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Features of passing a shock wave in a long communication passageway with walls of different rigidity

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Abstract. The problem of attenuation of a shock wave during its propagation in long communication channels of industrial buildings or mining workings is considered. It is shown that an explosion in a channel produces a head shock wave with a plane wavefront, where the dynamic pressure significantly exceeds the pressure at fronts forming by the incident and reflected shock waves. A physical model of the formation and propagation of a shock wave in a channel with walls of different rigidity is proposed. It is shown that if one of the channel walls is movable or easily deformed, this leads to a violation of geometry of plane wavefront of the head shock wave and its weakening. The necessity of arranging pressure-relief structure in communication channels of buildings with increased explosive hazard and mine workings is grounded.

1. Introduction and literature review

Emergency explosions in industrial buildings related to highly explosion hazard facilities always are resonant events [1, 2]. Despite the improvement of safety methods in the implementation of technological processes, explosions due to the leakage of explosive liquids and gases lead to human casualties, damage equipment, destroy labor results, and cause significant losses [3, 4, 5]. Also resonant events are emergency explosions in mine workings of mines and tunnels.

A feature of explosions in mine workings is that shock waves (SW) propagate in narrow channels (drifts, adits, crosscuts) and, without the use of special anti-explosive measures, retain destructive force for a long distance [4, 5, 6].

To weaken the action of a shock wave in mines, dissipation methods are used, which provide at least partial absorption of the shock wave energy. There are many ways to extinguish an explosive shock wave during blasting in a mine [7–10]. All these methods are used precisely during blasting operations, which exclude presence of people and expensive equipment in the danger zone.

However, safety equipment for blasting operations cannot be used for other types of work, as they will interfere with the production process, hindering communications on drifts, tunnels, crosscuts (in general they can be represented as communication passageways or channels). Since emergency explosions cannot be excluded, when operating the communication channels of the mine, it is necessary, on the one hand, to ensure the free movement of people and equipment, and on the other, to reduce the negative consequences of an accidental explosion. The relevance of this problem is obvious [11].

The problem of weakening the blast wave is also relevant in the protection of industrial buildings. When inspecting construction sites damaged by accidental explosions and the fires caused by them, it is often necessary to explain the causes of visible damage to building structures [12–14]. In industrial buildings with increased explosion and fire hazards, as a rule, the main focus of the design is on manufacturing facilities. They are equipped by explosion-relief structures, which most often are as window and door openings. In the event of an emergency explosion, the shock wave destroys the explosion-relief structures, and overpressure in the room decreases rapidly. Structures in such rooms also count on the possible impact of an explosion. And in the communication passageways, which can be corridors or tunnels, reaching considerable length in industrial buildings, and where, after overcoming of the explosion-relief structure, shock wave propagates, it acts on the building envelope. At the same time, the state of building envelope is unpredictable: some walls on the path are destroyed, while others, similar, remain practically intact.

Based on these observations, it makes sense to consider the problem of attenuation of shock waves during their propagation in long communication passageways of industrial buildings and mining channels, assuming their fundamental similarity.

The communication passageway can be represented as a semi-closed space (channel), in which, according to [15, 16], the energy of the shock wave dissipates more slowly than in a large room or in open space. At the same time, energy losses for air heating and friction are increased when shock wave interact with the channel walls. The walls of the channel as a surface of reflection also influence the process of formation and propagation of shock wave, determining its intensity. For these reasons, the study of the interaction of the walls and partitions of the channel with the shock wave is of interest for predicting the behavior of both the shock wave itself and building structures in an explosion. In publications [17–19] problems of accounting for the behavior of shock wave in channels were considered, but it was assumed that the walls were equally rigid. However, in real construction projects, walls and partitions of communication channels often differ both structurally and in materials.

2. Construction of the model and its analysis

The objective of this work is to formulate recommendations for improving safety, both for building structures of communication passageways of buildings with increased explosion hazard, and for communication channels of mine workings based on the formation of a physical model of the formation and propagation of shock wave in channel with walls of different stiffness, i.e. when one of the walls can noticeably deform in comparison with the other.

A specific feature of the propagation of a shock wave in a semi-closed space is its interaction with the surface of the obstacle (wall) on which reflected shock waves are formed [18, 19]. For a shock wave formed during an explosion with overpressure at its front of less than 700 kPa, when air can still be considered an ideal gas, the reduced overpressure of reflected wave P^*_R is calculated from [20]:

$$P_R^* = 2P_I^* + \frac{(\gamma+1)P_I^*}{2\gamma + (\gamma-1)P_I^*}, \tag{1}$$

where P^*_I is the reduced overpressure of the incident wave; γ is the ratio of gas specific heats.

$$P_R^* = \frac{P_R}{P_0}; \qquad P_I^* = \frac{P_I}{P_0}, \tag{2}$$

where P_R is the overpressure of reflected wave; P_I is the overpressure of incident wave; P_0 is the initial pressure.

The load on the wall surface depends on the parameters of shock wave, the orientation of the shock front relative to the surface, and the surface rigidity. When the shock wave falls at an angle to the surface ($0 < \alpha_I < \pi/2$), the pressure in the contact zone will be greater than the pressure at the front of the incident shock wave ($P > P_I$), since when air is braked behind the shock front, its kinetic energy is converted into potential compression energy. The surface will experience additional load (P_u) caused by the action of impact air pressure, which depends on the air flow rate (u) and its density (ρ_B):

$$P_u = \frac{\rho_B u^2}{2g}, \tag{3}$$

where g is the acceleration of gravity.

Such reflection of shock waves is non-stationary. It depends on the shock wave intensity, the properties and the nature of the distribution of the parameters of the gaseous medium behind its front, the geometry of the wave and the surface with which the interaction occurs [19–21]. The ratio of the incident (I_I) and reflected (I_R) wave pulses is estimated from considerations of similarity:

$$\frac{I_R}{I_I} \approx \frac{P_R}{P_I}. \tag{4}$$

At small angles of incidence of the shock wave (α_I), the so-called regular reflection occurs, and the angle of the reflected shock wave is greater than the incident one $\alpha_R > \alpha_I$. In [15], for the case of regular reflection, a formula is proposed that allows calculating the overpressure at the front of the reflected shock wave:

$$P_R = 2P_I + \frac{(\gamma+1)}{2}\rho_B u^2 cos^2 \alpha_I. \tag{5}$$

With an increase in the angle of incidence of the shock wave to a critical value ($\alpha_{Ikr} = \alpha_I$), a moment comes when regular reflection becomes impossible and only irregular (or Mach) reflection is possible [22, 23]. It is characterized by the fact that as a result of the interaction of the incident and reflected shock wave when $\alpha_{Ikr} > \alpha_I$ a third (Mach) wave is formed. The junction area of all three waves is called the triple point.

During the transition from regular to irregular reflection at near-critical angles of the shock wave incidence ($\alpha_{Ikr} = \alpha_I$), the trajectory of the triple point will be parallel to the rigid wall. If the angle of the shock wave incidence with an irregular reflection exceeds a critical value, then the triple point will move along the trajectory at an angle to the surface of the rigid wall. As a result, a continuously growing “Mach stem” is formed, which is a plane wave with a front normal to the surface.

Mach reflection is a rather complicated phenomenon. And if the pressure (and, correspondingly, the pulse) at the front of the reflected shock wave can be calculated for the zone of regular reflection of shock wave (see (5)), for irregular reflection this is difficult to do by simple methods, and only empirical methods remain. According to empirical estimates, the angle of movement of the triple point is 4...5 times smaller than the Mach transition angle α_{Ikr}. The Mach transition angle for the incident wave depends on the adiabatic index of detonation products and the Mach number of the shock wave (this angle lies within $\alpha_M = 39^o...47^o$) [20, 22, 23].

As mentioned above, internal emergency explosions of gas-air mixtures with subsequent propagation of shock wave in the channels are likely to occur in hazardous operations industrial facilities and in mine workings. The most important parameters of such explosions are geometric factors (the shape and cross-section of the channel, the presence of pressure-relief structures), the heat of gas combustion and the ratio of mixture components.

During the propagation of detonation products of explosion and/or shock wave in the channel, the limiting surfaces (walls), which are reflection surfaces, influence this process. The energy stored by the shock wave is dissipated much slower than in the atmosphere, but it is spent on air heating and friction when the shock wave interacts with the walls. The shock wave intensity in this case is determined not only by the explosion energy transmitted to the air, but also by the reflection processes.

The effect of the shock wave on the channel walls can be divided into two stages. On the first – the wall is loaded when the shock wave initially falls on it, and on the second – it is affected by several subsequent pressure pulses. This interaction can be very complex due to multiple reflections of shock waves and/or the presence of discharge openings.

A simplified model of how a shock wave is formed and propagated in a channel with rigid walls is shown in figure 1. This model can be represented in the following sequence:

1. The formation of curved surface of the front of shock wave.
2. Because the incident shock wave propagates in the channel in an unperturbed air medium, and the reflected shock waves propagate in the medium that has been compressed and heated by the transmitted incident shock wave, then the reflected shock waves propagate at higher speeds than the

incident shock wave and they can therefore catch up with the incident shock wave and merge with it [21].

3. The formation of a head shock wave (or bow shock wave) with a plane wavefront as a result of the confluence of the incident shock wave and the reflected shock waves. In the resulting head shock wave, the dynamic pressure significantly exceeds the pressures at the incident shock wave and reflected shock waves fronts.

The formation of a plane wavefront of the head shock wave is realized with oblique incidence of waves. If the angle of incidence is large enough, then Mach waves can form near the channel walls. Considering the angle of movement of the triple point trajectory, it can be expected that a continuous front of a plane head shock wave will form in a zone with a length of up to 8 characteristic dimensions of the channel cross section [22, 24].

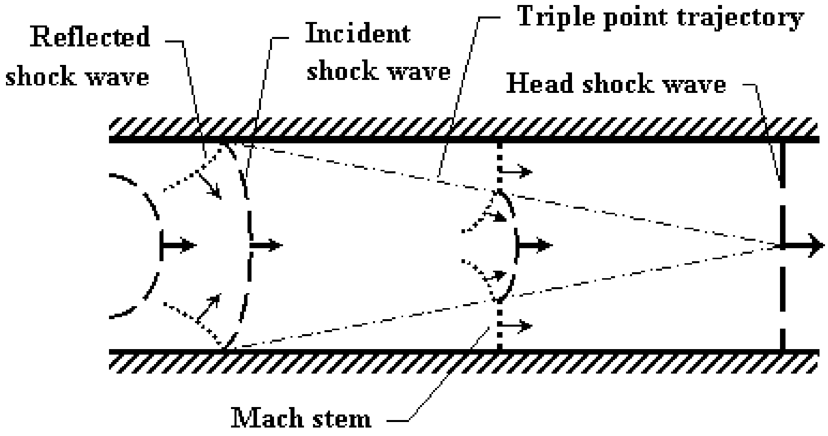

Figure 1. Scheme of interaction of shock waves in the channel with walls of the same rigid.

Formulas are known that describe the empirical dependence of overpressure (P_b) and specific impulse of head shock wave (I_b) during the explosion of a condensed explosive in a channel with rigid walls on the mass of explosive, the cross-sectional area, and the channel length [20]:

$$P_b = \left(a\frac{fm}{xS} + b\sqrt{\frac{fm}{xS}} \right) e^{-\beta x}; \tag{6}$$

$$I_b = c\frac{fm}{S} e^{-\frac{\beta x}{2d}}, \tag{7}$$

where P_b – overpressure, MPa; I_b – specific impulse, Pa·s; a, b, c – empirical coefficients; f – efficiency ratio of explosive as compared to trotyl; m – mass of explosive, kg; x – distance covered by the shock wave, m; S – channel cross-sectional area, m^2; β - reduced coefficient of aerodynamic resistance of the channel; d – reduced diameter of the channel, m.

Since, both in hazardous operations industrial facilities and in mine workings, accidental explosions of gas-air mixture are more likely, and when airborne shock wave propagate in the channel there is no fundamental difference in the nature of explosion, then formulas (6, 7) can be converted for the case of gas-air mixture:

$$P_b = \left(a\frac{\delta M Q_g}{xSQ_t} + b\sqrt{\frac{\delta M Q_g}{xSQ_t}} \right) e^{-\beta x}; \tag{8}$$

$$I_b = c\frac{\delta M Q_g}{SQ_t} e^{-\frac{\beta x}{2d}}. \tag{9}$$

where δ is the transition coefficient; *M* is the mass of explosive; *Q* is the calorific value of explosive; Q_t is the heat of TNT explosion.

The load that acts on channel walls during the passage of shock wave is characterized by the values of pressure P^*_1 and pulse I^*_1:

$$P_1^* = \frac{P_R F \sqrt{E_1}}{A_1 \sqrt{R_1^3}} \tag{10}$$

$$I_1^* = \frac{I_R h \sqrt{E_1}}{A_1 R_1 \sqrt{\rho_1}}, \tag{11}$$

where *F* – impact area of shock wave, m^2; *E* – modulus of elasticity, MPa; *A* – wall section area, m^2; *R* – tensile strength of the wall material, MPa; *ρ* – density of the wall material, N/m^3.

From the analysis of formulas (10, 11) it follows that if opposite walls of the channel are made of different materials, but with close values of tensile strengths and elastic modulus ($R_2 \approx R_1$; $E_2 \approx E_1$) that do not allow deformation under the influence of shock waves, then shock waves in the channel will be distributed according to the scheme shown in figure 1.

In the case when the strength and elastic modulus of one of the walls is much lower ($R_2 < R_1$; $E_2 < E_1$), and it is easily deformed, the reduced impulse required for its destruction decreases. This causes a decrease in the velocity of the reflected shock waves and an increase in the zone of formation of plane front of head shock wave. In this case, the front of shock wave unfolds towards a non-rigid wall, as shown in figure 2, the pressure increases on this wall, which can lead to its destruction.

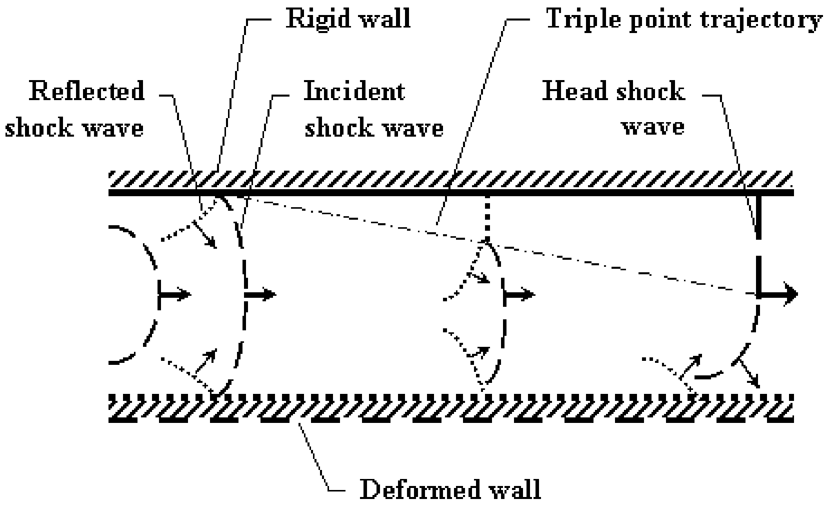

Figure 2. Scheme of the interaction of shock waves in the channel with one deformable wall.

Reversal of the front of shock wave means a violation of the geometry of plane front of head shock wave and a decrease in pressure at the front of shock wave. A new plane front will be able to form again only in zone with a length of 4…8 characteristic dimensions of channel section. For destruction of the wall and formation of a new plane front of head shock wave, energy must also be expended. For example, according to [25], even the creation of open dead end branch from the main channel with equal cross-section can reduce the load by 1.2...2 times.

Thus, if one wall is strong enough in the communication channel of large length and the other wall is easily deformed, then when a shock wave passes, a non-rigid wall can be fail fragmented in zones of formation of plane front of the head shock wave.

The proposed model allows us to justify a way to increase safety in long communication passageways of buildings with increased explosion hazard or mine workings. For this, it is necessary to provide easily breakable structures along the communication channel with an interval of 4-8 sizes of its width in the form of inserts (partitions) covering the expanders with a width and depth of not less than characteristic width of the channel. Such device of communication channels will prevent the formation of head shock wave and help to reduce the overpressure at the front of shock wave and its attenuation.

3. Conclusions

1. A physical model of formation and propagation of a shock wave in long communication channels is proposed, when one of the walls is easily deformed.
2. The proposed physical model explains the fragmentary damage of structures in long communication channels of communication passageways of industrial buildings and mine workings in case of emergency explosions.
3. The presented model shows that in the communication passageways of industrial buildings or the communication channels of mining, in which emergency internal explosions can occur, safety can be improved by reducing overpressure at the front of the shock wave, which contributes to its attenuation. For this, easily breakable structures in the form of partitions covering the expanders should be provided. Easily breakable structures should be located along the communication channel with an interval of 4-8 sizes of the width of this passageway.
4. The proposed physical model can be used to construct an algorithm for numerically calculating propagation of shock wave in a channel with walls of different rigid [26].

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