Discussion on the Mechanism of Coal and Gas Outburst Prevention and Control by the Coal Seam Water Injection

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Abstract. Coal seam waterflooding hydraulic wetting has been widely used in coal mines, and plays an increasingly important role in coal and gas outburst prevention, dust prevention, and rock burst prevention. In order to explore the mechanism of coal and gas outburst prevention and control by hydraulic wetting, this paper analyses the three stages of hydraulic wetting through Gibbs function: wetting, soaking and spreading; explains the solution of the three stages through Young's equation, and finally discusses the release and stress of coal gas potential caused by water movement in coal. The centralized influence provides a theoretical basis for the application of coal and gas outburst prevention and control technology in mines.

1. Introduction

Hydraulic wetting, making water permeate into coal fissures and pore space by injecting water into coal seam, is a natural phenomenon, increasing water content and plastic strength of coal body. After wetting by water injection, the physical and mechanical properties of coal body have been changed. At the same time, under the action of high-pressure hydraulic force, the cracks of coal body increase, permeability increases, and water injection destroys the original equilibrium state of coal body gas, resulting in disturbance. Coal seam water injection hydraulic wetting technology has been widely used in mine disaster prevention such as rock burst, coal and gas outburst and dust.

At present, there are many studies on mine disaster prevention through numerical simulation or field test, including coal seam water injection, rock burst prevention, dust prevention, and coal and gas outburst prevention. Liu Mengjie and Wang Kaide et al. [1, 2] studied the water injection pressure and seepage law of coal seam by means of numerical simulation software. Yu Yanbin, Jiang Yujing et al. [3] studied the effects of different pore water pressures on the permeability characteristics of coal and rock by experiments. Liu Lingsheng, Zu Haijun, et al. [4, 5] carried out numerical analysis of the wetting radius of coal seam water injection by fluent simulation software. Dong Xianwei et al. [6] inspected and analyzed the effect of coal seam water injection. Shi Biming et al. [7] studied the change law of wetting mechanics characteristics of outburst coal seam by experiment. Guo Huaiguang [8] studied the main control factors of evaluation of outburst prevention effect through coal seam water injection by means of experimental simulation. Li Xiangchun and Nie Baisheng [9] studied the characteristics of coal adsorbing water.
In summary, researches on coal seam water injection mainly focuses on parameter design, adsorption characteristics and water injection effect, while the study of mechanism of coal and gas outburst prevention by coal seam water injection is relatively less. The mechanism of preventing coal and gas outburst by wetting coal is analyzed and discussed by referring to a large number of literatures, which provides a basis for the prevention of mine gas disaster.

2. Water injection wetting process of coal body

Wetting is a common phenomenon, which is the process of infiltration of solid surface by liquid. Wetting is a kind of interfacial phenomenon when liquid contacts with solid. Under certain temperature and pressure, the process of wetting can be measured by the reduction of Gibbs function. The smaller Gibbs function, the easier it is to wet. Coal wetting includes three processes: wetting, wetting and spreading [10].

2.1. Wetting process

Coal wetting is a process in which liquid and coal never touch each other, and gas-solid interface becomes liquid-solid interface. The Gibbs function of the wetting process is:

\[ \Delta G_w = \gamma_{ls} - \gamma_l - \gamma_s \]  

In formula,

- \( \Delta G_w \) —— Gibbs Function
- \( \gamma_{ls} \) —— Liquid-solid interfacial tension
- \( \gamma_l \) —— Surface tension of liquids
- \( \gamma_s \) —— Solid surface tension.

If the wetting process is spontaneous, then there is \( \Delta G_w < 0 \).

2.2. Wetting process

Coal wetting is a process in which coal is immersed in liquid, and the gas-solid interface is completely replaced by the liquid-solid interface. At constant temperature and pressure, the Gibbs function of the wetting process is:

\[ \Delta G_i = \gamma_{ls} - \gamma_s \]  

In formula,

- \( \Delta G_i \) —— Gibbs function
- \( \gamma_{ls} \) —— Liquid-solid interfacial tension
- \( \gamma_s \) —— Solid surface tension.

If wetting is a spontaneous process, then there is \( \Delta G_i < 0 \).

2.3. Spreading process

Coal spreading wetting is a process in which a small amount of liquid develops automatically on the surface of coal body. If a small amount of liquid exists on the surface of a small droplet before spreading, the Gibbs function in the spreading process will be changed to the Gibbs function at a certain temperature and pressure.

\[ \Delta G_s = \gamma_{ls} + \gamma_l - \gamma_s \]  

In formula,

- \( \Delta G_s \) —— Gibbs function
- \( \gamma_{ls} \) —— Liquid-solid interfacial tension
- \( \gamma_l \) —— Surface tension of liquids
- \( \gamma_s \) —— Solid surface tension.
In formula,
\( \Delta G \) ——Gibbs function
\( \gamma_\text{ls} \) ——Liquid-solid interfacial tension
\( \gamma_\text{l} \) ——Surface tension of liquids
\( \gamma_\text{s} \) ——Solid surface tension.

If the spreading process is carried out spontaneously, \( \Delta G < 0 \) needs to be satisfied.

By calculating the Gibbs function variables of a wetting process, we can judge whether the process can be carried out and the degree of wetting. Because there is no reliable method to measure the surface tension and interfacial tension of solids, the above three expressions cannot be used to calculate directly. This problem can be solved by Young's equation, which is

\[
\gamma_\text{s} = \gamma_\text{ls} + \gamma_\text{l} \cos \theta
\]  

(4)

\( \theta \) ——Contact angle.

By substituting formulas (4) into (1), (2) and (3), we can obtain:

Wetting process: \( \Delta G_\text{w} = \gamma_\text{ls} - \gamma_\text{l} - \gamma_\text{s} = -\gamma_\text{l}(\cos \theta + 1) \)

Wetting process: \( \Delta G_\text{i} = \gamma_\text{ls} - \gamma_\text{s} = -\gamma_\text{l} \cos \theta \)

Spreading process: \( \Delta G_\text{s} = \gamma_\text{ls} + \gamma_\text{l} - \gamma_\text{s} = -\gamma_\text{l}(\cos \theta - 1) \)

If a wetting process can be initiated, there must be such a process. Because of the surface tension of the liquid, the contact angle must be developed to meet the following conditions.

Wetting process: \( \theta < 180^\circ \)

Wetting process: \( \theta < 90^\circ \)

Spreading process: \( \theta = 0 \) or nonexistence.

The above shows that as long as \( \theta < 180^\circ \) the wetting process can be carried out. Because the contact angle of any liquid on the solid surface is always less than 180 degrees, the wetting process can be carried out between liquid and solid. In the three wetting processes, the liquid can only wet the solid when the angle is \( 90^\circ < \theta < 180^\circ \), the liquid can wet the solid when the angle is \( 0^\circ < \theta < 90^\circ \), but also wet the solid when the angle is \( \theta < 0^\circ \) or nonexistent, the liquid can not only wet and wet the solid, but also spread on the solid surface. Therefore, the contact angle between water and coal surface can be used to judge the wetting ability of water injection.

3. Hydraulic Driving in Coal

Coal seam, composing of cracks and pores, is a porous medium. During the process of water injection, water overcomes the resistance of coal seam, and enters the coal body by the action of power. The external power is the pressure of the water injection orifice, mainly depending on the pressure of the water injection pump or the water injection network; the internal power is the capillary action of the coal seam fissures and pore water, mainly depending on the diameter of the pore, the surface tension of water and the wetting edge angle of water to coal. If the pore of coal is regarded as a circular microtubule, its capillary force on water can be expressed as:

\[
P_m = 4.08 \sigma \cos \theta d^{-1}
\]  

(5)

In the formula,

\( P_m \) ——The capillary force of the pore.
\( \sigma \) ——The surface tension coefficient of water.
\( \theta \) ——The wetting edge of water on coal.
\( d \) ——The diameter of the pore.
The sum of pressure and capillary force at the injection orifice is the power of water injection. In addition, coal gas plays an obstacle role in the process of coal seam water injection. If the gas pressure in coal seam is large, the resistance of gas to water cannot be ignored. The gas pressure depends on the occurrence of coal seam gas. The driving force of water injection in coal seam is actually the algebraic sum of water injection pressure at water injection orifice, capillary force of coal seam pore and gas pressure in coal seam. For a coal seam pore, the total pressure difference acting on both ends of the pore is as follows:

\[ \Delta h = P_z + P_m - P_w \]  

\( \Delta h \) —— The total pressure difference acting on the pore of coal seam, kPa.

\( P_z \) —— The pressure difference between the ends of the pore formed by water injection pressure, kPa.

\( P_m \) —— The capillary force of coal seam pore, kPa.

\( P_w \) —— Gas pressure in coal seam, kPa.

4. Analysis of Hydraulic Function of Water Injection and Outburst Prevention in Coal Seam

Coal and gas outburst is a very complex dynamic phenomenon, the mechanism of which has not been fully understood so far. Many hypotheses have been put forward by scholars at home and abroad. Only the comprehensive function theory is accepted, which holds that coal and gas outburst is the result of in-situ stress, high pressure gas and mechanical properties of coal.

When the coal seam is injected with water, water flows in the coal seam fissures, gas moves to free space by the action of water pressure, and finally extrudes the coal wall, thus reducing the content of coal seam gas. From the results of gas concentration measurement near coal wall during water injection, it can be seen that the gas concentration during water injection is significantly higher than that without water injection, which indicates that part of free gas in coal body is driven out by water injection in coal seam. Meanwhile, the content of adsorbed gas decreases with the increase of water content after coal is wetted. High pressure hydraulic fracturing produces a large number of cracks in coal, which increases the permeability of coal seam and reduces the gas pressure gradient in coal body. Because the gas content and pressure gradient of coal body decrease after water injection, and the channel of gas desorption is blocked after water wetting coal body, the speed of gas desorption is reduced, which greatly weakens the ability of gas destroying coal body.

Through the action of pressure water, coal loosened, stress released, pressure relief zone widened, strength decreased and deformation increased. After water injection, the stress of coal body decreases as a whole and the peak stress decreases, which reduces the possibility of outburst. Because of water entry, the coal body undergoes expansion deformation, void fraction increases, strength decreases, elastic modulus decreases and plasticity increases, which consumes elastic potential and is conducive to eliminating stress concentration.

The wetting of coal by water injection has a certain degree of influence on the gas in coal, the stress distribution of coal seam and the physical and mechanical properties of coal. The results of its action are beneficial to prevent coal and gas outburst.

5. Conclusion

(1) Coal wetting includes three processes: wetting, wetting and spreading. The wetting ability of water to coal can be judged by the contact angle between water and coal surface.

(2) The dynamic force of water movement in coal seam during water injection is actually the algebraic sum of water injection pressure at water injection orifice, capillary force of coal seam pore and gas pressure in coal seam.

(3) The wetting process of coal seam water injection is actually a typical unsaturated to saturated seepage process, mainly in unsaturated state, which is the result of the combined action of pressure
seepage, capillary and diffusion. The water injection pressure plays a decisive role in the movement and wetting state of water injection. The wetting process of pressure water injection can be roughly divided into three processes: water inflow, water storage and water adsorption.

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