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Application research of liquid CO_2 fracturing in coal seam penetration

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Abstract. Aiming at the characteristics of high gas content and low gas permeability in coal seams, high-pressure gas generated by the liquid phase transition of liquid CO_2 is applied to the coal rock mass to produce a cracking effect. By analyzing the cracking process of CO_2, using linear elastic fracture mechanics to analyze the crack propagation conditions and the damage and failure criteria of the coal body under the action of liquid CO_2 blasting, the crack expansion state at different times were numerically simulated by the finite difference software ANSYS_LS_DYNA3D. Field tests show that CO_2 cracking can improve gas drainage efficiency in the mining face.

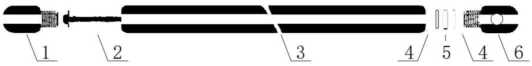
1. Introduction

In China, 70% of the state-owned key coal mines are high-gas mines, which are generally characterized by poor permeability of coal seams and difficulty in gas drainage, which affects the normal mining continuation of mines [1]. For low-permeability coal seams, using conventional drilling arrangements to pre-drain coal seam gas often fails to achieve the expected results. At present, the main anti-reflection technologies used in coal seams include mining protection layers, deep-hole pre-splitting blasting, hydraulic fracturing, and hydraulic slitting, etc. [2] The above-mentioned several anti-reflection methods have some limitations in field applications. In the 1950s and 1960s, developed countries such as Britain and the United States first applied liquid CO_2 cracking technology to coal mining. Liquid CO_2 phase change cracking technology is a type of high-pressure gas anti-reflection technology. Because the cracking process only has gas-liquid phase change process and jet process, it creates an inert gas environment without high temperature heat sources and flames. It can be well applied in high gas mines, coal and gas outburst mines. During the tunneling construction of the Shiquan Mine, due to the large gas content of the coal in the front and the poor permeability of the coal seam, the pre-draining time is long and the construction progress is slow. After research on CO_2 induced cracking and anti-reflection, it was applied to the anti-reflection of coal in front of the roadway and the expected performance was obtained.

2. Liquid CO_2 blasting process

2.1. Brief introduction of phase transition cracking process

The cracking of liquid CO_2 is a physical explosion. The liquid CO_2 in the liquid storage tube is heated by a heated medicine roll that is electrically shocked. The liquid CO_2 in the tube is instantly expanded into a supercritical fluid when heated. The liquid two-phase flow breaks through the shear blades and generates a high-pressure supercritical fluid jet coal. The supercritical fluid will have a very strong impact on the coal body, generate elastic waves with strong energy, and produce a cracking shock wave [3] (Shown as Figure 1).



1-filling valve 2-heating medicine roll 3-reservoir tube 4-sealing pad 5-shear sheet; 6-discharge head

Figure 1. Schematic diagram of the structure of the carbon dioxide cracker

2.2. Phase change cracking process analysis

The critical point of CO_2 is 31.1 ℃ and 7.38MPa. After the liquid CO_2 in the liquid storage tube is heated, the temperature and pressure will exceed the critical point, and it will transform into a supercritical state. The supercritical CO_2 jet acting on the coal body is in an adiabatic process, and most of the pressure potential energy will be converted into the kinetic energy of the fluid. The velocity of the fluid will approach and exceed the local sound velocity of supercritical CO_2 under certain conditions. In the process of supercritical CO_2, the initial supercritical state will eventually change into a gaseous state as the pressure continues to decrease. After the liquid CO_2 exploded in the borehole, a strong stress wave and high-pressure gas were generated. Stress waves generate stress concentration around the borehole. When the tangential tensile stress exceeds the ultimate tensile strength, the coal body will be destroyed to generate cracks, and the initial cracks will be expanded by the high-pressure gas cleavage effect [4, 5].

Assuming that the coal body is a linear elastic body, it is more suitable to use a linear elastic fracture mechanics analysis. According to the linear fracture mechanics, the stress intensity factor of the crack tip is

$$K_r = \sqrt{\pi L}\left[(1-2/\pi)p_m - \sigma\right] \tag{1}$$

Where:

L - The instantaneous length of the crack.

P_m - Pore wall pressure.

σ - Ground stress.

It can be seen from the above formula that as the ground stress increases, the stress intensity factor K_r decreases linearly. At a position far from the center of the blast hole, the blasting pressure is greatly reduced, and it is also greatly reduced. When the attenuation K_r is reduced to a certain value, the blasting rupture gap will no longer extend.

Under the action of high-pressure CO_2 gas stress generated by fracturing, the strong brittleness of the coal body is weakened, and the macro performance is quasi-brittle. The crack propagation conditions of quasi-brittle materials can be used as the damage failure criterion of coal bodies under high-pressure CO_2 blasting, that is:

$$\sigma = \sigma_c = \sqrt{\pi 4\sigma_a} K_{IC} \tag{2}$$

Where:

σ -Effective stress in coal body, MPa.

σ_c - Critical stress for micro-cracks to propagate, MPa.

K_{IC} -Fracture toughness of coal body.

σ_a -Initial crack radius, which is the average radius of the macro-crack formed by the cracking stress wave.

When $\sigma < \sigma_c$, the coal body is not affected by the damage and is in the linear elastic stage; when $\sigma > \sigma_c$, the coal body enters the non-linear damage stage, and the micro-cracks with initial radius a in the coal body begin to expand.

The tangential stress of the crack in the cracking area from the center of the cracking hole at **r** is

$$\sigma_\theta = \frac{\alpha^2}{r^2} p_0 - \sigma_\varepsilon (1 + \frac{\alpha^2}{r^2}) \tag{3}$$

Calculate the radius of the secondary expansion of micro-cracks as

$$r = \sqrt{(P_0 - \sigma_\varepsilon)/(\sigma_c + \sigma_\varepsilon)} \tag{4}$$

Where:

P_0 -Pressure of crack wall surface, MPa;

σ_c - Critical stress for micro-cracks in coal body to expand under tensile conditions, MPa.

2.3. Numerical simulation analysis

Finite difference software ANSYS_LS_DYNA3D was used for blasting numerical simulation. The numerical model was composed of blasting medium, air and coal. The CO_2 and air medium were modeled using Euler meshes, and the same size model was used to simulate the blasting of three high-pressure CO_2 blasting pipes and six high-pressure CO_2 blasting pipes in the coal body[6].

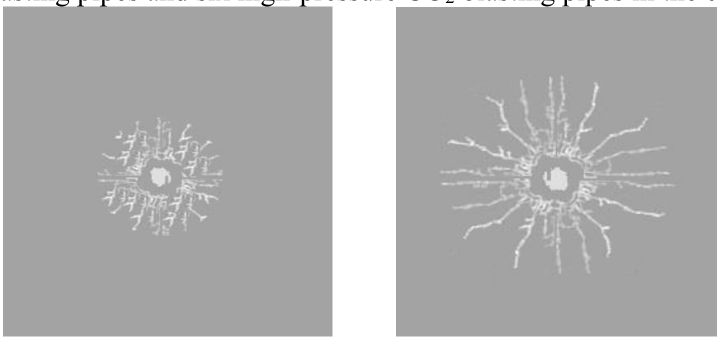


Figure 2. The expansion state of cracks in 3 pipes at different times

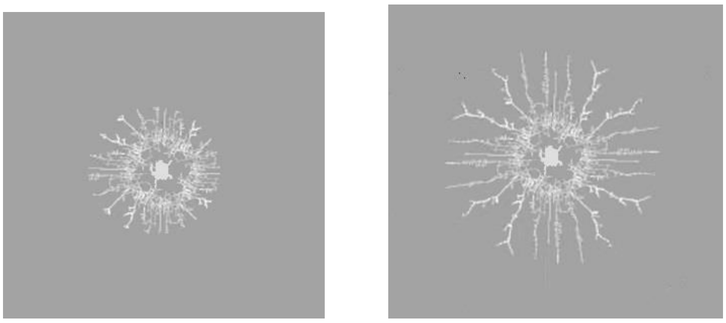


Figure 3. The expansion state of cracks in 6 pipes at different times

As shown in Figure 2, after the liquid storage pipe explodes in the borehole, firstly, the high-pressure stress wave causes a strong squeezing effect on the coal body around the borehole, causing the surrounding coal body to deform, compress, and even destroy. During the blasting process, different changes occur in the coal body at different times. In the initial stage of crack formation, the main crack was generated first due to the strong stress wave action. Due to the weakening of the stress wave action, the main crack increased with time. Decrease and stop extending after a certain period of time. In the initial stage of blasting, the main crack developed along the cross direction. The main reason for this phenomenon was that the strong shock wave and the direct wedging of the explosive gas caused the crack to develop un-idirectionally. In the middle and late stages, due to the gradual weakening of the stress wave, the effect of the explosive gas became smaller, and the secondary fractures began to develop. The secondary crack is extended from the main crack, so its direction is disordered and there is no consistency. Comparing Fig.2 and Fig.3, the 6 cracking tube model shows more main fractures than the 3 cracking tube model, showing a longer extension, and secondary cracks are more obvious. The more cracks, the more they grow down-hole. When penetrating, the more liquid a single detonation charge has, the more obvious the effect. The greater the permeability of the coal body, the easier the gas migration, and the more favorable it is for gas drainage in the coal seam.

3. Field test

Shiquan Coal Mine is a high-gas mine. The No. 3 coal seam is mainly mined. The thickness of the coal seam is 5.05-7.20m and the average thickness is 6.14m. According to the down-hole measured data and borehole gas test data during the geological survey, the methane content of No. 3 coal seam is 5.3-10.2m^3/t, the permeability coefficient of coal seam is 0.031m^2 /(MPa^2 • d), and the 102 belt is driven along the trenching face. During the period, conventional gas control measures such as long-drilling pre-drained gas and head-dried pre-drilled drilling were adopted to ensure the safe driving of the heading face, and the amount of coal falling from the heading face was 3.2-4.1m^3/min. Affected by the high gas content of the coal in front, the progress of the tunneling is slow. In order to solve the difficulty of the advancement of the mine, combined with the existing liquid CO_2 fracturing and anti-reflection technology, an experimental study on anti-reflection of coal bodies in front of the working face was carried out. The CO_2 cracker was pre-filled on surface, and then transported to the driving face. the cracker is connected in sequence and pushed into the crack hole, and the initiation bus is connected to the two poles of the cracker. The detonator is detonated by the detonator at a safe firing distance.

The drilling arrangement was designed according to the cross section of the heading face. Combining the results of numerical simulation and field investigation, the effective radius of liquid CO_2 in coal blasting is 4-6m. It is designed to construct a blasting hole with a diameter of 75mm and a length of 30m in the center of the rectangular tunneling working face[7]. Four extraction holes are set in the cross direction around the blasting hole. A 2m connecting tube is placed between the cracker and the cracker, and the sealing depth is 5m. After blasting, the coal body became loose and the hole cracks increased. The four drainage holes were quickly connected for drainage, and the drainage effect was examined.

By examining the gas extraction volume and gas extraction concentration before and after fracturing, the drilling pre-draining time can be found (Fig.4 and Fig.5): the average gas drainage concentration in the borehole before fracturing was 11.2%, and the gas drainage in the early stage of drainage The concentration is 15-20%, and it quickly decays to about 10% after five days. The single-hole gas drainage volume averages 0.012m^3/min. After five days, the gas drainage volume decreases sharply. A large amount of adsorbed gas of coal body still remains inside the coal body. The average gas drainage concentration of the borehole after fracturing was 37.2%. The gas drainage concentration has remained above 35% within fifteen days, and the fluctuation range is not large. The average gas drainage volume of a single hole is 0.036m^3/min. After ten days, the pure volume of gas drainage gradually decreases. This is because a large number of cracks are generated around the blast hole due to blasting, which destroys the equilibrium state of gas adsorption and desorption in the original coal seam, and a large amount of adsorbed gas is desorbed into a free state. When the blasting stress wave reaches the free surface, it will be reflected as a tensile wave. When the tensile wave is greater than the tensile strength of the medium, the Hopkinson effect will occur. At the same time, the reflected tensile wave and the stress field at the tip of the radial fissure are superimposed on each other, which promotes the radial fissure and hoop fissure to further expand, greatly increasing the range of the fissure zone. At the same time, a large amount of CO_2 gas is generated after blasting, and the competitive adsorption capacity of CO_2 gas is stronger than that of CH_4. As CO_2 is continuously adsorbed by the coal body, the desorption speed of CH_4 is accelerated.

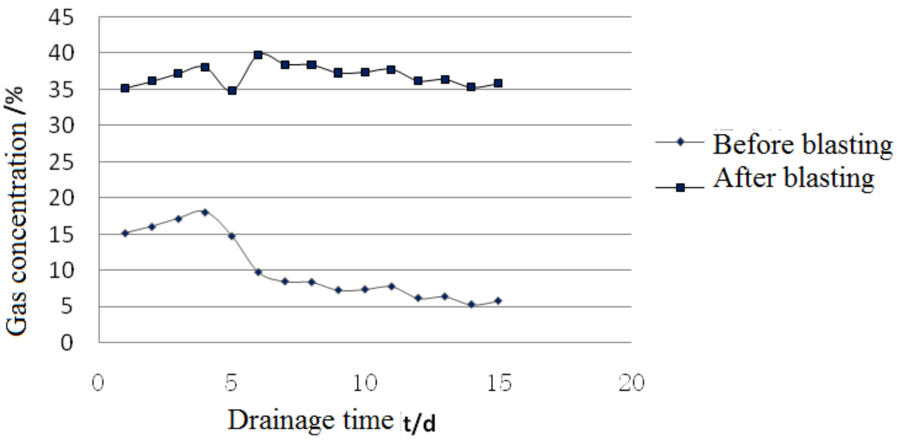


Figure 4. Change of drainage concentration before and after blasting

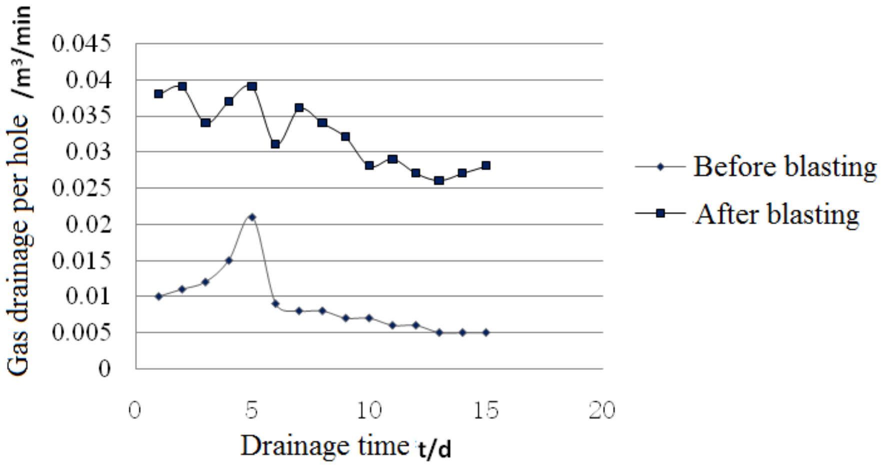


Figure 5. Variation of single-hole gas drainage before and after blasting

After the liquid CO_2 cracking and anti-reflection test was carried out in Shiquan Coal Mine, the pre-draining time of the mining face was reduced from two months to half a month. During the tunneling, the gas concentration decreased to 0.12% -0.23%, and the falling coal gas decreased by 50%, achieved the expected test results.

4. Conclusions

• Based on the theory of damage and fracture mechanics, the effective stress intensity factor of the initial macro crack tip formed by the cracking stress wave was calculated, the crack propagation process under the action of high-energy CO_2 and gas generated by the cracking was analyzed, and the dynamic crack propagation was studied.

• Liquid CO_2 fracturing technology applied to underground coal seams to increase permeability can significantly increase gas drainage flow, reduce pre-draining time, and increase heading speed. This technology can effectively ensure the safe and efficient production of mines.

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