Quantitative Analysis of Factors Affecting Coal and Gas Outburst Based on Energy Model

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Abstract: Ground stress, gas pressure, mechanical properties of coal and other parameters are important factors affecting coal and gas outburst, but the most obvious factor is unclear. In order to reveal the main influencing factors of outburst, this paper established a energy model based on the principle of energy conservation. With the help of MATLAB, the energy contribution of stress, gas pressure and physical and mechanical properties of coal was analyzed. The research shows that the gas expansion can be 2 orders of magnitude higher than the elastic energy of coal, and it is the main energy of coal and gas outburst. The gas pressure directly affects the size of gas expansion energy, it has the greatest contribution to the energy of coal and gas outburst. Stress has little contribution to the energy of coal and gas outburst, but the stress is the controlling factor of the energy release zone, the stress first controls the range of the energy release zone and then affects the release of gas expansion energy. mechanical properties of coal including Modulus of elasticity, Poisson ratio Cohesion, Friction angle etc. has little energy of coal and gas outburst.

Keywords: Mining Engineering, Coal And Gas Outburst, Energy Model, Quantitative Analysis

1. Introduction
Coal and gas outburst is a disastrous power phenomenon in the process of underground coal mining. When it happens, a lot of coal and gas will be thrown from the coal seam to the mining space in a very short time, accompanied by violent noise[1]. The jet of coal and gas mixture has a great amount of energy, not only to destroy underground production facilities, but also to impact buried workers, such
as fire sources, gas combustion and even explosion[2]. In 1843, the French entry work in Luaer coal mine face for the first time had a sack of coal and gas outburst accident in the world[3]. Subsequently, coal and gas outburst occurred in more than 20 coal producing countries including the former Soviet Union, Japan, the United States, Australia and Britain[4]. According to statistics, at present, the total number of coal and gas outburst accidents in the world has been over 40 thousand times[5]. Coal is the main source of energy in China. During the "12th Five-Year" period, the total coal production in China increased from 34.3 billion tons in 2010 to 37.5 billion tons in 2015, with an annual growth rate of 1.8%. During the "12th Five-Year", the proportion of Chinese coal in the energy consumption structure declined slightly, but in 2015, the proportion of coal to energy consumption structure was still up to 64% in 2015[6]. The number of coal mines in China accounts for 97%, and the mining conditions are complex. There are 1218 high gas mines and 1624 outburst mines. At present, 47 mines have been mined more than one thousand meters in depth in China[7]. As the mining level deepen to the deep, some mines with no prominent danger in shallow mining are also upgraded to outburst mines. After deep mining, the increase of in-situ stress and gas pressure and the increase of gas content lead to the more and more serious gas threat faced by deep mining[8]. In order to prevent and control the occurrence of coal and gas outburst, the major coal producing countries in the world have invested a lot of manpower and material resources to study the coal and gas outburst mechanism. However, the main controlling factors of coal and gas outburst are still controversial (ZHANG Qinghe, 2017). At present, in theoretical research, the energy model of coal and gas outburst can make quantitative research on the outburst, and it has been widely concerned by scholars. It is possible to analyze the main controlling factors of outburst based on energy model.

This paper established the energy equation of coal and gas outburst, and analyzed the energy contribution of ground stress and gas pressure based on the energy equation.

2. Theories

The process of coal and gas outburst is the process of accumulation, transfer and release of energy. Before the outburst occurred, the coal was in high stress state, and rich in large amount of high pressure gas, abundant elastic potential and gas internal energy. After the outburst, a lot of broken coal and gas burst out, and accompanied by sound, vibration and temperature changes, the corresponding outburst coal storage energy was consumed[9]. This process follows the first law of thermodynamics, which can be described as follows:

\[ W_1 + W_2 = A_1 + A_2 \]  \hspace{1cm} (1)

In the model, \( W_1 \) is the elastic energy of coal in the prominent range; \( W_2 \) is the gas expansion energy adsorbed in the coal; \( A_1 \) is the broken work of the outburst coal, and \( A_2 \) is the throwing work of the outburst coal.
2.1. Calculation of elastic energy of coal
The elastic energy of coal is produced by the ground stress. The calculation of the performance of the coal is closely related to the coal scope and the distribution of the stress in the interior of the area (WU Cai-fang et al., 2005). Therefore, the explicit range of energy release and the distribution of in-situ stress are the prerequisites and guarantee for solving the elastic energy of coal.

The roadway excavation causes the re distribution of ground stress in the surrounding rock, and the mining stress field is formed in the coal rock surrounding the roadway, which makes the stress in front of the coal below the original rock stress, and the coal rock and rock in the distance are higher than the concentrated stress of the original rock stress. The occurrence of the mining stress field is the dynamic response of the tunneling action in the ground stress. It is the result of the constant adjustment of the stress of the surrounding rock after the excavation of the roadway in the three-dimensional stress environment. When a new driving action is generated, the mining stress is adjusted accordingly, so the mining stress field is a dynamic stress field in theory.

In the above stress field, the existing research believes that the mining stress field can be divided into two subregions from the near to the distance (WEI Feng-qing et al., 2010), which are the plastic zone between the heading to the peak and the elastic zone between the peak to the original rock stress, and the original rock stress area outside the elastic zone.

The radial effective stress and tangential effective stress in plastic zone are as follows (ZHANG Qinghe, 2017).

\[
\sigma_{rr} = c \cot \varphi \left[ \frac{r}{R_0} \right]^{\frac{4 \sin \varphi}{1 - \sin \varphi}} - 1
\]

\[
\sigma_{\theta \theta} = c \cot \varphi \left[ \frac{1 + \sin \varphi \left( \frac{r}{R_0} \right)^{\frac{4 \sin \varphi}{1 - \sin \varphi}} - 1}{1 - \sin \varphi \left( \frac{r}{R_0} \right)^{\frac{4 \sin \varphi}{1 - \sin \varphi}} - 1} \right]
\]

The radial effective stress and tangential effective stress of coal in elastic zone are as follows.

\[
\sigma_{rr} = \sigma_0 \left( 1 - \frac{R_p^3}{r^3} + \frac{R_p^3}{r^3} \cot \varphi \left[ \frac{R_p}{R_0} \right]^{\frac{4 \sin \varphi}{1 - \sin \varphi}} - 1 \right)
\]

\[
\sigma_{\theta \theta} = \sigma_0 \left( 1 + \frac{R_p^3}{2r^3} - \frac{R_p^3}{2r^3} \cot \varphi \left[ \frac{R_p}{R_0} \right]^{\frac{4 \sin \varphi}{1 - \sin \varphi}} - 1 \right)
\]

As shown by head for the radius of plastic zone center.
The elastic energy of coal can be derived from formula 7.

$$W_i = 2\pi \int_0^{\pi/2} \int_{r_i}^{R_p} \left( 3(\sigma_0 + c \cot \varphi)(1 - \sin \varphi) \right) \left( 3 \sin \varphi \right) r^2 dr d\varphi$$

$$= 2\pi \int_0^{\pi/2} \sin \varphi \int_{r_i}^{R_p} \frac{1}{E} \left[ (3-\mu)\sigma_0^2 + \frac{3R_p^2k^2(1+\mu)}{2r^6} \right] r^2 dr d\varphi$$

$$= \frac{\pi(1-2\mu)}{E} \sigma_0^2 R_p^2 \int_{r_i}^{R_p} \left( 1 - \frac{R_p^2}{r^2} \right)^3 - 1 + \frac{k^2(1+\mu)}{2(1-2\mu)} \left( 1 - \frac{R_p^2}{r^2} \right) d\cos \varphi$$

In equations 1-7, \( \sigma_r \) is the radial effective stress of the coal body in the plastic zone, \( \sigma_{\theta r} \) is the tangential effective stress of the coal body in the plastic zone, \( \varphi \) is the internal friction angle of the coal, \( c \) is the cohesion of the coal, \( r_i \) is the radius of the circular roadway, \( r \) is the distance from the micro-body to the head, \( \sigma_r \) is the radial effective stress of the coal body in the elastic zone, \( \sigma_{\theta r} \) is the tangential effective stress of the coal body in the elastic zone, \( E \) is Elastic modulus, \( \mu \) is Poisson, \( \sigma_0 \) is the radial effective stress of the coal body in the original rock stress zone at infinity, \( R_p \) is Plastic zone radius.

### 2.2. Calculation of gas expansion energy

Gas expansion energy is an important power source for the outburst process (ZHANG Hao 1 et al., 2015). During the protruding process, the coal is broken, the surface area of the exposed surface increases, the coal adsorb gas fast desorption, together with the free gas in the pore of the coal, it expands rapidly, produces the gas expansion energy, and becomes the main energy source of the prominent occurrence and development. It is of great significance to calculate the gas expansion energy accurately.

The heat exchange area between coal and gas is large, so the heat exchange speed is very fast, and its process is more closely related to the isothermal process. For convenience of calculation, the multivariate index of gas is 1. The relationship between gas pressure \( P \) and gas volume \( V \) is satisfied. The formula is introduced into the thermodynamic calculation formula of swelling energy.

$$W_i = V_p \ln \left( \frac{P_0}{P_i} \right)$$

According to the different forms of gas in coal, gas can be divided into free gas and adsorption gas. The free gas exists in the pore of the coal in the free state. With the broken coal in the protruding process, the gas will expand rapidly to produce the expansion energy, and the adsorption gas needs to undergo the process of desorption and diffusion during the protruding process, and the gas can expand.
to do work and influence the strength of the outburst (KANG Hongpu et al., 2012). The difference of occurrence form between them leads to different contributions of expansion energy, so the amount of participation in the outburst process is also different, which needs to be considered separately. The proportion of free gas to the total gas content is about 20%, the size of which is determined by the gas pressure of coal seam and the pore of coal and is represented by the available formula of free gas content 9 in the range of energy release area. Because of its simple form of occurrence, the coal will expand and do work quickly after the coal is broken, so the free gas contained in the coal in the prominent range is often considered to be all involved in the protrusion process (LAN Hang et al., 2010).

\[ V_r = nV_s \]

(9)

The gas expansion energy involved in the outburst process in the energy release area is obtained.

\[ W_5 = \eta nV_s p_a f_n\left(\frac{p_s}{p_a}\right) \]

(10)

In equations 8-10, \( p_a \) is atmospheric pressure, \( p_o \) is to highlight coal seam gas pressure, \( V \) is the total amount of gas involved, \( V_s \) is the coal volume, \( n \) is the porosity of coal.

2.3. Coal crushing work

Coal is a typical brittle body. Currently, the representative hypotheses of coal crushing work include P.R.Rittinger new surface theory, G.Kick similarity theory and F.C.Bond's crack theory (GUO Chen ye et al., 2008). Although the above theory is different to the method of solving the crushing work, it is considered that the energy consumed in the broken coal is proportional to the new surface area and the effective surface energy of the material. In view of the existence of a large number of crack surfaces in the coal before the outburst, the new surface area is difficult to calculate. The above hypothesis is difficult to describe the complex crushing work in the protruding process. To this end, based on the basic calculation principle of the broken work, the previous 21 coal samples in the main outburst coal mines of the country have been tested for impact crushing, and the expression of the work of coal crushing is flow (HU Qian-ting et al., 2013).

The research shows that when is used to sifting data of coal samples after the outburst is stopped, But the projecting phase of the projecting coal is still further broken, and the breaking work of the outburst is obviously smaller than that at the end of the outburst. The factors are considered, and the energy equation is conciseness. What's more, it should be noted that any outstanding condition is constant, so it is incorporated into the proportional coefficient. Through the above simplification, the crushing work of coal can be expressed as follows.
\[ A_s = \xi \frac{2c \cos \phi}{10(1 - \sin \phi)} \rho V_s \] (11)

In equations 8-10, \( \rho \) is the density of coal, \( \xi \) is Scale factor.

2.4. Cast work of coal

The throwing force of coal is the kinetic energy when the crushed coal is thrown out in the energy release area, which can be approximately expressed as flow (WANG Gang et al., 2011).

\[ A_s = \frac{1}{2} B v^2 = \frac{1}{2} \rho V_s v^2 \] (12)

In equations 8-10, \( v \) is the speed at which coal is thrown.

2.5 Energy equation establishment

The formula of formula (7), type (10), type (12) and type (13) are brought into the form (1), and the specific expression of the energy equation of coal and gas outburst is obtained.

\[
\begin{align*}
\frac{\pi (1 - 2 \mu) \sigma_s^2 R_p^3}{E} & \left[ \frac{1}{2} \sum_{R_{min}}^{R_{max}} \left( \left( \frac{R_p}{R_{min}} \right)^3 - 1 + \frac{k^2 (1 + \mu)}{2(1 - 2 \mu)} \sigma_s \left( 1 - \frac{R_{max}^3}{R_{min}^3} \right) \right) \right] d \cos \phi + \eta n p_0 \ln \left( \frac{p_0}{p_a} \right) V_s \\
= \xi \frac{2c \cos \phi}{10(1 - \sin \phi)} V_s + \frac{1}{2} \rho V_s v^2
\end{align*}
\] (13)

3. Numerical calculation of the outburst energy

The form of energy equation is very complex. This article uses MATLAB's powerful mathematical computing capabilities to analyze.

The physical and mechanical properties of coal are selected from a coal seam in Huainan mining area. The in-situ stress is 13.5 MPa and 15 MPa. The gas pressure is 0.74 MPa and 1.0MPa. The parameters taken are shown in table 1.

**Table 1. Parameter table**

| \( \sigma \) /MPa | \( P \) /MPa | E/MPa | \( \mu \) | \( c^\infty \) | \( n \) | \( P_0 \) /MPa | \( \eta \) | R/m | L/m |
|-------------------|------------|-------|--------|----------|-----|-------------|-----|-----|-----|
| 13.5              | 0.74       | 15.2*10^3 | 0.31  | 28       | 6.5% | 0.1         | 2   | 2   | 2   |
| 13.5              | 1          | 15.2*10^3 | 0.31  | 28       | 6.5% | 0.1         | 2   | 2   | 2   |
| 15                | 0.74       | 15.2*10^3 | 0.31  | 28       | 6.5% | 0.1         | 2   | 2   | 2   |

The parameter values of Table 1 were introduced into the established energy model 14, and the elastic energy and gas expansion energy and energy release area of the coal in the three states were calculated, as shown in Table 2.
Table 2. Calculation results

| Sequence number | Elastic energy /MJ | Expansive energy /MJ | Energy release zone /m³ |
|-----------------|---------------------|-----------------------|------------------------|
| 1               | 0.46                | 12.95                 | 67.2                   |
| 2               | 0.46                | 20.13                 | 70.8                   |
| 3               | 0.60                | 13.63                 | 70.8                   |

It can be seen from Table 2 that the stress has a certain influence on the elastic energy, and the gas pressure has a significant influence on the expansion energy. The gas expansion energy is the main energy in the process of coal and gas outburst, and the gas expansion energy is one order of magnitude higher than the elastic energy of the coal body, the above. This is consistent with previous results. From the energy point of view, the ratio of elastic energy of coal is less than the proportion of gas expansion energy, but the role of ground stress in the process of protrusion is very obvious. The earth stress not only affects the elastic energy but also affects the gas expansion energy. In the process of protrusion, the ground stress affects the distribution of the energy release zone, so that the energy in the energy release zone has the risk of release.

4. Conclusions
1. Based on the calculation method of coal's elastic energy and gas expansion energy, the coal and gas outburst energy model is constructed, and the quantitative calculation of coal and gas outburst potential is realized.

2. With the help of MATLAB software, the control variable method is used to analyze the energy source of coal and gas outburst. The gas expansion energy is the main energy of coal and gas outburst, which is more than an order of magnitude higher than the elastic energy.

3. Gas pressure is the main factor affecting gas expansion energy, and attention should be paid to gas pressure prevention and control in engineering.

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