \frac{2abcp_n}{(1+bp)^2} + \frac{2abcp_n}{1+bp} \right] \frac{\partial p}{\partial t} - \nabla \cdot \left(\frac{k}{\mu} \cdot \nabla p^2\right) = I$$
(16)

The relationship between permeability and porosity of coal seam is based on the classical formula:

$$k = k_0 \left(\frac{\varphi}{\varphi_0}\right)^3 \tag{17}$$

Based on the relationship between coal permeability and the cubic power of porosity, the evolution law of coal porosity during outburst can be described as follows:

$$\phi = \begin{cases} \phi_0 \exp\left[\frac{b_{\sigma}}{3}(\Delta\Theta)\right] \left(1 + \frac{\gamma^p}{\gamma^{p^*}}\xi\right)^{\frac{1}{3}} \\ \phi_0 \exp\left[\frac{b_{\sigma}}{3}(\Delta\Theta)\right] (1 + \xi)^{\frac{1}{3}} \end{cases}$$
(18)

2.3. Temperature Equation

The adsorption, desorption, and seepage of gas in a coal seam all have a thermal effect, which is a non-isothermal process. The deformation of coal containing gas under the action of external force also produces a thermal effect, so the coupling temperature field equation of coal containing gas should be coupled with the influence of the stress field and seepage field. The adsorption, desorption, and seepage of gas in a coal seam all have thermal effect, which is a non-isothermal process. So the influence of the temperature field equation should be considered in simulating the process of coal and gas outburst. The formula of the first thermodynamic law of the coal skeleton follows:

$$\frac{\partial(\rho_s C_s \Delta T)}{\partial t} + T \alpha_s K \frac{\partial \varepsilon_v}{\partial t} + \nabla \cdot (k_{rs} \nabla T) = Q_{Ts}$$
⁽¹⁹⁾

The energy conservation equation of gas is Equation (20):

$$\frac{\partial \left((\phi_m + \phi_f) \rho_g c_g \Delta T \right)}{\partial t} + \nabla \cdot \left(\rho_g h_g q_g \right) + \left(\phi_m + \phi_f \right) \nabla \cdot \left(k_{rg} \nabla T \right) = \left(\phi_m + \phi_f \right) Q_{Tg} \quad (20)$$

The energy conservation equation of a gas-bearing coal body can be obtained by combining Equations (20) and (21):

$$\frac{\partial((\rho C_p)_{eff}T)}{\partial t} + \eta_{eff}\nabla T - \nabla \cdot (\lambda_{eff}\nabla T) + K\alpha_T T \frac{\infty \partial \varepsilon_v}{\partial t} + q_{st} \frac{\rho_s \rho_{gs}}{M} \cdot \frac{\partial V_{sg}}{\partial t} = 0$$
(21)

In Formula (21), from left to right are the variations of coal internal energy, convective heat transfer, heat conduction, coal skeleton thermal strain energy, and gas adsorption heat.

Therefore, the occurrence and development of coal and gas outburst involves multiple physical field parameters, such as the stress, gas pressure, temperature, and seepage fields (Figure 1).



Figure 1. THM coupling in the coal and gas outburst process.

3. Multi-Physical Field Response of the Outburst Process

3.1. Geometric Model Construction

It is assumed that the physical properties, gas parameters, and stress distribution of coal seams along each section of the driving face are the same. The geometric model of the numerical solution was simplified to a horizontal (x and y) two-dimensional plane model. The model size was 2.2 m in thickness of the coal seam, 6 m in the height of roof and floor, and 30 m in length. Coal and gas outburst induction was realized through two-step excavation, with excavation distance of 1.5 m at each step (Figure 2). The bottom end is fixed and the horizontal displacement is fixed on the left and right sides. The initial gas pressure in the coal seam is 0.5 MPa, and only the gas migrates in the coal seam. In addition, in order to obtain the response laws of the stress-strain field and the gas and temperature fields, the model uses a number of solid modules to carry out one-step mining to obtain the initial stress-strain field and disturbance stress-strain field, and uses a PDE module to solve the gas field and temperature field. Solid module: the upper boundary is a constant load boundary. The initial ground stress in the physical model is 16 MPa, and the initial load in the numerical model is also a constant load of 16 MPa. The lower boundary and the right boundary are roller boundaries, and the exposed surface formed after excavation is the free boundary. PDE module: the upper and lower boundaries and the right boundary of the coal seam are zero flow boundaries. Gas can only move in the coal seam, and the initial coal seam gas pressure is 0.5 MPa; the exposed surface after excavation is a constant pressure boundary, and the pressure is atmospheric pressure. The specific parameters in the model are shown in Table 1.



Figure 2. Geometric model and boundary conditions.

Table 1. Measured model parameters.

Parameters		Parameters	
Elastic modulus of rock E	20 GPa	Density of coal $ ho$	$1.4 imes 10^3 \text{ kg/m}^3$
Poisson's ratio of rock v	0.3	Initial porosity of coal seam	5.61%
Density of rock ρ	$2.5 \times 10^{3} \text{ kg/m}^{3}$	Coal cohesiveness	20 MPa
Cohesion of rock	20 MPa	Angle of friction in rock	40°
Angle of friction of rock	40°	Gas dynamic viscosity coefficient η	11.067 Pa·s
Elastic modulus of coal E	2.3 GPa	Density of gas ρ	0.716 kg/m ³
Working face pressure P	0.1 MPa	Initial gas pressure P	0.5 MPa
Poisson's ratio of coal v	0.192	Initial temperature of coal T	305.5 K

3.2. Calculation Method

The numerical solution of coal and gas outburst is an operation of multiple physical fields, including the stress field, gas pressure field and temperature field. Moreover, there are coupling relations among each physical field. The internal solid mechanics field is used to calculate the stress–strain relationship of coal–rock mass; the flow field of gas in coal is selected to calculate the flow field, the mechanical effect of gas on the coal body is applied by the volume force in the solid mechanics field, the yield of the coal body is calculated by the D–P matching criterion, and the steady-state solution is used in the calculation process, as shown in Figure 3.

3.3. Stress Field Response in the Whole Outburst

Figure 4 shows the stress field response at different time nodes in the process of outburst. The colors of different areas in Figure 4 represent different degrees of failure in different areas of coal. Figure 4a indicates the stress balance state near the working face after two steps of mining before outburst. The work of stress on coal increases the elastic potential of coal, which leads to the accumulation of high elastic energy and the expansion of coal cracks, providing conditions for the instantaneous gas release at the working face front. At the 12th s, the change rate of stress field accelerates, so it can be judged that the outburst occurs at this time. As can be seen from Figure 4b, after the occurrence of coal and gas outburst, the stress in the model begins to unload, and the coal body suffers tensile failure. The stress at the front of the working face has been completely unloaded, the vertical stress value has been approaching zero, the stress concentration has shifted. Meanwhile, the stress concentration has shifted to greater depth. The stress concentration area of the roof and floor present a symmetrical distribution. Figure 4c–e is, respectively, 18, 24, and 36 s in the process of outburst. The coal body continues to be damaged, and the strength of

coal is completely lost or decreased. The vertical load is also transferred to the coal body in the outer undamaged area. After 40 s, the stress field is stable and the stress no longer changes (Figure 4f).



Figure 3. Flowchart of numerical solution.





Figure 5 illustrates the stress curve at different distances from the coal wall. It can be concluded from Figure 5 that stress response is fastest at x = 5 m and x = 10 m, nearest to the coal wall. There is a negative correlation between stress and time at x = 5 m, which indicates that the coal nearest to the outburst is thrown out first, and the ground stress decreases rapidly and approaches zero. The stress curve at x = 10 m indicates a trend of

rapid decline after increasing to a maximum value of 17.5 MPa. The stress at x = 15 m, x = 20 m and x = 25 m rise and then tend to be stable with the development of outburst.



Figure 5. Stress field with time at different distances from the coal wall.

3.4. Gas Pressure Field Response in the Whole Outburst

Figure 6 describes the response characteristics of the gas pressure field during outburst in different time segments. Figure 6a shows the equilibrium state of gas pressure near the working face after two steps of mining before outburst, and the gas in the coal seam is 0.5 MPa. Figure 6b demonstrates that a large amount of gas begins to gush into the mining space.





Figure 6c–e shows the outburst development stage in which the gas keeps pouring out to the roadway; the gas pressure in the coal body continues to decrease, and the gas pressure gradient is formed in the outburst hole. At the same time, gas pressure has multiple "jump zones". Figure 6f demonstrates the outburst termination stage. At this time, there is still continuous gas desorption, but the rate of gas pressure drop has reduced significantly. Although the gas is still continuously desorbed, it is not sufficient to support the continuous occurrence of coal and gas outburst, and the gas internal energy accumulated by gas desorption cannot throw coal. Therefore, not all desorption gas is involved in coal and gas outburst work. Only the energy that can participate in tearing, throwing, and transporting coal does work to outburst. That is the initial gas expansion energy. Figure 7 reflects the variation trend of gas pressure over time at different distances from the coal wall. After the outburst occurred, the coal body near the outburst was destroyed and thrown out under the action of the stress field and gas pressure field, and the gas pressure in the coal body changed violently.



Figure 7. Gas pressure field with time at different distances from the coal wall.

3.5. Temperature Field Response in the Whole Outburst

From the point of view of the whole process of outburst, the temperature drop is the most obvious during outburst and the temperature drop rate is the largest, with a drop of 9 K, at the beginning of the burst. As the broken coal is thrown out, the temperature near the outburst begins to change, decreasing from 306 to 303 K, shown in Figures 8 and 9. To some extent, the change of coal temperature reflects the development and suspension of the outburst. In the process of continuous outburst, the temperature field shows a continuous decrease. When the gas pressure rises and the gas compresses, the temperature presents a slight rise. On the other hand, the temperature variation reflects the whole process of the outburst. Therefore, it can also be interpreted that the change of temperature field reflects the change of the stress field and gas pressure field. In the process of outburst, the decrease of temperature in coal is mainly caused by the work of gas expansion in the coal and the heat absorption and desorption of gas.

According to the thermodynamic formula, the gas expansion energy in the outburst process can be expressed as:

$$W = \frac{RT_1}{n-1} \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \right]$$
(22)

When the gas pressure drops from p_1 to p_2 , the gas expansion energy released by coal per unit volume is as follows:

V

$$V = \frac{\alpha MR\Delta T}{2V_m(n-1)} \int_{p_2}^{p_1} \frac{1}{\sqrt{p}} dp$$
(23)

The temperature change of the coal seam is proportional to gas expansion energy. The more gas expansion energy released from the coal seam, the greater the temperature change of the coal seam.



Figure 8. Temperature distribution at different times.



Figure 9. Temperature change rules with time at different distances from the coal wall.

3.6. Seepage Field Response in the Whole Outburst

The simulation results show that the permeability area affected by coal and gas outburst in front of the working face can be divided into three areas: sudden increase, medium growth, and growth. The sudden increase area is in the main pressure relief zone, and the coal body has been highly broken and a fissure developed under the influence of the outburst. At the same time, the stress has shifted, and the permeability is shown as a sudden increase. The medium growth area is mainly distributed in the stress concentration area. Part of the coal has broken up, but it can still support the coal. The growth area is far from the outburst outlet, and the number of fractures produced by the coal body under the influence of outburst has been greatly reduced, leading to the weakening of the growth range of permeability. However, the gas can still provide energy for outburst by continuous desorption in the process of outburst (Figure 10).



Figure 10. Permeability change rules with time and different distances from x = 0.

4. Multi-Physical Field Response of Coal and Gas Outburst under Different Stress Conditions

Stress Field Response in the Whole Outburst under Different Stress Conditions

Figure 11 shows the stress response during coal and gas outburst under different stress conditions. Figure 11 illustrates the response law of stress distribution at 5, 10, 15, and 25 m from the origin of coordinates on the central axis of the coal seam. In the process of coal and gas outburst, when the initial ground stress is 16, 24, 32, and 40 MPa, the response trend of ground stress is consistent. Figure 11a shows the broken coal is thrown out and the stress shifts rapidly after the outburst. The ground stress drops rapidly from 16, 24, 32, and 40 to 0 MPa. From the point of view of stress response rate, the initial ground stress decreases from 16, 24, 32, and 36 MPa to 4, 6, 7, and 7 MPa, respectively, in the range 12–18 s. Stress response rates are 2, 3, 3.8, and 4.8 MPa/s, respectively. It can be found that the higher the initial ground stress, the higher the stress response rate after outburst. Figure 11b,c respectively, shows the response law of stress with outburst development under different stress conditions at x = 10 m and x = 15 m. It can be seen that stress concentration stage and stress release stage are experienced in the process of outburst. Figure 11d indicates the stress response law with outburst development under different stress conditions at x = 25 m. After outburst occurred at x = 25 m, the stress response was weak, and there is a small increase under different stress conditions, which generally remained stable.



Figure 11. Gas pressure response in the whole outburst under different stress conditions.

Figure 12 shows the gas pressure response in the process of coal and gas outburst under different stress conditions, and Figure 12 illustrates the response law of gas pressure distribution at 5, 6, 8, and 10 m from the origin of coordinates on the central axis of coal seam. Figure 12a shows the broken coal is thrown out, and the gas pressure responds most rapidly after the outburst occurs. The gas pressure drops rapidly from 0.5 to 0.1 MPa. Figure 12b illustrates the gas pressure response at a position 1 m from the outburst under different stress conditions. It can be seen from the figure that the higher the stress, the greater the gas pressure variation range at the beginning of the outburst. At the initial stage of the outburst, the gas pressure suddenly increases, forming a large gas pressure gradient, and the coal and gas outburst have higher energy. With the increase of stress, the gas discharge zone in front of the working face becomes smaller, forming a larger gas pressure gradient. Figure 12c,d shows the change of gas pressure after outburst occurred at 3 and 5 m from the outburst port. After outburst, the higher the stress, the slower the gas pressure decreases, indicating that under the condition of high in situ stress, more areas can participate in the coal and gas outburst, so that more gas internal energy can supply the coal and gas outburst energy.

Figure 13 shows the temperature response in the process of coal and gas outburst under different stress conditions, and Figure 13 illustrates the response law of temperature at 5, 6, 8, and 10 m from the origin of coordinates on the central axis of coal seam. Under different stress conditions, the temperature response has the same variation trend after outburst, which shows that the temperature curve decreases rapidly after outburst. After about 10 s, the temperature curve decreases at a slower rate. When it reaches 20 s, the curve basically remains stable and no significant decline occurs. It indicates that the gas adsorbed in the pores of the coal body begins to desorb, leading to a rapid drop in coal body temperature, and the expansion of a large volume of desorbed gas also needs to absorb a large amount of heat, so the temperature of the coal body drops significantly after outburst. The response of the temperature field, stress field, and gas pressure show corresponding phenomenon. The temperature field responds strongly in the early stage of outburst, and



the temperature drops rapidly. The corresponding stress field and gas pressure field also show rapid stress transfer and the gas pressure decreases.

Figure 12. Temperature response in the whole outburst under different stress conditions.



Figure 13. Temperature response in the whole outburst under different stress conditions.

Figure 14 shows the permeability response in the process of coal and gas outburst under different stress conditions, and Figure 14 illustrates the response law of permeability distribution at 6, 10, 15, and 25 m from the origin of coordinates on the central axis of coal seam. The permeability is negatively correlated with the increase of the distance from the outburst port. The permeability area in front of the working face affected by coal and gas outburst can be divided into three areas: sudden increase, medium growth, and growth. The sudden increase area is in the main pressure relief zone, and the coal body has been highly broken and fissures developed under the influence of the outburst. The medium growth area is mainly distributed in the stress concentration area, part of the coal has broken, but it can still support the coal. The growth area is far from the outburst port, and the number of fractures produced by the coal body under the influence of outburst has been greatly reduced, leading to the weakening of the growth range of permeability. However, the gas can still provide energy for outburst by continuous desorption in the process of outburst.



Figure 14. Permeability response in the different stress stations.

5. Influence of Stress on Energy Condition of Coal and Gas Outburst

With the increase of mining depth, ground stress plays an increasingly important role. Taking Dingji coal and gas outburst accident on 19 April 2004 as an example, the influence of stress on the energy condition of coal and gas outburst is discussed. The values in Table 1 are selected for specific parameters, and the elastic energy formula in reference [30] is used to calculate the elastic energy in unit volume under different stress conditions.

It can be seen from Figure 15 that the elastic energy per unit volume is positively correlated with stress. With the increase of stress, the elastic energy per unit volume of coal keeps increasing. When the elastic modulus of coal is 2.0 GPa, the stress increases from 5 to 35 MPa, and the elastic energy of coal mass per unit volume increases by 19.8 kJ/m³. Under the condition of high stress, the energy condition of coal and gas outburst can still be satisfied because of the high elastic energy of coal and rock mass, even if the gas extraction reaches the standard.



Figure 15. The relationship between geo-stress and elastic energy.

Figure 16 reflects the relationship between elastic potential, gas internal energy ratio, and stress in the range 5–35 MPa. With the increase of stress, the proportion of elastic energy in total coal and gas outburst energy is increasing, and the proportion of elastic energy is positively correlated with stress. When the stress reaches 35 MPa, the contribution of elastic energy can reach 24.2%. Therefore, with the increase of stress, elastic energy has become an important part of the total energy of the coal and gas outburst.



Figure 16. The relationship between geo-stress, gas energy, and elastic energy ratio.

In order to explore the relationship between the critical gas pressure and stress of coal and gas outburst, the coal firmness coefficients are 0.2, 0.3, 0.4, and 0.5, while the outburst strength remains unchanged. It can be seen from Figure 17 that the smaller the coal firmness coefficient, the smaller the energy required for the occurrence of coal and gas outburst, specifically, the smaller the stress and gas pressure can meet the energy conditions for the occurrence of coal and gas outburst. The smaller the solidity of coal, the gentler the curve, and the less the effect of stress, while the sensitivity of gas is enhanced, and the energy source of coal and gas outburst is more dependent on the internal energy of gas. The critical gas pressure satisfying the energy condition of coal and gas outburst gradually

decreases with the increase of stress, indicating that under a high stress condition, a small gas pressure can also satisfy the energy condition of coal and gas outburst.



Figure 17. The relationship between stress, firmness coefficient, and critical gas pressure.

6. Conclusions

Based on the whole process of coal and gas outburst in temperature–flow–solid mutual coupling mechanism, the numerical model is established. The geometric model, boundary conditions, and solving method of the model are determined. Moreover, the evolution law of stress field, gas pressure field, temperature field, and seepage field in the process of coal and gas outburst under deep high stress conditions is discussed, as well as the response of multiple physical field parameters of coal and gas outburst under different stress conditions. The following conclusions are obtained:

- 1. The stress field response law of the coal and rock mass around the outburst hole is initial vibration–sudden attenuation–late stability.
- 2. The gas pressure field response law in different areas is that the gas pressure response rate decreases gradually with the increase of distance from the outburst port.
- 3. After the outburst occurs and near the outburst, the adsorbed gas in the broken coal rapidly desorbs and expands to work, which changes the temperature. Most of the gas in the stress area of raw rock far from the outburst does not participate in the outburst work, and only a small part of the gas continues to desorb.
- 4. The permeability changes in front of the driving face have the characteristics of zoning in the process of outburst. After outburst, the permeability changes significantly in front of the driving face under the influence of coal and gas outburst, which can be divided into sudden increase area, medium growth area, and growth area.
- 5. Under the condition of high stress, a small gas pressure can also meet the energy condition of coal and gas outburst, and it also has the risk of coal and gas outburst.

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