THE CRITICAL CONDITIONS OF INITIATING AIR-METHANE MIXTURE EXPLOSION WITH AN OPEN CHARGE

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Abstract

The investigation findings presented enable to determine the critical conditions of air-methane mixture (AMM) explosion initiation with an open charge in the test gallery. The findings enable to define the level of blasting safety in coal mines liable to gas explosions.

Abstrakt

Prezentované poznatky umožňují určit kritické podmínky pro spuštění exploze směsi metanu se vzduchem nálože v testovací důlní chodbě. Tyto poznatky umožňují definovat úroveň bezpečnosti těžby trhavinami v uhelných dolech, náchylé k explozím plynu. age.

Key words: air-methane mixture, permissible explosive, detonation, limit charge, shock wave, ignition, blasting safety

INTRODUCTION

Methane explosions become hazardous in face areas of underground working at gassy and dusty coal mines in terms of dust explosions. Such environment dictates to use only permissible explosives for blasting operations. Explosives of the permissible class differ from the others in that they do not ignite the highly flammable air-methane (AMM) and air-dust (ADM) mixtures when a charge is fired in such mixtures and therefore secure the safety of blasting operations under the hazardous conditions of gassy coal mines. It is a challenging task to further improve safety and efficiency of permissible explosives in gassy mines, which is essential both in terms of research and practice.

Review of recent studies and publications shows that better safety of permissible explosives used in coal mines can be attributed to better safety qualities of the explosives in relation to flammable air-methane and air-dust mixtures.

The level of explosive safety qualities can be quantified and expressed as the maximum weight of charge limit unable to ignite AMM when tested in the test gallery in a flammable environment.

It has been established earlier [1, 2] that the value of a charge limit considerably depends on the explosive detonation velocity and the explosion energy. Investigations [3, 4] have been started to study critical parameters of explosives permissibility (i.e. the safety of an explosive in relation to flammable air-methane mixture) with regard to the transition conditions of the detonation wave going through the charge and into the flammable air-methane mixture.

The object of the article is to discuss critical conditions of initiating air-methane mixture explosion with an open charge in the test gallery. Such investigations are of primary importance for the development of new high-safety explosives for coal mines.

ANALYTICAL INVESTIGATIONS

It has been established in [4] that for permissible explosive charges fired openly (free hanging in the blasting chamber of the test gallery or in the angle mortar) there is a coefficient defining the level of the explosive safety qualities. This coefficient has been called the explosive permissibility index (I) and is defined as follows:

$$I = \frac{(n+1)^2 \cdot \rho_v^2}{n \cdot P_н} = \frac{(n+1)^2 \cdot \rho_v}{n \cdot D^2}, \quad (1)$$

where n – polytrophic curve of explosive detonation process;

ρ_v – explosive density, kg/m^3;

$P_н$ – pressure in the detonation wave-front, Pa;

D – detonation wave velocity , m/s.

In the equation (1), the expression $\frac{D^2 \cdot n}{(n+1)^2} = Q_D$ defines the energy released in the detonation wave-front. The equation (1) analysis shows that the more explosive detonation energy, the lower its permissibility index is (I) resulting in a lower level of the safety qualities (low limit charge) in a flammable air-methane mixture.

Let's examine the explosion of an open charge in a flammable air-methane mixture. The transition of the explosive detonation wave into the air-methane mixture around the charge is followed by the transition into the same mixture of E_v energy, which value is dependent on the charge weight m_v and detonation energy Q_D. Velocity E of the explosion energy transition into an air-methane mixture is as follows:

$$\frac{dE_v}{d\tau} = \frac{m_v \cdot Q_D}{\tau_D}, \tag{2}$$

where τ_D - charge detonation time.

The value of τ_D depends on the velocity of detonation wave in the charge and the charge size, i.e. the length - ℓ_z:

$$\tau_D = \frac{\ell_z}{D}. \tag{3}$$

To transform the equations (2) and (3), the weight of explosive in a cylindrical charge is to be expressed through its volume and the explosive density in the shell ρ_v:

$$\frac{dE}{d\tau} = \frac{\pi}{4} d_z^2 \cdot \rho_v \cdot D^3, \tag{4}$$

where d_z – explosive charge diameter.

The equation (4) analysis shows that the product $\pi d^2 = S$ defines the surface area of an AMM-contacting charge, while $\frac{\rho_v \cdot D^2}{4} = P_н$ defines the pressure in the detonation wave-front when $n=3$. The force F_D, with which detonation products affect AMM, is obtained through the product $S \cdot P_н = F_D$ of the area and detonation wave pressure. The product of the force and detonation wave velocity $F_D \cdot D$ allows obtaining the power output of the detonation wave during transition into the surrounding AMM. Then the velocity of explosion energy transition into AMM is defined by the detonation wave power:

$$\frac{dE}{d\tau} = N_D, \tag{5}$$

where N_D - detonation wave power, J/s.

Similarly, let's consider the development of an AMM explosion resulted from methane oxidation initiated by atmospheric oxygen. Methane oxidation stimulates the liberation of the energy E_{AMM} which is calculated as the product ($m_{AMM} \cdot q_{AMM}$) of the AMM volume involved in the oxidation and liberated the specific energy q_{AMM}.

Similarly to the equation (2), the velocity of methane oxidation development in AMM can be defined as follows:

$$\frac{dE_{AMM}}{d\tau} = m_{AMM} \cdot q_{AMM} \cdot K_p \quad , \tag{6}$$

where K_p - velocity constant of methane oxidation by atmospheric oxygen, s $^{-1}$.

Comparing equations (2), (3) and (6) we can determine critical conditions needed for initiating methane oxidation in AMM after a charge firing, and express them as follows:

$$\begin{cases} \tau_D \cdot K_p \geq 1 \\ \dfrac{E_v}{E_{AMM}} \geq 1, or N_v \geq N_k \end{cases} \quad , \tag{7}$$

where N_k - critical value of initiation power.

The product of the detonation time τ_D and the methane oxidation velocity constant K_p must be equal to or greater than one. Such condition indicates that the duration of the source initiating the oxidation reaction in AMM (which is characterized by detonation time) is greater than or equal to the time necessary for oxidation, which defines the reaction velocity and constants. Over this time, some energy is liberated following the methane oxidation in AMM to be further used to support the explosion initiation (heat initiation) or to maintain ignition-forced burning of the mixture. The amount of energy transported into AMM during the explosion must be always more than the inherent energy of oxidation release into AMM over this period of time. Otherwise, the process of AMM explosion initiation attenuates as the oxidation does not have enough time to develop into a stationary process as a result of heat loss for gas expansion.

Theoretical conclusions indicate that any AMM explosion will not take place if the values of the initiation process are not sufficient or do not meet the requirements (7). It proves and explains the existence of a critical charge value (initiation power) and detonation parameters which prohibit an AMM explosion initiation. In practice this value is called a limit charge which defines explosive permissibility. At the same time it is interesting to find out the extent of stability of the critical conditions enabling the development of an AMM explosion initiation with an open charge firing in the mixture. The critical value N_k has not been defined yet.

RESULTS OF TEST GALLERY EXPERIMENTS

Ignition qualities of an explosive charge in regard to AMM were investigated in the MakNII test gallery. The investigation database includes the findings obtained during firing free hanging charges in shells of sand (quartz sand) (Paramonov P.A.), water and air (Shevtsov N.R. and Stikachev V.I.) as well as open charges in the angle mortar with a baffle wall (Weinstein B.I., Kukib B.N.). The charges were fired in the air-methane mixture with the methane concentration within 8,5…9,5%. The mixture was initiated with firing the charges of permissible and non-permissible explosives hanged up in the centre of the explosion chamber in the test gallery or placed at the angle mortar edge. The test findings have been integrated by means of the Curve Expert 1.3 software.

For water-shelled charges fired in air-methane mixtures the following relationship has been obtained:

$$\delta = 5{,}3079 \cdot \ell n N_D - 125{,}6527 \text{, mm,} \tag{8}$$

where δ - thickness of protective water shell making AMM explosion impossible, mm;

N_D – power of detonation wave affecting the shell, J/s.

The correlation coefficient /r/ = 0,979, root-mean-square deviation S= 1,081.

For sand-shelled charges fired in the air-methane mixtures the following relationship has been obtained:

$$\delta = 0{,}104242(N_D - 1{,}4173357 \cdot 10^{10})^{0{,}23823} \text{, mm.} \tag{9}$$

The correlation coefficient /r/ = 0,993, root-mean-square deviation S= 2,414.

For air-shelled charges contacting the flammable air-methane mixtures the following empirical relationship has been obtained:

$$\delta = 430{,}418 \ell n N_D - 8400{,}1448 \text{, mm.} \tag{10}$$

The correlation coefficient /*r*/ = 0,912, root-mean-square deviation *S*= 143, 6.

When firing waxed-paper open charges that contact AMM all around, the following empirical equation defining the limit charge value M_p unable to ignite the flammable mixtures with the detonation wave power, has been obtained:

$$M_p = exp\left[48{,}228763 - \frac{2{,}031655 \cdot 10^9}{N_D} - 2{,}1172\ell n N_D\right], \text{ kg.} \quad (11)$$

The correlation coefficient /*r*/ = 0, 9236, root-mean-square deviation *S* = 0,1796.

For charges fired 0.6m to the edge of the baffle-walled angle mortar placed in the explosion chamber of the test gallery the following empirical equation has been obtained:

$$M_p = \frac{5{,}4964 \cdot 10^9}{N_D} - 0{,}2471, \text{ kg.} \quad (12)$$

The correlation coefficient /*r*/ = 0,893, root-mean-square deviation *S* = 0,1697.

ANALYSIS OF THE INVESTIGATION RESULTS

Relationships (8) - (12) enable to make a general analysis of the critical conditions for initiating AMM explosion with an open charge. At the beginning we shall consider the critical power of the detonation wave appearing in pure AMM under a large scale spherical detonation of the mixture (over 10m^3). For the spherical volume of a detonating air-methane mixture the power of the detonation wave according to the equation (4) is as follows:

$$N_{D_{CH_1}} = 12{,}56 \cdot r_{AMM}^2 \cdot \rho_{AMM} \cdot D^3, \text{ J/s .} \quad (13)$$

In the equation (13) we assume that radius $r_{AMM} = r_k$ of the AMM sphere equals to the critical radius of the spherical detonation r_k, and the critical velocity of the AMM detonation *D equals* to the critical velocity of the detonation wave inducing the spherical detonation of the mixture. According to Adushkin V.V., Kogarko S.M. [5], r_k = 0,65m while D_k = 1255 - 1450m/s according to Mindeli E.S. et al [6], and Murray V.L. [7]. Substituting the average of these values in the equation (13) we obtain the following:

$$N_k^{CH_1} = 12{,}56 \cdot 0{,}65^2 \cdot 1{,}17 \cdot 1353{,}0^3 = 1{,}537785 \cdot 10^{10}, \text{ J/s.}$$

According to the critical conditions in the equation (7), the detonation is initiated during explosive firing in AMM if $N_D \geq N_k^{CH_1}$. Let's check this critical condition. To this purpose we assume the value of the protective shell $\delta = 0$ in the equations (8), (9), (10). After solving the equations we obtain the power output of the detonation wave at the initial moment of its affecting the protective shell: for air shell $N_D^a = 2{,}990876 \cdot 10^8$ J/s, for sand shell $N_D^s = 1{,}4173357 \cdot 10^{10}$ J/s and for water shell $N_D^{H_2O} = 1{,}90965 \cdot 10^{10}$ J/s. Comparing the findings with critical values for AMM we can conclude that the critical conditions are absolutely impossible to be met for an air shell ($\frac{N_a}{N_k} = 0{,}0194$). This fact indicates that an air shell drastically facilitates and intensifies the AMM initiating with an explosive charge. It can be attributed to secondary chemical reactions in the air when it is mixed with explosion products. In case of a shell of dry quartz sand the critical conditions are practically satisfied for the charges fired in such shells $\frac{N_s}{N_k} \approx 0{,}93$, and are surely satisfied in case of water shells $\frac{N_w}{N_k} = 1{,}24$.

Considering the results obtained it is possible to state that the true value N_k for AMM must be close enough to the calculated value $N_k^{CH_1} = 1{,}537785 \cdot 10^{10}$ J/s. This can be also proved by a simple analysis of physical and chemical properties of the shell material used for charges. Quartz sand in a sand shell is a loose porous material. Supposedly, the air inside the shell might have had a negative effect on the charge permissibility. Anyway one should remember about quartz piezoelectric qualities that can appear upon exposure of the shell to impact loads. Therefore, the value N_k is rather conservative compared to theoretical calculations. Water contained in the shell has quite opposite effect on explosion products. In this case, a water shell is an efficient heat filter which separates and cools down the detonation products on the one hand and practically brings about no changes to the shock wave generating in the ambient. Therefore, the true value N_k is closer to the value for a water shell than for a sand shell, and in the first approximation it can be assumed to be equal to the calculated value, i.e. $N_k=1{,}537785 \cdot 10^{10}$ J/s. Now it is worthwhile to analyze to what extent the critical conditions are satisfied in case of the AMM explosion initiation with open charges without a protective shell fired immediately in the test gallery. For this case we shall express the charge radius through the explosive limit weight and transform the equations (4) and (13) into the following:

$$m_v = \frac{6{,}0216 \cdot N_D^{1{,}5015}}{\rho_v^{0{,}5015} \cdot D^{4{,}5045}}, \text{ kg} . \tag{14}$$

For critical conditions of the AMM explosion initiation with an open charge it is necessary that $N_D \geq N_k$, then substituting N_k into the equation (14) we obtain:

$$M_p = m_v = \frac{1{,}18942114 \cdot 10^{16}}{\rho_v^{0{,}5015} \cdot D^{4{,}5045}}, \text{ kg}. \tag{15}$$

The equation (15) helps to determine the limit charge weights for permissible explosives (PE) used in coal mines in Ukraine, Russia and in the Czech Republic. The weight values for PE calculated charges have been compared with the limit charges calculated according to the equations (11) and (12) and to the actual values of the safe charge weights obtained in the course of the test gallery investigations. The calculation data have been summarized in the table below.

Table Permissible explosive limit charges: Comparison of critical weight values in relation to flammable AMM

Permissible explosive	Where used	Explosive parameters		Critical weight according to equation (15), kg	Limit charges in AMM calculated according to equations (11) and (12), kg		Tested in test gallery, safe harge, kg
		density, kg/m^3	detonation velocity, m/s		open	angle mortar	
Ammonite Г-5	Ukraine	1050	4100	0,0194	0,008	-	0,020 - -open charge
Ammonite ПЖВ-20	Russia	1050	4000	0,022	0,010	-	0,020 - -open charge
Uglenit Э-6	Russia	1220	2224	0,285	0,265	0,155	0,25 - -open charge
Uglenit 13П	Ukraine	1200	2320	0,235	0,213	0,113	0,1 – -angle mortar
Uglenit M	Russia	1220	2200	0,296	0,282	0,169	0,25 - -open charge
Uglenit № 5	Russia	1250	1750	0,82	0,99	0,560	0,5 - -angle mortar
Uglenit 10П	Ukraine	1220	1948	0,512	0,571	0,352	0,4 - -angle mortar
Uglenit 12ЦБ	Russia	1300	1925	0,524	0,541	0,335	0,6 - -angle mortar
Ionite	Russia, Ukraine	1170	1676	1,03	1,408	0,734	1,0 - -angle mortar
Ostravit C (Ø 30 мм)	Czech Rep.	1210	1960	0,50	1,1	0,61	0,6 - -angle mortar

The Table shows a satisfactory coincidence of charge critical weights regarding the conditions of AMMoxidation initiation during open charge firing in the course of the experiment in the test gallery. The Russian results have been submitted by VostNII (Russian research institute engaged in safety in mines). The knowledge of critical conditions essential for AMM explosion initiation enables to simplify the investigation and development of new permissible explosives for coal mines.

CONCLUSIONS

Critical conditions have been defined for initiating AMM explosion with an explosive charge fired in thus enabling to determine the results of the testing permissible explosives for safety (permissibility) in the test gallery. Positive results have been obtained by comparing the AMM-safe charges in the test gallery with the critical weight of the permissible explosive obtained through the calculations. This facilitates the development of new permissible explosives for coal mines making it much easier and more efficient and avoiding labor-consuming and sophisticated experiments in the test gallery.

ZÁVĚR

Byly definovány kritické podmínky pro spuštění exploze směsi metanu se vzduchem trhací nálože, a tím určit výsledky testování přípustných trhavin z hlediska bezpečnosti v testovací větrní chodbě. Byly získány pozitivní výsledky porovnáním bezpečných nálože pro směsi metanu se vzduchem s kritickou váhou přípustné trhaviny, získanou výpočty. Tím je umožněn vývoj nových přípustných trhavin k snadnějšímu a účinnějšímu použití v uhelných dolech bez nutnosti pracných a náročných experimentů v testovací větrní chodbě.

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