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Study on Effect of Liquid CO2 Blasting Crack Propagation in Coal Rock with Natural Fissure based on ANSYS/LS-DYNA

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Abstract: In order to study the influence of natural cracks in rock mass on the blasting effect of liquid CO2, and to better promote this technology, the law of energy propagation and crack propagation after blasting of liquid CO2 in coal rock mass containing natural cracks was studied based on ANSYS/LS-DYNA numerical simulation software. The results show that natural cracks in coal and rock will block the energy propagation after liquid CO2 blasting, reflect most of the stress wave energy, and form a crushing zone of 49.6cm×10.6cm in front of natural cracks in coal and rock. Stress concentration occurs at the tip of the natural crack, forming the initial guide crack, changing the direction of crack development. The crack develops along the direction perpendicular to the natural crack of coal rock mass, and the final shape of crack growth is 69.8cm. The research results can provide a theoretical basis for the determination of the actual blasting scheme.

Keywords: Liquid CO2 Blasting; Natural Cracks; Stress Concentration; Initial Guide Crack; Crack Propagation Law.

1. Introduction

Liquid CO2 blasting technology was originally invented and researched by CARDOX Company in the UK, and was mainly used for rapid and safe blasting in various processes such as underground and open-pit mining, blasting source, pipeline blockage clearing, large storage tank tube wall cleaning and cement manufacturing in the early stage [1]. In the complex environment, the risk of rock blasting is high, and non-explosive blasting is a problem that people have been studying. The development of liquid CO2 blasting technology started relatively late in China. The General Institute of Coal Science used liquid CO2 blasting cylinders to conduct simulation experiments on Pingdingshan, and achieved certain results, proving the feasibility of the development of this technology [2].

With the gradual popularization of this technology in China, it has been widely used in coal seam anti-reflection, roadbed excavation and other engineering fields, and related scholars have carried out research on it. Jia Jinzhang et al. [3] used LS-DYNA to simulate and analyze the crack propagation rules of single hole and double hole blasting with different hole spacing and addition of control holes. Dong Qingxiang et al. [4] used ANSYS/LS-DYNA simulation software to determine the calculation method of TNT equivalent of liquid CO2 blasting. Xu Mingbiao [5] et al. determined a series of blasting parameters through the combination of pre-split blasting test and numerical simulation. Zhu Shuancheng et al. [6] used liquid CO2 blasting for roof hanging treatment in the triangle area to eliminate the risk caused by sudden roof collapse. Zhang Liwei et al. [7] optimized the blasting scheme through ANSYS/LS-DYNA numerical simulation, proving the feasibility of rock damage evolution law optimizing the layout of gun holes. Gong Min et al. [8] proved that the stress wave propagation and failure characteristics of coal seam in pre-cracking blasting are significantly different from those of rock. Zhou Xihua et al. [9] determined better drilling parameters of liquid CO2 blasting by detecting the pressure time history curve of high-pressure gas in the blasting device and conducting numerical simulation with FLAC3D. Yuan Hailiang et al. [10] established a high-pressure jet impact rock breaking model based on SFH algorithm, providing a new idea for the numerical simulation of liquid CO2 blasting. Wang et al. [17] determined that gas pressurization plays a leading role in rock crushing by setting two liquid CO2 blasting simulation schemes.

Therefore, this paper uses ANSYS/LS-DYNA numerical simulation software and equivalent TNT equivalent method to study the influence of natural cracks in coal and rock mass on blasting effect during the process of liquid CO2 blasting, and obtains the crack propagation rule after liquid CO2 blasting under the influence of natural cracks in coal and rock mass blasting. It provides a scientific reference for the formulation of the actual liquid CO2 blasting scheme and improves the utilization rate of liquid CO2 blasting energy.

2. Liquid Liquid CO2 Blasting Equipment and Technical Introduction

2.1. Liquid CO2 Blasting Equipment

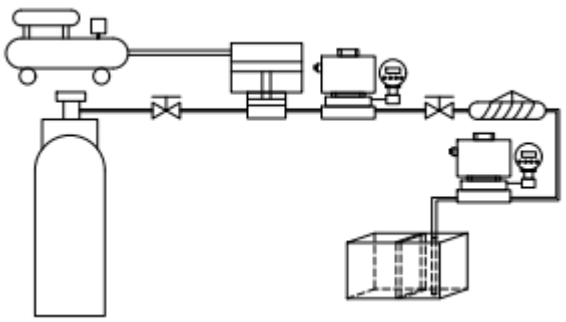


Fig 1. Liquid CO2 blasting equipment

The composition of liquid CO2 blasting equipment is shown in Figure 1. Liquid CO2 blasting equipment is mainly composed of CO2 cracking device, CO2 charging machine,

CO2 gas storage tank and air compressor.

Through the joint action of the CO2 filling machine and the air compressor, the CO2 in the CO2 storage tank is injected into the cracking device to form a closed space and store CO2. The fully loaded CO2 splitters can be transported to the well for direct connection, greatly reducing risks during transportation.

2.2. Mechanism of Liquid CO2 Blasting Rock Breaking

After the CO2 splitter is connected, the detonator sends out a current to stimulate the electric heat pipe in the CO2 splitter, which instantly releases a lot of heat and vaporizes the liquid CO2 in the CO2 splitter. The pressure in the tube increases greatly. After breaking the constant pressure sheet, the high-pressure CO2 gas is released through the energy discharge terminal and acts on the rock mass.

First, the high pressure CO2 gas jet acts on the rock mass near the energy discharge end in the form of shock wave. Under the impact of high pressure gas, the rock mass will produce radial displacement, and the rock mass around the energy discharge end will produce radial compression and tangential tension. When the tangential tensile stress exceeds the ultimate tensile strength of rock mass, cracks will occur in tensile failure of rock mass. When the attenuation of shock wave is lower than the tensile strength of rock mass, cracks will no longer occur. The shock wave transforms into a stress wave and continues to propagate. Under the combined action of high-pressure CO2 gas, cracks continue to crack and form secondary cracks. When the stress wave continues to propagate outward, the strength of the stress wave is no longer enough to cause rock damage, and the damage range of the rock mass no longer increases [11].

3. Model Building

3.1. Rock Model

The liquid CO2 blasting rock model as shown in Figure 2 is established. The size of the rock in the model is 4m×4m×0.001m (length × width × thickness), the diameter of the gun hole is 0.09m, the size of the rock crack is 1.7m×0.002m×0.001m (length × width × thickness), and the distance between the center of the gun hole and the rock crack is 1m. Non-reflective boundaries are set around the rock to simulate rock blasting in real rock formations.

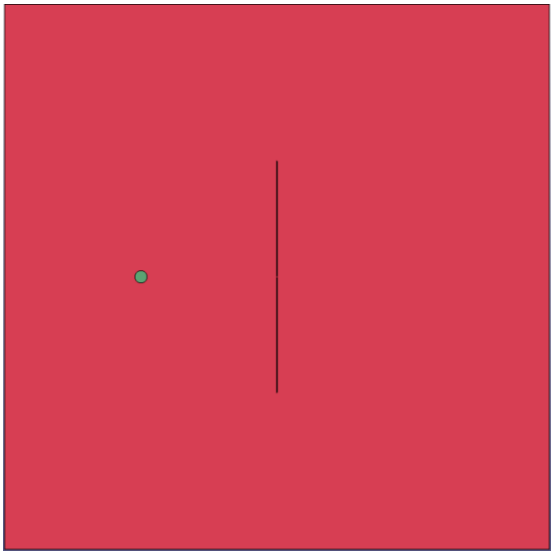


Fig 2. Coal and rock mass model

3.2. Material Model

H-J-C model with material number 111 is selected for rock mass. The model mainly considers the large deformation and strain rate under high pressure, so it can be used to simulate the coal and rock under the action of explosive dynamic load. Jiang Shichao [12] conducted a numerical simulation study on the dynamic impact mechanical characteristics of coal and rock mass by ANSYS, citing the parameter selection of its H-J-C constitutive model, as shown in Table 1.

Table 1. H-J-C parameters of coal rock

Parameters	numerical value
Coal rock densityρ_O/(kg/cm^3)	141O
Shear strength G/GPa	O.58
Normalized cohesion strength A	O.41
Pressure hardening coefficient B	O.7
Strain rate effect coefficient C	O.O5
Normalized pressure hardening index N	O.76
Uniaxial compressive strength f_c/MPa	12.O
Tensile strength T/MPa	2.14
Reference strain rate $\dot{\varepsilon}_0$/(1/s)	1.O
Material fracture plastic strain EFMIN	O.O1
Maximum normalized equivalent stress SFMAX	7.O
Elastic peak pressure p_c/MPa	4.O
Elastic volumetric strain μ_c	O.OO21
Pressure peak pressure p_l/MPa	O.34
Compacted volumetric strain μ_l	O.1
Damage factor D_1	O.O3
Damage factor D_2	1.O
Pressure constant K_1/GPa	1.6
Pressure constant K_2/GPa	-O.17
Pressure constant K_3/GPa	5.8

Since there is no numerical simulation method for liquid CO2 blasting directly at present, the equivalent TNT

equivalent method is used for simulation. Li Wenwei et al. [13] studied and obtained the energy calculation formula of CO2 phase change cracking device as shown in equation (1):

$$Q = \frac{P_1 V}{K-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right] \quad (1)$$

Where: Q is the energy (kJ) of CO2 phase change cracking device; P1 is the absolute pressure (KPa) of the gas in the CO2 phase change cracking device. P2 is the standard atmospheric pressure, 101.325KPa; V is the volume of CO2 phase change cracking device (m3); K is the adiabatic index of CO2, which is 1.295.

The TNT equivalent of liquid CO2 phase transition cracking is calculated as shown in equation (2):

$$W_{TNT} = \frac{Q}{Q_{TNT}} \quad (2)$$

Where: WTNT is equivalent to TNT (kg); QTNT is the explosive energy of 1kgTNT, and 4250kJ/kg is taken.

Since there are TNT explosion overpressure data in LS-DYNA, after WTNT is obtained by connecting the lines (1) and (2), we define the keywords of TNT equivalent in the simulation program *LOAD of LS-DYNA, including TNT equivalent, initiation point, explosion type and contact surface of explosion wave [14].

CO2 splitter Select the liquid CO2 splitter [15] whose reference model is MZL2OO-51/1OOO. Table 2 lists the parameters

Table 2. Parameters of the MZL2OO-51 splitter

Model	Length(mm)	Diameter(mm)	Shear slice threshold (MPa)
MZL2OO-51	1OOO	51	2OO
Peak pressure (MPa)	Pressure rise time(s)	Explosion energy (KJ)	TNT equivalent(g)
165	O.OO1	1384.95	325.87

The explosive material is selected as OO8High-Explosive Burn model with ANSYS number, and its model parameters are shown in Table 3.

Table 3. Explosive material parameters

MID	RO	D	PCJ
3	1.7O	1.OO	O.22
BETA	K	G	SIGY
O.O	O.O	O.O	O.O

The Null model OO9 of ANSYS is selected for air material, and the model parameters are shown in Table 4.

Table 4. Air material parameters

MID	RO	PC	MU
2	O.OO12	O.O	O.O
TEROD	GEROD	YM	PR
O.O	O.O	O.O	O.O

4. Numerical Simulation based on ANSYS/LS-DYNA

In order to improve the blasting efficiency of liquid CO2 blasting and make effective use of blasting energy, the influence of natural cracks in coal and rock mass on the blasting effect of liquid CO2 was analyzed.

4.1. Analysis of Stress Wave Transmission After Blasting of Liquid CO2

The direction facing the hole was defined as the front of the crack, and the pressure-time curves at 0.1m in front of the crack, 0.1m behind the crack and at the top of the crack were compared. See Figure 3. The stress wave transfer process of coal and rock after sorting and solving is shown in Figure 4.

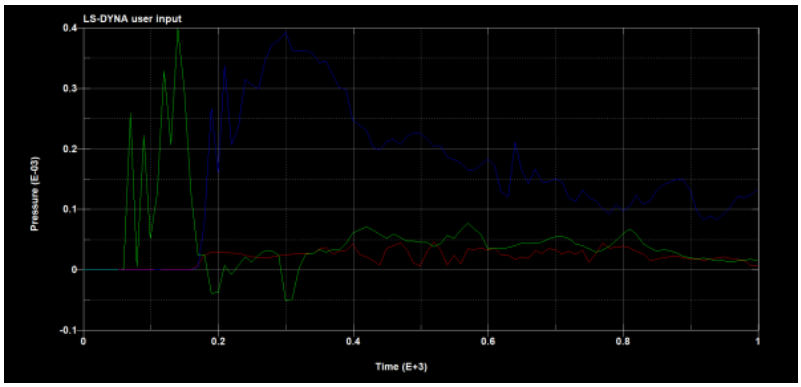


Fig 3. Pressure-time curve

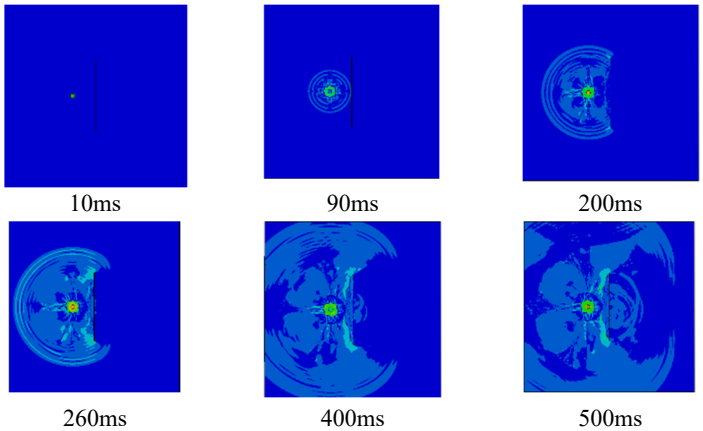


Fig 4. Cloud image of gravitational wave transmission

As can be seen from Figure 4, the stress waves generated by liquid CO2 blasting propagate in coal and rock mass. When there are natural cracks in coal and rock mass, the stress waves cannot propagate through the natural cracks. At 90ms, the wave front breaks when it comes into contact with the natural cracks in coal and rock mass and cannot continue to propagate. The stress wave is reflected after contacting the natural cracks in coal and rock mass. The propagation of this part of energy and subsequent stress waves intensifies the accumulation of blasting energy in front of the natural cracks in coal and rock mass. Greater stress concentration is formed in this region, which intensifies the development of cracks in this region, and thus produces a new crushing zone. The propagation of stress waves in other directions is not affected, and the diffraction continues to propagate after passing through the natural fissure of coal rock mass. At 400ms and 500ms, a small part of stress waves propagate through natural cracks in coal and rock mass.

During 200ms-260ms, the stress wave diffracted through the natural crack of coal and rock mass, and the stress concentration phenomenon appeared at the tip of the natural crack of coal and rock mass, and the crack produced by blasting started from the tip of the natural crack of coal and rock mass and developed towards the propagation direction of the stress wave.

4.2. Research on Liquid CO2 Blasting Crack Propagation in Coal Rock with Natural Cracks

In the actual mining process, there are often natural cracks in coal rock mass, which undoubtedly has a non-negligible influence on the actual blasting effect. Through the simplified simulation of natural cracks, numerical simulation was carried out based on ANSYS/LS-DYNA, and the solution results were shown in Figure 5. Compared with explosive blasting, liquid CO2 blasting does not form an obvious crushing zone [16]. Because the numerical simulation is carried out by equivalent TNT equivalent method, the crushing zone around the blasting hole is not analyzed. It is assumed that the blockage is completely dense, and CO2 can only flow in the drill hole and the cracks connected with it, but the actual gas flow process in the cracks is extremely complicated, and to clarify the law of this process is a problem faced by any numerical simulation of rock blasting [18].

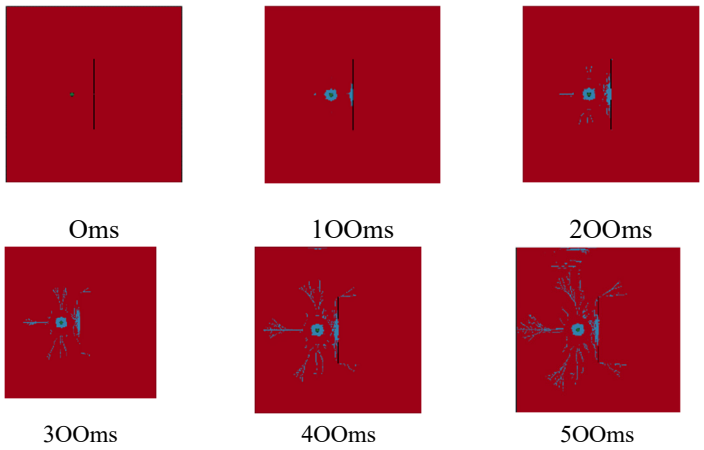


Fig 5. Crack development results of coal rock mass

As can be seen from Figure 5, after liquid CO2 blasting, the stress wave gradually diffused over time, resulting in cracks in the coal rock around the energy discharge end. After 100ms after blasting, cracks gradually occurred around the gun hole, and a small crushing area began to emerge in the contact area with the natural cracks in the coal rock mass. From 100ms to 200ms, the stress wave diffusion range increases, the crack develops along the stress wave diffusion direction, the area of the crushing zone in contact with the natural crack of coal and rock mass increases, and the crack development trend at the tip of the natural crack is perpendicular to the natural crack direction of coal and rock mass. From 200ms to 500ms, cracks start from the crack tip of the natural body of coal and rock, and continue to develop along the direction perpendicular to the natural crack of coal and rock. With the weakening of the peak stress, cracks in coal and rock will no longer develop and form the final failure mode of coal and rock when the stress peak is less than the dynamic tensile strength of coal and rock. Although a small part of stress wave transmission passes through the natural cracks in coal rock mass, it is not enough to produce cracks behind the natural cracks in coal rock mass.

Based on the parameters set by the numerical simulation, the final shape of the crack developed along the tip of the natural crack of coal and rock mass is 69.8cm, and a crushing zone of 49.6cm×10.6cm (length × width) is formed in front of the natural crack of coal and rock mass. With the passage of time, the damage range of coal and rock mass increases gradually. At 200ms, due to the phenomenon of stress concentration at the natural crack tip of coal rock mass, the initial guide crack, which plays a key role in controlling the development of subsequent cracks, is formed. At 300ms, the stress wave continues to act on the coal rock mass while propagating forward, and the initial crack along the propagation direction of the stress wave begins to develop. During the period of 300-500ms, the intensity of the stress wave continued to decay, and under the superposition of the explosive gas, the development of the crack reached the maximum of 69.8cm. After that, the intensity of the stress wave gradually weakened, and the seismic wave continued to propagate after forming, forming a shaking zone in the distant area of the blasting.

Liquid CO2 blasting is mainly caused by stress wave propagation and cooperative action of high-pressure explosive body to destroy coal and rock mass. Natural cracks in coal and rock mass block most of the stress wave energy

transfer through reflection, forming different local stress concentrations, thus changing the distribution of energy generated by liquid CO2 blasting and changing the development direction of cracks.

5. Conclusion

In order to study the effect of natural cracks in coal rock mass on the crack propagation rule after liquid CO2 blasting, the H-J-C model of coal rock mass with natural cracks was established based on ANSYS/LS-DYNA for the numerical simulation of liquid CO2 blasting. The following conclusions can be drawn from the simulation results.

(1) Liquid CO2 blasting results in stress waves propagating in coal and rock mass. Most of the stress wave energy reflects and forms a new crushing zone in front of the natural crack. A small part of the stress wave energy continues to propagate through the natural crack in the form of seismic waves, which is lower than the tensile strength of coal and rock mass and does not produce cracks.

(2) Stress concentration occurs at the natural crack tip of coal and rock mass after blasting, and the crack propagation direction changes to be perpendicular to the natural crack direction and continues to develop. A small part of the stress waves transmitted through the natural crack of coal and rock mass are influenced by the stress concentration phenomenon at the natural crack tip to guide the initial crack, and the crack continues to develop in the original direction.

(3) Natural cracks in coal and rock mass will affect the crack development law after liquid CO2 blasting and change the energy transfer. In practical engineering applications, using this characteristic is conducive to improving the utilization rate of liquid CO2 blasting energy.

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