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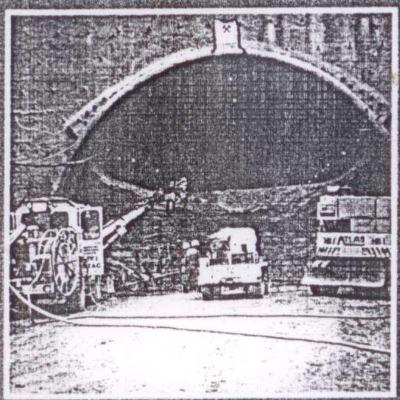

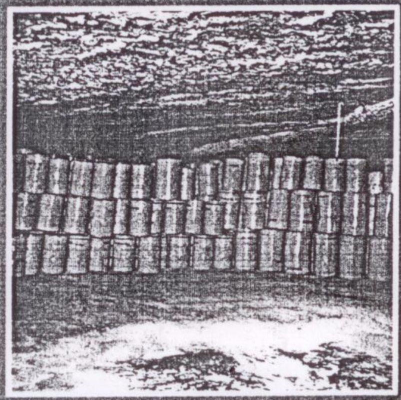

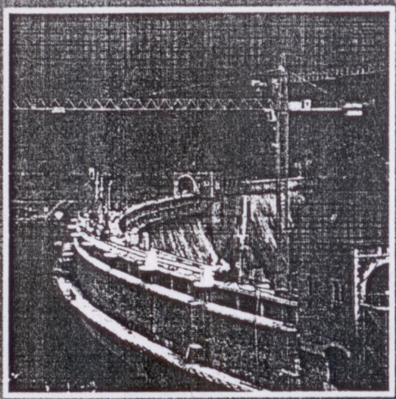

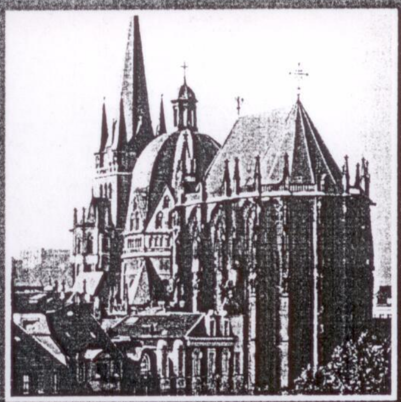

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The Mechanism of Rock Breakage by Liquid Corbondioxide

Die Mechanik Eines Felseinbruches Durch Flüssiges Kohlendioxyd

{ 27-31 Mart 2000 Aachen da "Kaya mekaniği sempozyumu" }

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ABSTRACT: In this paper, the mechanism of breakage by liquid carbondioxide (CARDOX) which is stored in special tube is explained. The tube filled with liquid CO_2 is inserted into a hole drilled in the rock. Afterwards, the liquid CO_2 is expanded by a chemical energiser and during this expansion the liquid CO_2 changes into gas state. During this process the volume of CO_2 increases 600 times and the pressure in the tube reaches to 250 MPa. This pressure results in rupturing of the mild – steel disc and CO_2 installed in the tube is discharged into the surrounding rock via discharge head. The discharge process takes place within a millisecond period in the form of a shock pressure. In terms of breakage mechanism it resembles to explosive fracturing. But, the resulting explosion in this system is free from vibration. During the discharge of CO_2 a considerable cooling effect occurs. In this work, the sum of energy transferred to the rock, its transfer period and amount of cooling are calculated. Furthermore, the resulting energy is compared with the energy created by a methane safe dynamite.

ZUSAMMENFASSUNG: In diesem Bericht wird die Mechanik eines Einbruches durch flüssiges Kohlendioxyd (CARDOX), das in einer spezialen Tube gespeichert ist, erläutert. Die mit flüssigem CO_2 gefüllte Tube wird in ein Loch, das in einem Fels gebohrt wurde, gelegt. Danach dehnt sich das flüssige CO_2 aufgrund eines chemischen Heizers aus. Durch diese Ausdehnungen gerät das flüssige CO_2 in einen Gaszustand. Während dieses Verfahrens steigert sich das Volumen des CO_2 auf das 600 Fache und der Druck in der Tube erreicht 250 MPa. Dieser Druck führt zum zerreissen des sich am Ende der Tube befindenden Stahlplatte und das CO_2, das sich in der Tube befindet, wird an den umliegenden Fels entladen. Dieser Entladungsvorgang findet innerhalb einer Periode von einer Millisekunde in Form eines schlagartigen Drucks statt. Von dem Mechanismus her ähnelt es sich dem Sprengstoffeinbruch, aber die resultierende Explosion in diesem System ist frei von Erschütterungen. Während der Entladung von CO_2 entsteht ein beachtlicher Kühlungseffekt. In dieser Studie wird die Summe der an den Fels übertragenen Energie, seine Übertragungsperiode und die Menge der Kühlung berechnet. Ausserdem wurde die resultierende Energie mit der Energie die durch einen gegen Grubengas gesicherten Sprengstoff erzeugt würde, verglichen.

1. Introduction

Rock breakage by the liquid CO_2 has been a well-known system for a long time. When the liquid CO_2 is heated to a certain degree it changes to gas state and its volume increases considerably. The resulting energy during this reaction is used in rock excavation and in many other different applications. Since the occurrence of the energy is quite similar to the detonation of explosives, the system is known as CARDOX.

The usage of the system is fairly simple. A high grade alloy-steel tube filled with liquid CO_2 is inserted into a hole drilled in the rock to be fractured. A chemical energizer is located within the tube for the expansion of liquid CO_2. The chemical energizer is ignited by a 12-V hand-driven exploder. After the initiation, the chemical energizer provides a temperature of 1170 ^oC and the liquid CO_2 filling the tube changes to gas state. During this reaction, the volume increases 600 times and the pressure inside the tube reaches to 250 MPa. Due to this pressure, the rupture disc made from mild-steel and located at the discharge head of the tube is cut off (Fig.1). Consequently, high pressure shock waves are transferred into the surrounding rock from the discharge end. These high pressure shock waves propagate in two directions. High pressure shock waves penetrate into the deepest part of the rock mass along the discontinuity planes and fracture the rock mass (1,2).

In this paper; firstly, the application areas of the CARDOX system and its benefits will be given and, then, the breakage mechanism starting from the rupturing of the disc will be discussed.

2. Application Areas of the CARDOX System

Since the CARDOX system is not classified as an explosive, there are no permits for its transport, storage or usage. The tube types used in the CARDOX system are selected according to the application conditions, rock type and its properties.

The CARDOX system is used in both underground and surface mining. As the system is not classified as an explosive, the discharged CO_2 produces a cooling effect in the underground environment and, therefore, it can be used safely in underground coal mines with methane problem. Since the system does not produce toxic gases, it is possible to continue to work immediately after the firing. During the firing of the system, there is no dust, scattering or significant vibration set up by the reaction. The above mentioned features are the advantages of the system over the conventional blasting by explosives. Since the fracturing mechanism is achieved by shock waves which breaks down the material along the least line of resistance, coal can be produced in big lumps. The shock waves attenuate when they encounter a discontinuity. This phenomenon also helps to separate the coal from intercalations. Moreover, the roof and its support elements of the opening are not effected from the shot (1).

The system can be used in bench blasting operations in surface mines, where vibration may create problems due to the close proximity to the housing estates.

The CARDOX tubes are used for the production of large blocks in dimensional stone quariying. About 2 m^3 of granite block can be produced with a single tube. The system is also used in limestone, calcite, etc. quarries. It is also widely used in tunnelling and shaft sinking operations. In addition, it is preferred for the drivage of tunnels in dam construction projects since the system does not cause any vibration or overbreak in the surrounding rock.

Its one of the most widely used areas is the concrete demolition works. It is successfully applied to the demolition of buildings, bridges and concrete machine bases where the damage risk for the surrounding is the top priority. Its safety, economy and efficiency are well appreciated advantages over the other methods. Another reason for its preference in the excavation works is the attenuation of sock waves across at the discontinuity (bedding, jointing etc.) planes with no effect of the surrounding.

The CARDOX system is also regarded as a good alternative for the explosives for the underwater excavations. In such works, since it does not produce vibration and noise, the divers and water creatures are not likely to be subjected to any danger or harm.

Its other application areas are the dislodgement of silos, blockages in the rotary furnaces, hang-ups in the cement and gypsum kilns. The CARDOX tubes are located within the blocked or hang-up zone . The silos, kilns or furnaces are not effected from the shot and the grains are not subjected to any toxic effect.

3. Breakage Mechanism

The rock breakage mechanism of the system will be dealt with after the explanation of rupturing the disc located in the discharge head of the tube. Upon the change of liquid CO_2 into gas state in the tube, followed by the cut off the disc, the pressure is transferred from two sides of the discharge head. These reactions take place within milliseconds. Hence there is not a heat exchange between the tube and surroundings. In other words, the process is adiabatic. The change of state for the CO_2 inside the tube can be assumed free of friction and the expansion process of the gas till shock plane can be accepted as isentropic.

In order to explain the breakage mechanism there are as of process starting from inside the tube up the discharge, will be mentioned. These areas are: area-A (where liquid CO_2 is installed), area-B (located just behind the rupture disc) and area-C-C' (where sock waves leave the discharge head) (Fig.2).

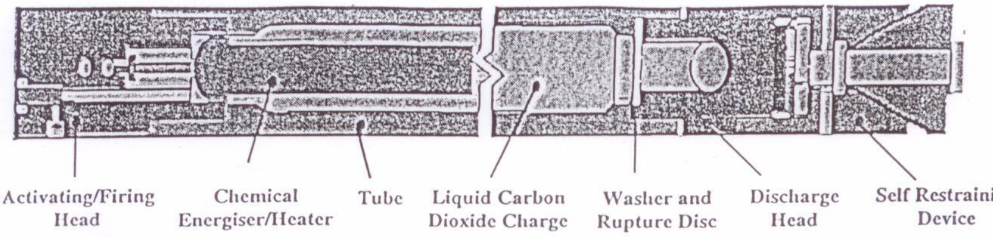

Fig.1 CARDOX tube (F57)

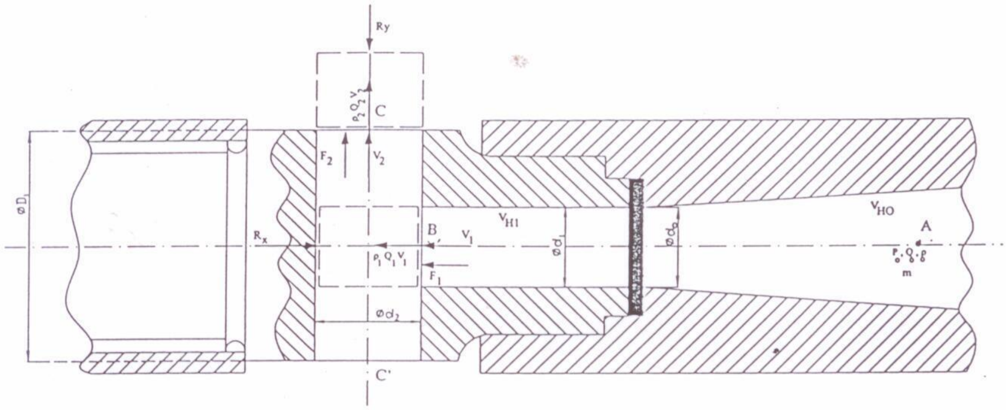

Figure 2. Breakage mechanism of CARDOX system

In the system, two control volumes are defined; from area-A to B and from area-B to passing to surrounding rock. For the control volumes shown with dashed lines in Fig.2 " rate of movement theory" is applied and the mechanism is explained in this way (3,4,5).

The mechanism of the system is solved for the F57 tube used in coal excavation. Some of the data this tube associated with the above mentioned areas shown in Fig.2 are given below:

For area-A:

amount of liquid CO_2 in the tube, m=0.82 kg
pressure created after detonation, P_o= 236 MPa
diameter of the disc being ruptured, d_o= 23.6 mm
the volume of the area, $V_{Ho}=7.25\times10^{-4}$ m^3
the thickness of the disc, S= 4.4 mm

For area-B:

the diameter of the area, d_1= 23.5 mm
the length of the area, L_1= 42.5 mm
the volume of the area, V_{H1}= 1.8434×10^{-5} m^3

F_1 denotes the face effect the control volume of area-B. The amount of movement entering the control volume can be expressed as $\rho_1 \cdot Q_1 \cdot \vartheta_1$.

For area-C:

the diameter of discharge head, d_2= 25 mm

F_2 denotes the force effect of control for area-C. The amount of movement entering the control volume can also be expressed as $\rho_2 \cdot Q_2 \cdot \vartheta_2$.

During discharge, the reaction forces effective in the vertical and horizontal directions; R_y (vertical) and R_x (horizontal) occur. R_x reaction force pushes the tube outwards from the hole. In order to prevent this movement a self restraining device installed at the end of the discharge head..

The density of the fluid in area-A can be calculated with the following equation.

$$\rho_o = \frac{m}{V_{Ho}} \qquad [1]$$

By inserting the required values in this equation, the resulting density is $\rho_o \cong 1131$ kg/m^3.

Prior to the rupturing of the disc, the absolute temperature, T_o , in this area can be determined by the following equation:

$$T_o = \frac{P_o}{\rho_o \cdot R} \qquad [2]$$

If the gas constant of CO_2 is taken as $R = 188$ J/kg.°K, then the .temperature can be found as $T_o \cong 1110$ °K.

If one assumes that the transition (transformation) from area-A to area-B is "Quasi-Equilibrium State", the following equation can be written.

$$P_o \cdot V_{Ho} = P_1 \cdot (V_{Ho} + V_{H1})^k \qquad [3]$$

By introducing the values into the above equation the pressure in area-B can be calculated as $P_2 = 228.5$ MPa. The absolute temperature can be expressed as:

$$\frac{T_1}{T_o} = \left(\frac{P_1}{P_o}\right)^{\frac{k-1}{k}} \qquad [4]$$

For CO_2, $k = 1.289$ °K; then the absolute temperature can be calculated as $T = 1102$ °K.

The density of the fluid passing to area-B can be expressed as:

$$\rho_1 = \frac{P_1}{R \cdot T_1} \qquad [5]$$

By introducing the values into this equation the density can be calculated as $\rho_1 = 1103$ kg/m^3.
The energy equation between two areas can be expressed as:

$$c_p \cdot T_o + \frac{\vartheta_o^{\,2}}{2} = c_p \cdot T_1 + \frac{\vartheta_1^{\,2}}{2} \qquad [6]$$

Here,
c_p = Specific heat at constant pressure
ϑ_o and ϑ_1 = the rate of flow

Since $\vartheta_o = 0$ in area-A, ϑ_1 the rate of flow in area-B can be derived from equation [6] as:

$$\vartheta_1 = \sqrt{2 \cdot c_p \cdot (T_o - T)_1} \qquad [7]$$

If one takes c_p=841.8 J/kg.°K for the CO_2 the velocity can be calculated as ϑ_1 = 116 m/s.

The continuity equation for the transformation from areas-B to C an C' can be written as:

$$A_1 \cdot \rho_1 \cdot \vartheta_1 = 2 \cdot A_2 \rho_2 \cdot \vartheta_2 \qquad [8]$$

The follow splits into two lines after area-B. The energy equation for the transformation state can be written as:

$$c_p \cdot T_1 + \frac{\vartheta_1^2}{2} = c_p \cdot T_2 + \frac{\vartheta_2^2}{2} \qquad [9]$$

By employing equations [8] and [9], the absolute temperature in this area can be found as $T_2 \cong 461.3$ °K .

The pressure released from area-C to the surrounding rock can be calculated by following equation:

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}} \qquad [10]$$

By introducing the values to the pressure can be calculated as. P_2 = 4.7 MPa. This indicates that there is not a considerable impact effect.

The density of the fluid in this area can be calculated with the following equation:

$$\rho_2 = \frac{P_2}{R \cdot T_2} \qquad [11]$$

The resulting density is found as $\rho_2 = 54.2$ kg/m^3. The velocity of the fluid can be expressed with the following equation:

$$2 \cdot c_p \cdot (T_1 - T_2) = \vartheta_2^2 - \vartheta_1^2 \qquad [12]$$

The calculated velocity (ϑ_2) is 1045 m/s. This velocity can be defined as supersonic.

The detonation energy created by the fluid released from both sides of the discharge can be calculated by the following equation:

$$E_c = \frac{1}{2} \cdot m \cdot \vartheta_2^2 \qquad [13]$$

This energy can be found as 448 kJ. The specific energy of the methane-safe dynamite used in underground coal mines is $E_D = 880$ kJ/kg (6). The produced energy from a blasthole containing a charge of 0.25 kg of dynamite can be found as:

$$E_{DI} = 880 \times 0.25 = 220 \text{ kJ.}$$

When it is considered that one tube per hole is installed in the CARDOX system, the energy comparison with dynamite reveals an energy ratio of $E_C / E_{DI} = 2.04$.

If one assumes that the energy derived from the CARDOX system is fully utilized in the breaking process, it is possible to claim, by using one tube, twice energy can be produced per hole. Since the work is done by one hole instead of two, the resulting breakage is in the form of big lumps.

The released CO_2 mass from one side of the discharge lead can be expressed as:

$$m_2 = A_2 \cdot \rho_2 \cdot \vartheta_2 \qquad [14]$$

By putting the values in the above equation the mass of CO_2 becomes $m_2 = 27.8$ kg/s. The discharge time can be expressed as:

$$t_2 = \frac{m/2}{m_2} \qquad [15]$$

From the above equation, the discharge time can be found as $t_2 = 15$ ms.

The temperature of the CO_2 released with a pressure of 4.7 MPa can be calculated from the equation below:

$$\frac{T_2}{T_e} = \left(\frac{P_2}{P_e}\right)^{\frac{k-1}{k}} \qquad [16]$$

By assuming the environmental pressure $P_e = 0.1$ MPa, the temperature can be found as $T_e = 194.5$ °K. This temperature is equal to −78.5 °C. So, this explains a considerable cooling effect experience during the detonation. This feature is one of the main application reasons of the system to the gassy underground coal mines.

The propagation velocity of shock waves in area-C can be calculated from the following equation:

$$c_2 = \sqrt{k \cdot R \cdot T_2} \qquad [17]$$

The resulting velocity is, $c_2 = 334.35$ m/s. The Mach Number valid for the both areas (area-C and C') can be determined from the following equation:

$$M_2 = \frac{\vartheta_2}{c_2} \qquad [18]$$

The resulting Mach number is $M_2 = 3.12$. Since the Mach number is greater then one, the resulting propagation velocity should be supersonic. This indicates the certain of shock waves upon the release of CO_2 from the discharge head. Following the shock waves, a sudden increase takes place in both pressure and temperature, and the velocity drops to subsonic level.

Let's assume that ϑ_2, P_2, T_2 and ρ_2 are the values of CO_2 gas prior to the detonation, and ϑ_3, P_3, T_3 and ρ_3 after the detonation; the Mach Number of this transformation, M_3, can be expressed as:

$$M_3^2 = \frac{1 + \frac{k-1}{2} \cdot M_2^2}{k \cdot M_2^2 - \frac{k-1}{2}} \qquad [19]$$

The corresponding Mach Number can be calculated as $M_3 = 0{,}44$. The indicates the reason for the propagation velocity being under the sound level. The corresponding pressure, P_3, after the detonation can be calculated from the equation below:

$$\frac{P_3}{P_2} = \frac{1 + k \cdot M_2^2}{1 + k \cdot M_3^2} \qquad [20]$$

The pressure is found as $P_3 = 50.9\,\text{MPa}$. The temperature after the detonation can be expressed as:

$$\frac{T_3}{T_2} = \frac{1+\frac{1}{2}\cdot(k-1)\cdot M_2^2}{1+\frac{1}{2}\cdot(k-1)\cdot M_3^2} \quad [21]$$

The resulting temperature is, $T_3 = 1079.8\ ^{\circ}\text{K}$. The velocity at this moment can be found from the following equation:

$$\frac{\vartheta_3}{\vartheta_2} = \frac{\frac{2}{M_2^2}+(k-1)}{k+1} \quad [22]$$

The velocity calculated from this equation is $\vartheta_3 = 225$ m/s. All the calculation results in this context are presented in Fig.3 the temperature-entropy (T-s) diagram.

The calculations can be repeated by changing the thickness of the rupture disc used in the discharge head and the design of discharge head. In these calculations, the discharge diameter, d_2, can be increased and two-sided discharge can be decreased to one side of the tube. One-sided discharge system can be employed in tunneling, in the periphery holes.

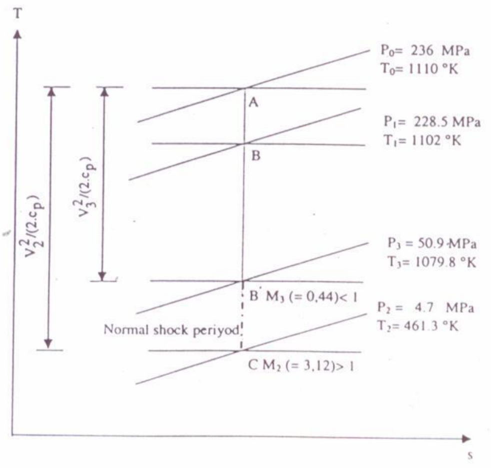

Figure 3. Temperature (T)-Entropy (s) diagram based on the calculated data results

4. Conclusions

The studies carried out on the breakage mechanism of the CARDOX system have shown that the main fracturing is achieved by the shock waves. For this reason, there is not any vibration effect after the shot and the impact effect is minimum. A total of 448 kJ energy is produced bay a single shot from both sides of the F57-type tube.

One-half of the above energy is obtained from one side of the tube. This amount of energy (i.e. 220 kJ) is equal to the energy produced by 0,25 kg of methane-safe dynamite. In other words, the total energy obtained from a shot of one hole containing only one tube corresponds to the dynamite ,energy obtained from two blastholes. This feature is also one of the main reasons for the production of lumpy coal. The cooling effect occurring after the detonation of the system is another significant reason for its application to the underground coal mining.

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