Article

Research on Initiation of Carbon Dioxide Fracturing Pipe Using the Liquid Carbon Dioxide Phase-Transition Blasting Technology

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Abstract: Liquid carbon dioxide (L-CO₂) phase-transition blasting technology (LCPTB) has caused wide concern in many fields, but there is a lack of research on the initiation of the carbon dioxide fracturing pipe. Studies regarding the carbon dioxide fracturing pipe initiation are critical for controlling and optimizing the LCPTB. Therefore, in this article, a series of exploratory experiments of carbon dioxide blasting were carried out to investigate the qualitative and quantitative relationships between the carbon dioxide fracturing pipe initiation and the three key variables (the filling mass of liquid carbon dioxide (L-CO₂) (X_1), the amount of chemical heating material (X_2) and the thickness of the constant-stress shear plate (X_3)). The failure mechanisms of three variables on the phase-transition blasting process of a carbon dioxide fracturing pipe was analyzed qualitatively based on experiment temperature, strain curve and failure form of constant-stress shear plate. An empirical model between the carbon dioxide fracturing pipe initiation (Y) and the three key variables (X_1 , X_2 , X_3) was obtained after processing experiment result data quantitatively. Based on the phase-transition and blasting process of carbon dioxide, two methods, the Viral–Han–Long (VHL) equation of gas state (EOS) and the strength-failure method were used to calculate the blasting pressure and determine the failure mode of the fracturing pipe. The proposed blasting empirical model can be used to optimize the structural design of carbon dioxide fracturing pipes, guide on-site carbon dioxide blasting operations and further achieve the best blasting effect of LCPTB, so this work can enable LCPTB to be better applied to practical projects.

Keywords: liquid carbon dioxide; fracturing pipe; initiation; empirical model; failure mode

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1. Introduction

Liquid carbon dioxide (L-CO₂) phase-transition blasting technology (LCPTB) has caused wide concern in many fields, and utilizes the conversion characteristics between carbon dioxide gas and liquid phases for blasting fracturing [1]. The fracturing pipe is the core of the entire LCPTB system, which is used to realize the phase-transition blasting process of L-CO₂ (LCPTB). As shown in Figure 1, the carbon dioxide fracturing pipe is mainly composed of a charging head, activator (chemical heating material), liquid storage tube, constant-stress shear plate, gasket and energy releasing head. The activator is a composite device, which is used to store the chemical heating material. Under the stimulation of the instantaneous high pressure generated by a remote detonator, the chemical heating material is ignited to realize the heating of the fracturing pipe. After absorbing a large amount of thermal energy generated by the activator, L-CO₂ gasifies quickly and its volume instantly expands more than 600 times [2]. When the gas pressure reaches the ultimate strength of

the constant-stress shear plate, the constant-stress shear plate will be destroyed. After that, the high-energy carbon dioxide gas is released from the front end of the energy releasing head, and the blasting occurs and causes the rock mass crack, then the high-pressure gas migration makes fractures secondary development and expansion. The blasting products are gaseous CO₂ and water vapor, with no sparks or flames, and the releasing pressure and energy can be controlled and modified easily according to user requirements [3]. Therefore, the LCPTB has the significant advantages in controllable blasting pressure, uniform seam formation, being economical and pollution-free, and having intelligent control. Meanwhile, it overcomes the disadvantages of heavy harm, serious pollution, and high cost in the chemical blasting process. As such, the blasting technology has caused a wide concern in geotechnical engineering [4], municipal transportation [5], geological engineering [6], gaseous industry [7], geothermal engineering [8–11] and other fields [12,13].

Figure 1. The structure of carbon dioxide fracturing pipe.

LCPTB is also known as the cardox tube system, which was proposed by a British company in 1914, and it began to be used during the early 1950s [14–16]. In 1989, it was introduced into licensed coal mines in South Wales and recently was successfully used on a shaft sinking project in granite rock [17]. Patrick [18] and Caldwell, T [19] contrasted the advantages of CO₂ blasting relative to traditional chemical blasting. Then, in 1998, Singh simply described a rock breaking project with this blasting technology at quarrying in Turkey. At the end of the 20th century, LCPTB was introduced to the coal mining industry and has been greatly applied in the enhancement of coal seam permeability [2–4,7,20,21]. Nowadays, with the help of field experiment, laboratory simulation, comparative analysis, numerical simulation and other scientific research methods, the blasting fracturing process [22–25], blasting fracturing energy [26–30], blasting fracturing mechanism [22,26,31] and blasting phase-transition process of the LCPTB were discussed in detail [23,30–33]. The blasting process of the LCPTB can be accurately controlled by the carbon dioxide fracturing pipe, and many scholars have also focused on this research. Chen et al. [17] designed experimental equipment to monitor shock wave pressure during the LCPTB, which is convenient for in-depth study of the LCPTB mechanism. Based on in-depth research on gas blasting, Hu et al. [6] proposed a new CO₂ static pneumatic fracturing technology. Li et al. [34] proposed novel liquid carbon dioxide rock-breaking technology and designed the relative device. Finally, the technology was successfully applied in rock excavation at a metro station construction site.

In summary, most of the LCPTB research focuses on phase-transition mechanism [22,26,31], rock blasting [32,35], blasting antireflection [2–4,7,20,21] and blasting fracture propagation [11,20,36,37]. However, there is a lack of research on the initiation of the fracturing pipe and especially research on the relationship among controllable blasting parameters, blasting pressure and blasting effect in the LCPTB. The filling mass of L-CO₂, the amount of chemical heating material and the thickness of the constant-stress shear plate are three key variables which directly determine the fracturing pipe initiation. These three key variables have mainly relied on practical experience, which is not completely scientific

and reliable. Studies regarding the carbon dioxide fracturing pipe initiation are critical for controlling and optimizing the LCPTB. Furthermore, the fracturing pipe initiation directly affects the effect of blasting and fracturing. The successful blasting of the fracturing pipe is conducive to improving blasting efficiency, saving blasting costs, and achieving optimal blasting benefits. Therefore, it is necessary to study the relationship between the fracturing pipe initiation and the three key variables. Hence, in this article, according to the results of carbon dioxide blasting experiments, the quantitative and qualitative relationships among the three key variables (X_1 , X_2 , X_3) and the fracturing pipe initiation (Y) were explored. The calculation models of blasting pressure were used to determine the failure mode of the fracturing pipe. The proposed blasting empirical model can be used to optimize the structural design of carbon dioxide fracturing pipes, guide on-site carbon dioxide blasting operations, and further achieve the best blasting effect of LCPTB. This will enable the LCPTB to be better applied to practical projects, so this work has great practical guiding significance.

2. Experimental Methodology

2.1. Experimental Apparatus

A carbon dioxide blasting experiment system consists of a filling system, blasting system and detection system. The filling system is used to complete the transfer of L-CO₂ from the storage container to the fracturing pipe, and is equipped with a carbon dioxide storage tank, a filling machine and a fracturing pipe screwing machine. The blasting system is the key to successful experiment, and it is also the location of the three key variables in the experiment, including fracturing pipe and high-energy pulse detonator. The detection system plays the role of recording real-time temperature and strain changes during the experiment, and consists of a 8852K.J.T. thermocouple temperature meter and DH5956 strain dynamic measuring instrument. The fracturing pipe-95 was used in the experiment (Figure 1), with a length of 910 mm, an outer diameter of 95 mm, an inner diameter of 65 mm and a volume of 1.93 L. The diameter of the constant-stress shear plate used in the experiment was 42 mm, and the material was 45 steel. The physical diagram of the carbon dioxide blasting experiment system is shown in Figure 2.

Figure 2. Carbon dioxide blasting experiment system.

2.2. Experimental Setup

In this article, 17 groups of exploratory experiments on carbon dioxide blasting were carried out in a 10×10 m abandoned boiler room. The experimental object was the carbon dioxide fracturing pipe, which has no action object. The experiments were used to explore the empirical model between the three key variables and the fracturing pipe initiation. During the experiment, the thickness of constant-stress shear plate and the amount of chemical heating material are considered as specific variables. The constant-stress shear plate of 4.0 mm, 4.5 mm and 5.0 mm, and the amount of chemical heating material of 250 g and 300 g were designed, respectively. The filling mass of L-CO₂ is an undetermined variable, which needs to be adjusted according to the field experiment situation. At the same time, considering the experiment cost and sealing requirements, the experiment adopted the method of attaching the temperature measurement probe to the outside of the liquid storage tube, and used the stress-strain method to measure the pressure value indirectly. The strain gauge and temperature gauge were used to record the strain and temperature data of the entire experiment, and the remote intelligent control of the detonator was adopted in the blasting field to make this experiment safe and operable.

2.3. Experimental Process

The experimental filling-blasting process is shown in Figure 3. Firstly, the thickness of constant-stress shear plate and the amount of chemical heating material used in the experiments were selected, the internal volume V of Fracturing pipe was measured by water injection, and the mass (m) of the fracturing pipe before filling was measured. Secondly, the filling mass of L-CO₂ (M) in the experiment was measured, and the L-CO₂ storage tank and L-CO₂ charging machine were used to complete the filling of L-CO₂. Furthermore, after meeting the air tightness requirements of a fracturing pipe, the experimental site was arranged, and the strain gauge and the temperature probe were fixed as shown in Figure 1. Finally, the detonating wire was connected to high-energy pulse detonator, and the detonator was switched on to realize blasting.

Figure 3. The experimental filling-blasting process.

3. Results and Discussion

Among the 17 groups of carbon dioxide blasting experiments, 10 groups were successfully blasted, while 7 groups failed, and the specific values of the experiment variables are shown in Table 1. The constant-stress shear plate of the successful blasting fracturing pipe was broken into fragments and showed different degrees of distortion. However, the failed blasting fracturing pipe did not fracture, and showed a convex shape with different widths.

Table 1. The values of the experimental variables.

Experiment Number	Chemical Heating Material Dosage (g)	The Thickness of Constant-Stress Shear Plate (mm)	The Filling Mass L-CO ₂ (kg)	Initiation Situation
1	250	4.0	1.31	NO
2	250	4.0	1.40	NO
3	250	4.0	1.49	YES
4	250	4.5	1.30	NO
5	250	4.5	1.40	NO
6	250	4.5	1.51	YES
7	250	4.5	1.60	YES
8	250	5.0	1.20	NO
9	250	5.0	1.50	NO
10	250	5.0	1.59	YES
11	300	4.0	1.31	YES
12	300	4.0	1.39	YES
13	300	4.0	1.60	YES
14	300	4.5	1.22	NO
15	300	4.5	1.31	YES
16	300	4.5	1.40	YES
17	300	5.0	1.50	YES

3.1. Variables that Affect the Phase-Transition of Liquid Carbon Dioxide (L-CO₂)

CO₂ is a strong sublimation substance, which generally exists in a gaseous state in nature. Studies have shown that it can exist as liquid form when the pressure exceeds 5.1 times the atmospheric pressure [3]. When the temperature is higher than 31.4 °C and the pressure exceeds 7.385 MPa, the interface between liquid phase and gas phase of carbon dioxide disappears and carbon dioxide transforms into the supercritical state [21], which has the dual properties of a high density liquid and high diffusion gas.

In the carbon dioxide blasting experiments, chemical heating material supplied thermal energy to the system and raised the temperature of the system, then L-CO₂ was vaporized. The filling mass carbon dioxide determines the expansion pressure of L-CO₂ phase-transition, and the two key variables jointly control the entire CO₂ phase-transition process and directly affect the blasting effect of the fracturing pipe. Exploring the effects of the above two variables on the phase-transition of CO₂ is helpful to reasonably determine the combination parameters, improve the efficiency of blasting operations, optimize the structure design of the fracturing pipe, and achieve the best blasting effect.

(1) The amount of chemical heating material

The thickness of the constant-stress shear plate and the filling mass of L-CO₂ remain unchanged, only the amount of chemical heating material was changed from 250 g to 300 g. The fracturing pipe is likely to be detonated from failure to success. Experiment 1 and 11, 9 and 17 were used to analyze in this paper, and the experimental parameters are shown in Table 1. The constant-stress shear plate of experiment 1 is not damaged, the gas pressure makes it protrude outwards, and the maximum convex width is 10.4 mm. The constant-stress shear plate of experiment 11 is broken into fragments, and the fragments show varying degrees of distortion (Figure 4).

Temperature can be used to reveal the mechanism and effect of the activator. Figure 5 shows the real-time temperature curves of experiments 1, 11, 9 and 17, in which 250/4.0/1.30 means the amount of chemical heating material is 250 g, the thickness of constant-stress shear plate is 4.0 mm, and the filling mass of L-CO₂ is 1.30 kg.

Figure 4. Displays after experiments of constant-stress shear plate (the maximum width of convex area of each constant-stress shear plate is shown in the figures).

(a)

(b)

Figure 5. Real-time temperature curve of texts. (a). Real-time temperature curve of experiments 1 and 11; (b). real-time temperature curve of experiments 9 and 17.

The temperature of experiment 1 increases by 4.36 times from 21.6 °C to 94.1 °C, and then gradually decreases to room temperature. The temperature of experiment 11 increases by 1.10 times from 19.4 °C to 21.4 °C, then gradually parallels to room temperature, and room temperature stabilizes at 27.4 °C. The temperature of experiment 9 increases by 4.07 times from 32.6 °C to 132.8 °C, and then gradually decreases to room temperature. The temperature of experiment 17 increases by 1.08 times from 28.4 °C to 30.8 °C, then gradually decreases to room temperature, and room temperature stabilizes at 27.9 °C. There is an obvious difference between successful blasting and failure blasting. When the blasting is successful, most of the thermal energy is taken away by the gas rushed out from the energy releasing head, so that the temperature of the outer wall is too late to rise. By contrast, when the blasting fails, high-pressure gas accumulates in the tube, and the gas

slowly leaks out from the convex deformed part of the constant-stress shear plate, and the outer wall is fully heated, so that the temperature of the outer wall rises sharply.

The temperature curves of experiment 1 and experiment 9 fluctuate greatly, with local oscillation, and increase rapidly before the curve highest point. The local oscillation of the temperature curves is mainly due to the local uneven heating of the outer wall and the softening of thermometry probe rubber induced by high temperature. The temperature curves of experiment 11 and experiment 17 increase slightly and the growth rate of the latter is slower than the former, the increase does not exceed 11%. It is further illustrated that the 300 g of the amount of chemical heating material can fully gasify L-CO₂, and a large amount of thermal energy is taken away through the gas rushing out, while the thermal energy absorbed by the outer wall is less.

In conclusion, the increase of the amount of chemical heating material will increase the amount of heat released, which aggravates the phase-transition reaction process of carbon dioxide and increases the blasting pressure, and finally, the blasting effect of the fracturing pipe is improved.

(2) Carbon dioxide mass

The thickness of constant-stress shear plate and the amount of chemical heating material remain unchanged, and only the filling mass of L-CO₂ was changed. The experiment was divided into two groups, and the first group included experiments 4, 5, 6 and 7. The results show that the experiments were not blasted when the filling mass was 1.30 kg and 1.40 kg, while others blasted successfully. The second group included experiment 8, 9 and 10. The results show the experiments were not blasted when the filling mass was 1.20 kg and 1.50 kg, and the other one blasted successfully.

The experiment parameters are shown in Table 1, and only the first group of experiments are researched and analyzed in this paper. The constant-stress shear plates of experiment 4 (250/4.5/1.30) and experiment 5 (250/4.5/1.40) are not broken, and the maximum outward convex width is 10.4 mm and 10.9 mm, respectively. In experiment 6 (250/4.5/1.50), the constant-stress shear plate was divided into multiple sections, and the fragments show bending deformation. In experiment 7 (250/4.5/1.60), the constant-stress shear plate was directly sheared off (Figure 4). The damage degree of constant-stress shear plate in experiments 4–6 increases in turn, which indicates that the volume of carbon dioxide, the gas formed by L-CO₂ phase-transition, increases in turn. The blasting pressure increases in turn, so that the experimental phenomena are more obvious.

Figure 6 shows the real-time temperature curves of the outer wall in experiment 5, 6 and 7, and the temperature curves of experiment 6 and 7 are basically parallel to the room temperature line and lower than the room temperature line. The temperature of experiment 6 increases from 21 °C to 21.7 °C. Experiment 7 increases from 24.5 °C to 27.6 °C and experiment 5 increases rapidly from 20.9 °C to 129.4 °C, with a rising rate of 5.4 °C /s, then decreases gradually. The temperature curve shows that the increase of the filling mass of carbon dioxide will improve the intensity of the carbon dioxide phase-transition reaction in the tube, and a large amount of L-CO₂ gasifies and expands. When the expansion pressure in the tube reaches the yield strength of the constant-stress shear plate, the blasting is successful.

Figure 7 shows the strain variation trend of the fracturing pipe outer wall with time in experiments 8, 9 and 10. The paper is a simple analysis of the strain-time diagram of the successful blasting experiment 10 (250/5.0/1.60). Before the activator is electrified, the strain value swings back and forth in a very small range due to the electromagnetic interference of surrounding environment. After the activator is electrified, the curve of strain versus time can be divided into three stages in general. The first (I) stage is ABC (strain rising stage), the curve initially rises rapidly from point A to point B, then experiences a slight decrease and, finally, rises rapidly again until the curve reaches the highest at point C. The stage takes a short time and the curve rises quickly. A large amount of heat is released instantly when the activator is activated, which causes a slight thermal strain of the strain gauge. The first high point B appears, then L-CO₂ absorbs heat and

expands externally. After that, the high-pressure gas continues to act on the outer wall, and the deformation of the strain gauge increases exponentially, until reaching the highest point C.

Figure 6. Temperature–time curve of experiments 5, 6 and 7.

Figure 7. Strain–time curve of experiments 8, 9 and 10.

The second (II) stage is CDE (“V”-shaped change stage); the curve drops quickly from the highest point C to the point D, then rises slowly to the point E again, and the point E is lower than the highest point C, which manifests a “V” shape. The rapid release of high-pressure gas makes the pressure in the tube drop sharply, and the deformation of the strain gauge recovers to a certain extent. However, because of the restriction of the symmetrical outlet hole of the energy releasing head and the closed design of the front-end, the release speed of high-pressure gas is reduced. The low-speed gas that is not fully released from the front end, the blockage of partially reflected gas and the squeezing effect of subsequent high-pressure gas make the internal pressure rise temporarily. Then the deformation of the strain gauge increases, thus forming a “V”-shaped trend.

The third (III) stage is EF (strain recovery stage), the curve decreases slowly, and gradually tends to be stable with a low decline and a long time. After the blasting is completed, the high-pressure gas fully overflows, and the pressure in the tube gradually returns to normal atmospheric. Then the deformation of the strain gauge is also gradually

recovered, but the plastic deformation cannot be recovered, so the curve declines and gradually tends to a stable value.

In conclusion, the increase in the amount of chemical heating material will increase the amount of heat released, which aggravates the phase-transition reaction process of carbon dioxide and increases the blasting pressure, and finally the blasting effect of the fracturing pipe is improved.

3.2. Variables that Affect the Damage of the Fracturing Pipe-Constant-Stress Shear Plate

The constant-stress shear plate is equivalent to the control valve of the blasting energy releasing channel, and controls whether the whole system is successfully blasted. When the pressure in the tube is greater than the yield strength of the constant-stress shear plate, the constant-stress shear plate is destroyed, then the high-pressure gas rushes out quickly, and the blasting is successful. Otherwise, the blasting fails. The thickness of the constant-stress shear plate is directly related to its yield strength, and indirectly determines the blasting pressure released by the whole blasting system. The research on the influence of the thickness of the constant-stress shear plate on the blasting performance of the fracturing pipe has greatly guiding significance, which can optimize the structural design of carbon dioxide fracturing pipes, guide on-site carbon dioxide blasting operations and further achieve the best blasting effect of LCPTB.

The paper analyzes the experimental phenomena and data of experiment 3.6.9, experiment 9 (250/5.0/1.50) fails to blast, the constant-stress shear plate remains intact as a whole, and the maximum convex width of the central part is 11.3 mm (Figure 4). The constant-stress shear plates of experiment 6 (250/4.5/1.50) and experiment 3 (250/4.0/1.50) have different degrees of bending and torsion deformation, and the degree of deformation and fracture in experiment 6 is greater than that in experiment 3. The main reasons are as follows: firstly, L-CO₂ gasifies and expands the instant when activator is excited, which makes the internal pressure of the fracturing pipe rise sharply, and the blasting occurs when the yield strength of the constant-stress shear plate is less than the internal pressure of the fracturing pipe. Secondly, at the moment of blasting, the constant-stress shear plate is simultaneously sheared and stretched. Coupled with the special structure of the front energy releasing head, the fragments are initially pushed by internal pressure to hit the front end of the energy releasing head, then pushed out of the tube by carbon dioxide airflow. So this reciprocating process aggravates the distortion of the fragments. Finally, when the amount of chemical heating material and the filling mass of L-CO₂ are fixed, the maximum gas released pressure that can be generated inside the tube is determined. Therefore, the lower the failure pressure required for the constant-stress shear plate and the shorter the blasting time, the lower the degree of distortion of the fragments.

As shown in Figure 8, the temperature of experiments 3 and 6 increase slowly, and the temperature difference of experiment 6 ($\Delta T_1 \Delta T_1$) is 52.6% larger than that of experiment 3 ($\Delta T_2 \Delta T_2$). The temperature of experiment 3 (250/4.0/1.50) increases from 22.9 °C to 24.8 °C, which takes 19 s and the growth rate is 0.10 °C/s. The temperature of experiment 6 (250/4.5/1.50) increases from 24.5 °C to 27.4 °C, which takes 17 s and the growth rate is 0.17 °C/s. The temperature of experiment 9 (250/5.0/1.50) increases obviously, and the maximum value is much higher than that in experiments 3 and 6. The temperature of experiment 9 increases from 32.6 °C to 132.8 °C, which takes 35 s and the growth rate is 2.86 °C/s. The main reasons are as follows: with the increase of the thickness of the constant-stress shear plate, the constant-stress shear plate needs greater gas pressure to cause damage. The carbon dioxide gas inside the tube continues to absorb heat and heat up, and the continuous process of CO₂ phase-transition becomes longer, then the temperature transferred to the outer wall becomes higher.

Figure 8. Real-time temperature curve of experiments 3, 6 and 9.

To sum up, the yield strength of the constant-stress shear plate can be approximately regarded as the actual outlet pressure of the fracturing pipe, and the increase of the thickness of the constant-stress shear plate can significantly improve the blasting pressure of the fracturing pipe. The greater the thickness of the constant-stress shear plate, the greater the gas pressure required. However, when the internal gas pressure tends to the maximum, the thickness of the constant-stress shear plate will also limit the progress of the blasting.

3.3. The Quantitative Relationship between the Variables and Blasting

The filling mass of L-CO₂ and the amount of chemical heating material jointly control the internal phase-transition reaction process of the fracturing pipe, and both directly affect the maximum gas pressure that can be released. The thickness of the constant-stress shear plate controls the blasting and energy release process of the fracturing pipe, which directly affects the blasting effect of the fracturing pipe. The process of L-CO₂ from phase-transition to blasting is controlled by the three key variables. In order to explain the internal relationship between the successful blasting of the fracturing pipe and the three key variables, whether the fracturing pipe is blasted or not is regarded as the logical dependent variable Y ("1" stands for successful blasting and "0" stands for blasting failure), and the amount of chemical heating material, the thickness of constant-stress shear plate and the filling mass of L-CO₂ are defined as independent variables X_1 , X_2 , X_3 , respectively. Then, Fisher discriminant analysis was used to quantify the experimental results, and the mathematical representation equation between Y and X was obtained.

$$Y = \omega_1 X_1 + \omega_2 X_2 + \omega_3 X_3 + \omega_4 \quad (1)$$

$$Y = 0.043X_1 - 0.384X_2 + 9.923X_3 - 23.839 \quad (2)$$

Among them, the coefficients in front of the independent variables X_1 , X_2 , X_3 respectively represent their weights ω_1 , ω_2 , ω_3 for the dependent variable Y , and ω_4 represent the weight of unconsidered factors for dependent variable Y .

According to the analysis of the equation, it can be seen that the filling mass of L-CO₂ (kg) and the amount of chemical heating material (g) have a positive effect on whether the fracturing pipe is blasted. And the influence degree of the filling mass of carbon dioxide

is about 231 times higher than the amount of chemical heating material. Yet the thickness (mm) of constant-stress shear plate has a negative effect. In the actual blasting operations, the filling mass of L-CO₂ is also the most easily controlled variable, so the filling mass of L-CO₂ can be properly increased to ensure the success of blasting. This result is consistent with the analysis of the previous experimental results and the conclusion of the pressure, volume and temperature (PVT) equation of high-pressure gas. The equation can be further explained that the area above the plane ($Y > 0$) indicates successful blasting, while the area below the plane ($Y < 0$) represents failed blasting. This result can quantitatively explain the mathematical relationship between the successful blasting and the three key variables, predict whether carbon dioxide blasting operations can be successfully carried out under the relevant blasting parameters, guide the actual on-site blasting work, and improve the efficiency of carbon dioxide blasting.

4. Failure Mode of the Fracturing Pipe

In a prior study of this paper, how the filling mass of L-CO₂, the amount of chemical heating material and the thickness of constant-stress shear plate affect the phase-transition blasting process of the carbon dioxide fracturing pipe have been analyzed qualitatively and quantitatively. It can be found that these three key variables also determine the blasting pressure of the whole carbon dioxide fracturing pipe. From the perspective of the phase-transition of L-CO₂, most of the CO₂ in the tube exists in a gaseous and supercritical state. The comparative state Viral–Han–Long (VHL) equation can be used to quantitatively describe the relationships among pressure, temperature and volume of carbon dioxide in the tube. Then, the theoretical value of internal pressure (P) can be derived as the blasting pressure. From the perspective of the damage of the constant-stress shear plate during the blasting of the fracturing pipe, the constant-stress shear plate is subjected to tension and shear simultaneously, and then the blasting pressure P acting on the constant-stress shear plate is determined by the breaking strength when the constant-stress shear plate is broken. At the same time, only when the pressure of the high-pressure gas released by the phase-transition of L-CO₂ is greater than the ultimate yield strength of the constant-stress shear plate, the fracturing pipe is successfully blasted.

(1) Strength-failure method

As shown in Figure 9, there are two failure modes of the constant-stress shear plate. (1) Tensile failure with non-surging internal pressure, (2) Punching-shear failure with surging internal pressure. In this paper, the material of the constant-stress shear plate is 45 steel, which belongs to the flat plate with a diameter of 42 mm, and the diameter of area of thrust surface on which carbon dioxide gas acts is 32 mm.

Some simplifications and assumptions for these two failure modes:

(i) Tensile failure with non-surging internal pressure. Before the force is applied, the thickness of the constant-stress shear plate is d_0 , and after being deformed into a spherical structure, the thickness is d , the height of the spherical crown is h , the radius of the sphere is R , and the actual diameter of the internal pressure acting surface is D . The blasting pressure equation is expressed as follows [38,39]:

$$P_b = \frac{8d_0\sigma_b}{D} \sqrt{(\sqrt{1+\delta}-1)/(1+\delta)} \quad (3)$$

(ii) Punching-shear failure with surging internal pressure. Due to the surge in internal pressure, the increase of this pressure is greater than the yield strength of the constant-stress shear plate within milliseconds, then the central part of the constant-stress shear plate is damaged before being deformed, and the whole compressed part of the constant-stress shear plate is sheared off. The blasting pressure equation is expressed as follows [40]:

$$P_b = 4d_0\sigma_t/D \quad (4)$$

where σ_b is the tensile strength of the constant-stress shear plate, MPa; δ is the elongation rate in the direction of tensile stress; σ_t is the shear strength of the constant-stress shear plate, MPa; P_b is the blasting pressure, MPa.

Figure 9. Schematic diagram of two different failure mode of constant-stress shear plates.

(2) Viral–Han–Long Equation of Gas State (VHL-EOS)

At present, the gas state equation under high temperature and high-pressure has the forms of Becker–Kistiakowski–Wilson (BKW), Jones–Wilkins–Lee (JWL) [41], Jacobs–Cowperthwaite–Zwisler (JCZ) [42], etc. The VHL equation based on the L–J potential energy function [43], which has been thoroughly studied the thermodynamic state transition of the gas components in explosive products under high temperature and high-pressure [44,45]. It can effectively describe the thermodynamic relationship of PVT of gas in detonation environment [46–48], so the theoretical value P of the internal pressure can be derived by taking the internal temperature of tube and the filling mass of L- CO_2 as variables in the gas state VHL equation.

The specific form of the VHL equation of state is expressed as follows [49,50]:

$$\frac{PV}{nRT} = 1 + \omega B + \omega^2 C + \omega^3 D + \omega^4 E + (a + bT_1)\omega^f \quad (5)$$

$$B = \sum_{j=0}^{\infty} \frac{-2j+\frac{1}{2}}{4j!} \Gamma\left(\frac{2j-1}{4}\right) T_1^{-\frac{2j-1}{4}} \quad (6)$$

$$C = c_1 T_1^{c_2} + c_3 T_1^{c_4} + c_5 T_1^{c_6} + c_7 T_1^{c_8} + c_9 T_1^{c_{10}} \quad (7)$$

$$D = d_1 T_1^{d_2} + d_3 T_1^{d_4} + d_5 T_1^{d_6} + d_7 T_1^{d_8} + d_9 T_1^{d_{10}} \quad (8)$$

$$E = e_1 T_1^{e_2} + e_3 T_1^{e_4} \quad (9)$$

$$T_1 = \frac{T}{\delta} \quad (10)$$

$$\omega = \frac{b_0^2 n}{b_{\text{CH}_4} V} \quad (11)$$

where P , V , T are the actual pressure (GPa), volume (ml), and temperature (K) of the gas. n is the number of molar of carbon dioxide gas filled in a fixed volume, mol. R is the molar gas constant 8.3145×10^{-5} . The second-order dimensionless virial coefficient B is approximately calculated by the variable step sinbsen quadrature method [49–51]. C , D are the third-order and fourth-order dimensionless virial coefficients respectively, and c_1 – c_{10} , d_1 – d_{10} are constants. For the dimensionless virial coefficients above the fifth order, they are represented by a combination function, the values of coefficients e_1 – e_4 , a , b and f are the thermodynamic data of non-polar molecules CH_4 . b_{CH_4} b_{CH_4} is 67.21. $\omega \cdot \delta \omega \delta$ is the LJ potential parameter, the VHL equation of state realizes the comparison of the equation of state of other gases and methane through the parameter $\omega \cdot \delta \omega \delta$.

The successful blasting experiment 10 (250/5.0/1.60) was taken as an example. By using the above two methods to calculate the blasting pressure and determining the failure mode of the fracturing pipe, the calculation results are shown in Table 2. The shear strength σ_t , tensile strength σ_b and elongation rate δ of 45 steel were 355 MPa, 600 MPa, and 16%, respectively. It was concluded that the gas blasting pressure of experiment 10 was 202.56 MPa, which was compared with the blasting pressure of the two failure modes of the constant-stress shear plate calculated by the strength-failure method. The blasting pressure was between the tensile failure stress and the punching-shear failure stress. The constant-stress shear plate was stretched and sheared under the pressure P of the high-pressure gas released by the phase-transition of L-CO_2 . The constant-stress shear plate will only fail when the pressure P is greater than its ultimate yield strength. Hence, the fracturing pipe of experiment 10 was successfully blasted, and the constant-stress shear plate suffered tensile failure. Finally, the data of experiment 10 were put into the initiation empirical model. The result was $Y = 0.77$, which was above the plane $Y = 0$, and indicated that the blasting was successful, which was consistent with the experimental result. Therefore, the new set of blasting empirical model and experience can be considered to guide on-site blasting operations.

Table 2. Blasting pressure of experiment 10.

Experiment 10			Blasting Pressure (MPa)
Viral–Han–Long Equation of Gas State (VHL-EOS)	The filling mass of L-CO_2 $m(\text{kg})$	1.60	202.56
	Number moles of carbon dioxide gas $n(\text{mol})$	36.36	
	Internal temperature $T_f(\text{K})$	410	
Punching-shear failure	Shear strength $\sigma_t(\text{MPa})$	355	221.9
	the thickness of constant-stress shear plate (mm)	5.0	
Tensile failure	Tensile strength $\sigma_b(\text{MPa})$	600	193.3
	Elongation rate δ	16%	

Therefore, comparing the blasting pressure calculated by the Viral–Han–Long equation of gas state (VHL-EOS) and the strength-failure method, and when the gas blasting pressure is between the tensile failure stress and the punching-shear failure stress, the constant-stress shear plate will suffer tensile failure. When the gas blasting pressure is greater than the punching-shear failure stress, the constant-stress shear plate will suffer tensile punching-shear failure. Otherwise, the fracturing pipe fails to blast, and the constant-stress shear plate will not be broken.

5. Conclusions

In this paper, a series of exploratory experiments of carbon dioxide blasting were carried out. Based on experiment temperature, strain curve and failure form of constant-stress shear plate, the main conclusions are as follows:

- (1) The filling mass of L-CO_2 and the amount of chemical heating material jointly control the phase-transition reaction process of carbon dioxide. The thickness of constant-stress shear plate controls the carbon dioxide blasting, so the three variables determine the initiation of the fracturing pipe together.

- (2) An empirical model between the carbon dioxide fracturing pipe initiation (Y) and three key variables (the filling mass of liquid carbon dioxide ($L\text{-CO}_2$) (X_1), the amount of chemical heating material (X_2) and the thickness of constant-stress shear plate (X_3)) is obtained, which can be used to explain, predict and guide on-site carbon dioxide blasting operations.
- (3) Two methods for the blasting pressure of the fracturing pipe are summarized. (a) The comparative state VHL equation is used to quantitatively describe the relationships among pressure, temperature and volume of carbon dioxide in the tube, and then the theoretical value P of the internal pressure is derived as the blasting pressure; (b) the blast stress P acting on the constant-stress shear plate is determined by the yield strength of constant-stress shear plate.
- (4) The failure model of the fracturing pipe can be determined by comparing the blasting pressure calculated by the VHL-EOS with the blasting pressure calculated by the strength-failure method.

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