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Mechanisms and Numerical Simulations of Liquid CO_2 Phase Transition-Induced Permeability Enhancement in Coal Seams

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Abstract

The geological structures of the coal fields in China are complex. With the continuous increase in the mining depth, the coal seams show the characteristics of high gas and low permeability, and the disaster potential of a coal and gas outburst intensifies in the process of coal mining. Gas drainage is one of the primary measures to prevent and control gas disasters. How to effectively improve the permeability of a coal seam is an urgent problem to be solved. Currently, the method of loose blasting is used in engineering to enhance the permeability of coal seams. However, the technology of loose blasting easily leads to the poor development of coal fractures or the severe crushing of coal, which will affect the gas drainage. Thus, this paper studied the technology of liquid CO_2 phase transition fracturing in a coal seam. COMSOL was used to determine the influence radius of the liquid carbon dioxide phase transition cracking, which was 13.4 m, and to design the scheme of the borehole. The field test was carried out in the 81506 working face of the Baode Coal Mine. Through the onsite monitoring data, the results showed that the drainage effect increased by 293.9%, the gas drainage concentration increased by 242.4%, the permeability coefficient of the coal seam increased by 3–7.75 times, and the permeability enhancement effect was good.

Keywords

Coal Seam Permeability; Gas Drainage; Coal Seam Permeability Improvement; Carbon Dioxide Fracturing.

1. Introduction

For a long time, gas has seriously restricted the safe production of coal mine enterprises [1–2]. With the increase in the mining depth, the permeability of the coal seam becomes lower and lower. Enhancing the permeability of a coal seam is a prerequisite for gas extraction and the safe production of coal mines. At present, hydraulic fracturing technology is widely used in gas extraction [3]. However, the effect of the coal seam permeability improvement is poor for the downward layer through the borehole. The influence of the different thicknesses and hardness of a coal seam on the effect of permeability enhancement has been less studied. The understanding of the coal breaking mechanism of hydraulic punching, and the mechanism of increasing permeability and pressure relief are lacking. The process and technical parameters of hydraulic punching need to be further studied. The common punching process can easily cause problems such as holding holes, plugging holes, sticking, and running water. In particular, the coal water mixture flushed from the upward hole tends to accumulate at the upper opening of the casing, which directly affects the drilling and flushing process [4]. Therefore, there is an

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urgent need to find a penetration enhancement method with a good penetration effect and high safety. This paper analyzes and evaluates the technology of the liquid CO_2 phase transition fracturing in a coal seam to enhance permeability.

The liquid carbon dioxide phase transition cracking device uses a heating tube to heat the liquid carbon dioxide in the fluid storage tube, changing it from a liquid state to a gas state, and the pressure increases sharply [5]. Then the high-pressure gas smashes the constant pressure energy sheet and generates stress waves that propagate. The generated gas passes through the release channel of the exhaust pipe and reaches the coal mass in a short time to form an explosive airflow. Stress waves and high-energy gas can not only generate new cracks in the coal mass but can also make the original cracks expand [6].

The liquid carbon dioxide phase change fracturing technology was first proposed by the Cardox International, UK, called the Cardox Tube System [7]. Singh introduced the main structure and application method of the device and pointed out that the device can be used for large-scale mining and excavation of a quarry. Due to its high safety, the device can be used for underwater operation and for fast and safe blasting near reservoirs and dams [8]. In Turkey, coal mines use the Cardox device in the working face to split the coal mass by the high-pressure carbon dioxide gas generated instantly, thus improving the lump coal rate [9]. Lekontsev compared several explosion-proof rock fracture technologies and suggested that the Cardox device does not belong to the scope of explosion but only a high-pressure gas generator [10]. Therefore, it is not limited by the control of explosives, which have a limited scope of use. With its safety and stability, the liquid carbon dioxide phase change cracking can be applied to the cleaning of large storage tank walls. As carbon dioxide gas is an inert gas, the device can be applied to the treatment of flammable and combustible materials. Lisienko studied the carbon dioxide cannon by simulating coal blasting on the ground and stated that the liquid carbon dioxide blasting was a slow, expansive, diffusing, and shearing process, which caused the released carbon dioxide gas to cut along the natural cracks of coal or explosives and was most suitable for the blasting of porous brittle materials. Xiang Cheng tested carbon dioxide blasting in the working face of Luling Coal Mine. After blasting, the effect of the coal briquetting was good, the amount of coal thrown was large, and the ratio of fine coal was significantly reduced.

The phase change fracturing technology of liquid carbon dioxide is a new technology for the coal industry, which uses the huge energy released by liquid carbon dioxide in the process of the liquid-gas two-phase transformation in a confined space to act on the original fractures, and the fracturing effect of the high-energy gas expands the original fractures At the same time, the impact force generated during fracturing breaks the hole wall, creating new cracks, which increases the crack development of materials, improves the permeability of materials, and even breaks materials.

1.1. Effect of the Stress Wave on the Coal Mass

When high-pressure carbon dioxide gas is ejected from the fluid storage pipe, it is accompanied by the generation of stress waves. When the coal mass is regarded as an ideal elastomer, the motion equation of the coal-rock particle when the elastic wave propagates is as follows:

$$(\lambda + G)\frac{\partial \theta}{\partial x_i} + G\nabla^2 u_i = \rho \frac{\partial^2 u_i}{\partial t^2} \quad i=1,2,3\ldots \tag{1}$$

where u_i is the displacement of the particle in the coordinate direction; $\theta = \varepsilon_{ij} = u_{ij}$ is the volumetric strain; ∇^2 is the Laplace operator; λ, G is the lame elastic constant; ρ is the density of coal-rock mass; and t is time.

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1.2. High-pressure Gas Gathering Cutting by the Phase Change of Liquid Carbon Dioxide

The unique design of the end of the release pipe in the liquid carbon dioxide phase transition equipment can solve the problem of the blasting energy dispersion and dilution. The exhaust hole of the release pipe allows the gas to be discharged in a fixed direction, so that the energy is gathered and fractures the coal mass. When the high-pressure liquid carbon dioxide gas impacts the coal in the form of jet, the high-pressure gas radiates from the center of the jet.

The impact of the high-pressure carbon dioxide gas to fracture the coal mass is divided into the following categories: the cavitation damage, the impact cutting effect of the high-pressure gas, the dynamic pressure effect of high-pressure gas, and the gas wedge effect formed by high pressure gas. Under the impact of high-pressure carbon dioxide gas, the internal stress distribution of the coal mass is similar to the half-space elastomer under the concentrated load. When the compressive stress generated by the impact of high-pressure gas reaches or exceeds the compressive strength of the coal body, the original coal body is damaged, and cracks are formed in the coal body. When the compressive stress generated by the impact of high-pressure gas exceeds the compressive strength of the coal mass, the original coal mass is damaged, and cracks are formed. The high-pressure gas entering the cracks causes the cracks to develop and expand rapidly, resulting in the fracture of the coal seam.

1.3. Coal Seams Fractured by the Liquid Carbon Dioxide Phase Change Expansion Force

The liquid carbon dioxide in the liquid storage pipe gradually changes into gaseous carbon dioxide after heating, the volume expands continuously, and the pressure of the carbon dioxide gas increases continuously [9]. When the carbon dioxide gas breaks through the constant pressure valve and is ejected through the release pipe, the carbon dioxide gas still expands and increases, generating expansion work [10]. The high-pressure carbon dioxide gas exerts pressure on the wall of the fracturing boreholes, forcing new fractures in the coal seam. Otherwise, the high-pressure carbon dioxide gas enters the coal seam and expands the original fractures in the coal seam.

2. Methods

2.1. Numerical Model

Table 1. The parameters of the model

Symbol	Parameter	Value	Unit
ρ_1	Density of coal seam	1490	kg/m^3
E	Elastic modulus	2×10^9	Pa
V	Poisson ratio	0.35	–
K	Permeability	10^{-17}	m^2
K_1	Porosity	6.58	%
c	Cohesion	4	MPa
φ	Internal friction angle	33	°
ρ_2	Density of CO_2	1.977	kg/m^3
μ	Dynamic viscosity of CO_2	1.48×10^{-5}	Pa•s
Z	Compressibility factor of CO_2	1.02	–

To study the influence radius of the liquid carbon dioxide phase transition cracking, taking the #8 coal seam of Baode Coal Mine China as the engineering background, COMSOL was used for analysis. In the numerical calculations, a gas pressure of 270 MPa was applied to simulate the cracking gas pressure generated during the phase transition of liquid carbon dioxide. The parameters of the coal mass are shown in Table 1.

The model was constructed with the 81506 working face of Baode Coal Mine as the engineering background, and the model is shown in Figure 1. The size of the model was 150 m×100 m, and the fracturing boreholes were in the middle of the calculation model. To facilitate the calculation, the mesh size was differentiated. The mesh size near the fracturing boreholes was small and dense, and the mesh size away from the fracturing boreholes was large and sparse. The boundary of the model was fixed, and the diameter of the borehole was 113 mm. The boundary condition of the orifice was Darcy's law, and the pressure was 270 MPa to simulate the fracturing gas pressure generated during the phase change of liquid CO_2. The upper boundary of the model was subject to a uniformly distributed original rock stress of 2.08 MPa.

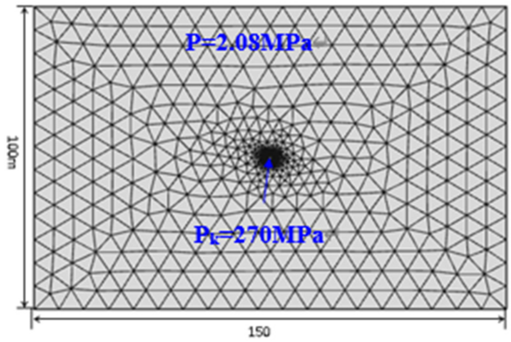


Figure 1. Numerical simulation model of phase transformation cracking

2.2. Theoretical Calculation

According to the theory of elastic mechanics and fracture mechanics, the fracturing radius of the coal mass of the gas phase transition can be calculated by the following formula:

$$r_c = r_h \times \left(\frac{P_{max}}{K_t S_t}\right)^{\frac{1}{\alpha}} \tag{2}$$

where r_c is the fracturing radius of the coal mass of the gas phase transition in m; r_h is the radius of the borehole in mm; P_{max} is the pressure peak of the gas phase transition in MPa; K_t is the improving coefficient of tensile strength with dynamic load; S_t is the tensile strength of coal mass with static load in MPa; α is the attenuation index.

The static stress of the coal mass around the borehole can be calculated by the following formula:

$$\sigma_r = P \times \left(\frac{r}{r_c}\right)^{-\alpha} \tag{3}$$

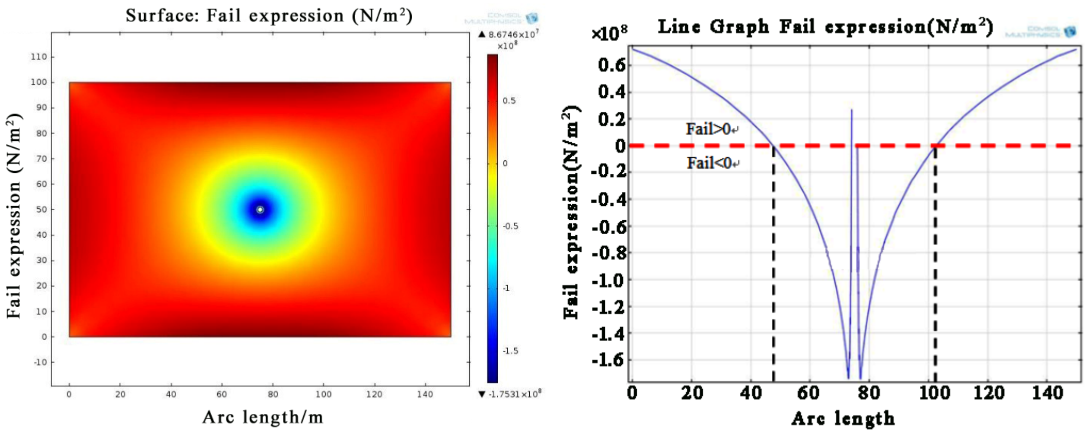
where P is the gas pressure in the initial crack area in MPa; K_b is the bulk modulus of the coal mass in MPa; σ_r is the static stress of the coal mass around the borehole, MPa; r is the distance from the borehole, m.

When the value of σ_r is equal to the extreme tensile strength of the coal mass, the value of r is the crack radius of the gas phase transition. According to the actual conditions of the Baode coal mine, the field parameters were chosen as follows: r_h=113mm, P_{max}=270MPa, K_t=6.6, St=5MPa, α=1.5, P=150MPa, K_b=10.5×10^3MPa.

According to the aforementioned theoretical calculation, when the σ_r=0.9MPa, which is equal to the extreme tensile strength of the coal mass, the crack radius of the gas phase transition is 13.8m.

3. Results and Discussion

According to the numerical model and the stress applied to the model, as shown in Figure 2(a), the plastic deformation characteristics of the coal mass around the borehole after phase transition cracking were simulated. To analyze the damage area by high pressure gas on the coal mass, as shown in Figure 2(b), a section was made in the middle of the coal mass.



(a) Plastic deformation area (b) Sectional view of plastic deformation area

Figure 2. Plastic deformation

Increasing the pore pressure was equivalent to applying tensile stress to the coal matrix. Due to the tensile stress, cracks in the coal matrix began to develop and expand, and plastic deformation occurred in the coal mass. With the condition that the gas pressure of 270 MPa was applied at the orifice, fail = 0 meant it was in a critical state of destruction; fail < 0 meant that plastic deformation had occurred; and fail > 0 meant it was in a stable state. The numerical simulation results showed that the radius of plastic deformation of the coal mass was 23 m. According to the numerical simulation, the plastic deformation region of the coal mass was divided as follows: the area of fail < 1.0×-10^8 Pa was the broken circle, the radius r_1 was 4.6 m; the area of 1.0×-10^8 Pa < fail < 0.5×-10^8 Pa was the fissured circle, the radius was 4.6 m< r_2 <13.4 m; and the area of 0.5×-10^8 Pa < fail < 0 was the disturbance circle, the radius was 13.4 m< r_3 < 23.1 m. The area was divided as shown in Figure 3.

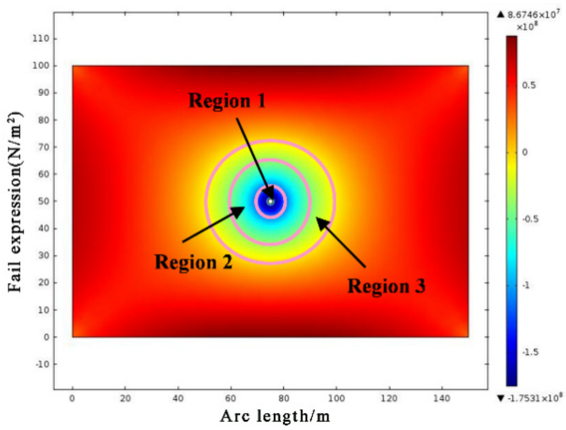


Figure 3. Division of the plastic deformation zone

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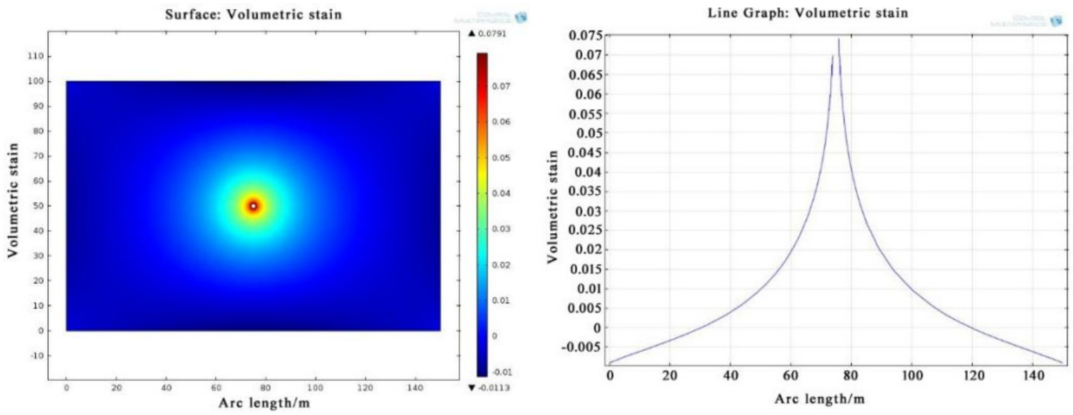
As shown in Figure 3, the plastic damage of the broken circle (Region 1) was the most serious, the plastic damage of the fracture circle (Region 2) was smaller, and the plastic damage of the disturbance circle (Region 3) was the smallest, and it still had a promotion effect on the gas drainage. For the borehole to have a good gas drainage effect, the borehole should be arranged within the range of the fissured circle. According to the numerical simulation, the influence radius of the fissured circle was 13.4 m, which was basically consistent with the results of the aforementioned theoretical calculation.

To improve the accuracy of the division of different regions, the volumetric strain was obtained during the simulation process by COMSOL, as shown in Figure 4(a). According to the position of the section line in Figure 3, the volumetric strain contour in Figure 4(a) was cross-sectioned, and the result is shown in Figure 4(b).



(a) The nephogram of the volumetric strain (b) The section value of the volumetric strain

Figure 4. The volumetric strain

As shown in Figure 4, a gas pressure of 270 MPa was applied at the orifice, and the volumetric strain of the coal mass showed that the closer the distance to the orifice, the larger the volumetric strain. The distribution of the volumetric strain was consistent with the distribution of the plastic deformation of the coal mass. The volumetric strain in the broken circle was the largest, followed by the fissured circle, and the disturbance circle was the smallest.

4. Conclusion

In this paper, the mechanism of the liquid carbon dioxide fracturing coal seam to enhance permeability was studied. The COMSOL software was used to numerically analyze the influence radius of the liquid carbon dioxide phase transition fracturing, which provided a basis for reasonable field distribution parameters and analyzing the effect of the onsite liquid carbon dioxide fracturing. The main conclusions were as follows:

(1) The technology of liquid carbon dioxide fracturing coal seam enhanced the permeability through three aspects. First, the action of stress wave caused new cracks in the coal mass, and stress concentration occurred at the tip of the crack, which promoted the expansion and development of tiny cracks. Second, the intrusion of the high-pressure liquid carbon dioxide gas into the coal, resulted in cutting, impact, and a gas wedge. Third, the carbon dioxide gas broke through the constant pressure valve, and a large expansion thrust was generated, which acted on the coal mass, generating new cracks and disturbing the primary cracks in the coal seam.

(2) The COMSOL software was used to simulate the influence radius of the liquid carbon dioxide cracking, and it was determined that with the geological conditions of the #8 coal seam in the Baode Coal Mine, the influence radius of the carbon dioxide phase transition cracking was 13.4 m.

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