Quantitative Risk Assessment of Miners Injury During Explosions of Methane-Dust-Air Mixtures in Underground Workings

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The article proposes procedural guidelines of quantitative assessment of probability of coal miners' injury upon methane/coal dust/air explosions in mine excavations. In the course of calculating the indicator of the effective energy storage of the explosive mixture, quantitative dependences of the excess explosion pressure on the initial parameters of the mixture have been established, taking into account the initial content of combustible components. Models are presented that allow determining the change in the magnitude of excessive pressure in the shockwave front as it passes through the excavations, taking into account the aerodynamic, geometric and topological parameters of mine excavations. With the further use of the probit analysis, a model is proposed for quantifying the probability of fatal injury to miners, taking into account the distance to the explosion area boundaries, initial composition and amount of explosive mixture, parameters of excavations. For the purposes of verification of the proposed method, injury probability upon methane/coal dust/air explosion in the preparation face of the mine at different distances from explosion area boundary is determined, the size of dangerous area is defined. It is indicated that the given method of probabilistic assessment has practical significance in the management of professional risks caused by underground explosions: in particular, in determining the safe distances during explosions, choosing the parameters of protective measures, and designing barrier protective equipment.

Keywords: coal mine, labor safety, risk-oriented approach, professional risk, shockwave, probit model.

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1. Introduction

In recent decades the restructuring of coal mining industry and improvement of labor safety systems decreased total fatal injury rate during underground coal mining. However, the number of fatal injuries is still at extremely high level: thus, from 2004 more than 550 miners suffered during explosions with more than 330 deaths amounting to 33 % of all fatalities in Russian coal mines in the considered period. Extremely hard social and economic consequences of such accidents require for their immediate prevention under the conditions of growing load on working faces and increase in gas content of excavations [1–5].

Nowadays the principles of risk-oriented approach are implemented in coal mines aiming at appropriate prevention of explosions and safety provision of mining operations [6]. The risk-oriented approach is based on approved methods of risk assessment taking into account a set of risk factors and facilitating detection of dangerous situations for appropriate adoption of protective measures. Various approaches to assessment of risks of methane and dust explosion in coal mines [7–11] are available including quantitative risk explosions assessment [12–14]. However, these methods focus on determining the probability of an underlying event – methane and/or dust explosion in underground excavations (P_e, %) – and do not allow determining miners' injury probability during this explosion (P_t, %). Herewith, quantitative index of professional risk of miners' injury upon explosion (probability of injury) R_t, % can be calculated only if both of the indicated values are present:

$$R_t = P_e \cdot P_t \quad (1)$$

Compared to existing approaches to assessing professional risk based on the P_e indicator, the use of the $R_t = f(P_e, P_t)$ indicator proposed in this study is the most preferable in determining protective targeted measures due to its greatest detail and information content. This result is achieved due to the involvement in the calculation of additional factors affecting a person (affecting P_t), which were not taken into account in similar studies earlier: the distance from a person to the boundary of the explosion area; the initial composition and volume of the explosive mixture; aerodynamic, geometric and topological parameters of mine excavations.

For this reason, in this study, the shockwave is considered as the main damaging factor determining the damage rate upon assessment and forecast of professional risk, and the purpose of this work is to create a method of quantitative assessment of probability of miners' fatal injuries upon impact of shockwaves of methane/coal dust/air explosions in underground excavations. The main purpose is the creation of a model of accounting principles of factors effecting on damage probablity P_t, for which the account of effective energy content of various explosive mixtures as well as the specifics of propagation of air shockwaves across the network of underground excavations is carried out.

2. Methods

Damaging action of shockwaves and the desired probability of personnel injury P_t are determined by excessive pressure in wave front: ΔP_f, MPa and the duration of its impact (compression phase): τ, s [15]. Herewith, ΔP_f in the considered point depends on the parameters affecting the intensity of the shockwave's loss of kinetic energy as it passes through the mine excavations:

- excessive pressure in the front of shockwave in explosion area: ΔP, MPa;
- propagation distance of shockwave along straight segments of excavations: x_l, m;
- parameters of straight segment of shockwave propagation: excavation perimeter Π, m and cross section area S, m^2; coefficient of aerodynamic resistance of excavations α_a, kgf·s^2/m^4;
- parameters of local resistances: type of resistances; turning or transition angle γ, degrees; ratio of cross section areas of excavations δ, % [15].

In this connection, the assessment of the likelihood of injury to miners in the explosion of methane-dust-air mixtures in P_t mine excavations can be performed in the following sequence.

2.1. Determination of the indicator of effective energy storage of an explosive mixture

It is obvious that there is direct dependence of the value of excessive pressure ΔP on the volume of the initial explosive mixture V_m, m^3, on the concentration of methane in it C_{CH_4}, vol %, and coal dust C_{dust}, g/m^3. These parameters can be taken into account using the value of the effective energy storage of the mixture - E, J [16], which allows formalizing the dependence $\Delta P = f(V_m, C_{CH_4}, C_{dust})$ and quantifying the probability of injury to miners during explosions in accordance with the expressions [16]:

$$\Delta P = P_0 \cdot \exp(-1.124 - 1.66 \cdot ln(R_x) + 0.260 \cdot ln(R_x)^2 \quad (2)$$

$$R_x = \frac{R_l}{E/P_0^{1/3}} \quad (3)$$

$$E = \sum_{i=1}^{2}(E_i \cdot m_i) \quad (4)$$

$$m_{CH_4} = \begin{cases} V_m \cdot \rho_{CH_4} \cdot C_{CH_4}, & C_{CH_4} \leq C^{st}_{CH_4} \\ V_m \cdot \rho_{CH_4} \cdot C^{st}_{CH_4}/C_{CH_4}, & C_{CH_4} > C^{st}_{CH_4} \end{cases} \quad (5)$$

$$m_C = \begin{cases} V_m \cdot C_{dust}/1000 \cdot C_C, & (C_{dust} \cdot C_C) \leq C^{st}_C \\ V_m \cdot \frac{C^{st}_C}{C_{dust} \cdot C_C \cdot 1000}, & (C_{dust} \cdot C_C) > C^{st}_C \end{cases} \quad (6)$$

where P_0 is the ambient pressure, P_a; R_x is the dimensionless distance from the center of explosive mixture; R_l is the actual distance from the center of explosive mixture, m; E_i is the specific heat of combustion of the i-th substance, J/kg; m_i is the weight of the i-th substance in the mixture (m_{CH_4} and m_C are the weights of methane and dust in terms of carbon, respectively), kg; ρ_{CH_4} is the methane density, kg/m^3; ${C_{CH_4}}^{st}$ is the methane stoichiometric concentration, vol %; $C_{{CH_4}^{st}}$ is the carbon content in dust, unit fractions; ${C_{dust}}^{st}$ is the dust stoichiometric concentration, g/m^3 [16].

It is necessary to take into account the concentration limits of air mixture of methane and coal dust explosibility for determination of contents of methane and dust which could participate in potential explosion. The work [17] shows that methane air mixture becomes hazardous with regard to combustion in the range of 5.0 % < C_{CH_4} < 16.0 % and with regard to detonation in the range of 6.3 % < C_{CH_4} < 13.5 % . Herewith, explosion occurs according to one of the main stoichiometric reactions of combustion [17]:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \quad (7)$$

$$2CH_4 + 3O_2 = 2CO_2 + 4H_2O \quad (8)$$

$$3CH_4 + 5O_2 = CO_2 + 2CO + 6H_2O \quad (9)$$

While analyzing Eqs. (7–9), the lower stoichiometric limit of methane explosibility was detected: (according to Eq. (7)), at which maximum explosion force was achieved [18], as well as the upper stoichiometric limit of methane explosibility: C_{CH_4} = 12.28 % (according to Eq. (9)) [17]. Explosibility of air dust mixture (ADM) depends on concentration of coal dust in air, its particle sizes distribution, volatile content, and content of mineral noncombustibles. Absolute limits of ADM explosibility are in the range from 10 g/m^3 to 2,000 g/m^3 and higher [19]. The main stoichiometric reactions of carbon combustion in coal dust upon ADM explosions are [17]:

$$C + O_2 = CO_2 \tag{10}$$

$$2C + O_2 = 2CO \tag{11}$$

Thus, Eq. (10) corresponds to the upper stoichiometric limit of explosibility of pure carbon: [C] = 178.25 g/m^3, including its complete oxidation under conditions of oxygen excess; Eq. (11) corresponds to the lower stoichiometric limit of explosibility: [C] = 96.25 g/m^3, when carbon is underoxidized with generation of carbon monoxide [17].

While using these values, it is possible to obtain conventional stoichiometric composition of these mixtures, which makes it possible to account for the most negative variant of events – the maximum explosion. The selected stoichiometric concentration of explosive component makes it possible to determine the volume of potential explosive mixture generated upon decrease in ventilation and violation of dilution conditions. It is also required to account for the required dilution ratios to safe concentration: thus, in order to dilute air mixture in outflowing jet to allowable content of methane C_{CH_4} = 0.75 % , it is required to supply 133 m^3 of clean air per 1 m^3 of evolved methane [17]. The selected approach allows to account for intensity of methane evolution and to assume that the amount of undiluted methane reduced to stoichiometric concentration is directly proportional to decrease in ventilation intensity. Under actual conditions, the undiluted methane volume can be accumulated in the form of local and layered amounts, and in the case of serious violation of ventilation – in the form of total gas accumulation of overall excavation site.

2.2. Determination of excessive pressure in the shock front in the explosion area

Application of Eqs. (2–6), taking into account the results of stoichiometric analysis of combustion (Eqs. (7–9, 10–11), allowed establishing the dependence of the excessive pressure in shockwave front in explosion area ΔP on effective energy content of the mixture E. The resulting model, shown in Fig. 1, reflects the direct relationship between the amount of potential energy in the initial explosive mixture and the kinetic energy of the blast shockwave. The boundary conditions of this model are determined primarily by the mass of combustible substances in the initial explosive mixture. Thus, Fig. 2 shows the dependence of ΔP on methane content $m_{C_{CH_4}}$ and dust content m_C in air mixture: with an increase in the content of methane and dust in the initial mixture, the rate of increase in the excessive pressure of the explosion ΔP decreases, which is explained by an increase in the content of noncombustible reaction products in the explosion area, as well as by an increase in the aerodynamic resistance of the medium, a change in combustion conditions, etc. The dependence shown in Fig. 2 indicates the possibility of reaching the ultimate explosion pressure at the level of ΔP < 6 ÷ 7 MPa, which shows satisfactory convergence with empirical data on the maximum pressure of the explosions in real mine excavations $\Delta P \leq 6$ MPa [17, 20].

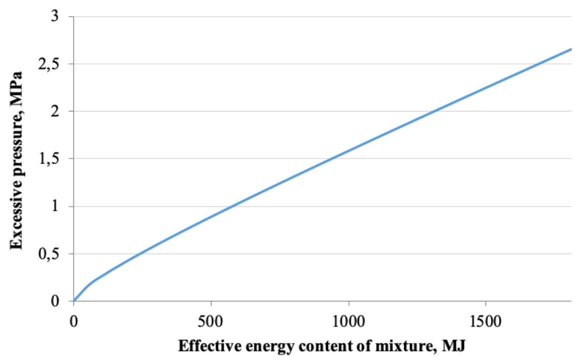

Fig. 1. Excessive pressure in shockwave front at the boundary of explosion area as a function of effective energy content of mixture.

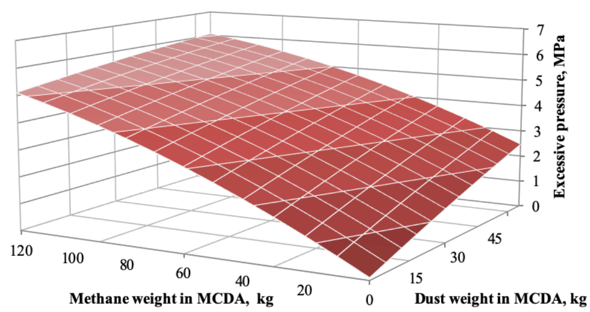

Fig. 2. Excessive pressure in shockwave front at the boundary of explosion area as a function of methane and dust content (as per carbon) in methane/coal dust/air mixture.

2.3. Determination of excessive pressure in the shock front at a distance from the boundary of the explosion area

The obtained ΔP value underlies the determination of the change of excessive pressure in shockwave leading edge upon its propagation along straight segments of excavations to the distance x_l from explosion area: ΔP_x, MPa, and upon passing through local obstacles: ΔP_R, MPa [15]:

$$\Delta P_x = \Delta P_f \cdot \exp(-k_z \cdot \frac{\Pi}{S} \cdot x) \quad (12)$$

where ΔP_f is the excessive pressure in shockwave front at the beginning of straight segment, MPa; k_z is the dimensionless coefficient of attenuation [15]:

$$k_z = [4.1 - 3.1 \cdot \exp(-3\Delta P_f)] \cdot \alpha_a \quad (13)$$

Variation of excessive pressure in shockwave leading edge ΔP_R, MPa after turning (transition, narrowing) is determined as follows [15]:

$$\Delta P_R = \frac{0.4A - 0.29 + \sqrt{(0.4A - 0.29)^2 + 2.8A}}{4.8} \quad (14)$$

where A is the variable determined as a function of local resistance according to [15]. Application of the proposed method to calculating the indicators ΔP, ΔP_x, ΔP_R makes it possible to assess probability of human fatality under the baric impact of a shockwave at different distances from the explosion area, taking into account the parameters of the initial mixture and parameters of the mine excavations using the probit model [2]: a function that reflects the relationship between the probability of injury and the intensity of the impact of the damaging factor, and being the upper limit of the integral function of the normal distribution of damage.

2.4. Determination of the probability of injury to miners, depending on the excessive pressure in the shockwave front

The analysis of scientific sources has shown that for probabilistic assessment of the risk of injury to workers in explosions in mine excavations, it is advisable to use the below probit model, which shows sufficient convergence with empirical data and is most often used in practice [21]:

$$Pr = 5 - 5.74 \cdot ln(\frac{4.2}{1 + \Delta P_x / P_0} + \frac{1.3 \cdot P_0^{0.5} \cdot m^{0.33}}{I_+}) \quad (15)$$

where m is the human weight, kg; I_+ is the pulse of compression phase, Pa·s [16]:

$$I_+ = P_0^{0.67} \cdot E^{0.33} \cdot \frac{\exp(-3.4217 - 0.898 \cdot ln(R_x) - 0.009}{C_0} \cdot ln(R_x)^2 \quad (16)$$

where C_0 is the speed of sound in air, m/s.

Application of Eqs. (15–16) determines the required probability of fatal injury P_t as a function of excessive pressure of shockwave upon methane/coal dust/air explosion which is illustrated in Fig. 3. The resulting dependence largely corresponds to the generally accepted theoretical values and boundary indicators of the probabilities of injury, but at the same time, it allows determining the probability of injury to a person taking into account the real parameters of mine excavations.

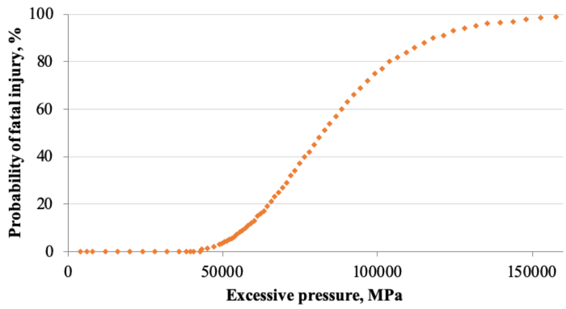

Fig. 3. Probability of fatal injury as a function of shockwave pressure.

3. Results and Discussion

The obtained in the course of this study interrelations make it possible to carry out quantitative assessment of human injury with consideration for the distance to explosion area boundary, initial composition and volume of explosive mixture, aerodynamic, geometrical and topological parameters of mine excavations.

Verification of this method was exemplified by generation of methane/coal dust/air mixture in a rectangular segment of development face with the sizes equaling to 2 m and the coefficient of aerodynamic resistance of 0.0009 kg·s^2/m^4 as a consequence of decrease in ventilation intensity by 20 % below the designed value of 70 m^3/min for 1 h. Herewith, the intensity of methane evolution at the site was preset at 0.5 m^3/min, and the concentration of suspended explosive coal dust evolved during operation of tunneling machine reached 1.5 g/m^3 as per pure carbon. Under such conditions there exists danger of accumulation of undiluted methane in amount of 6 m^3, which is equivalent to 63.15 m^3 of methane/coal dust/air mixture with stoichiometric concentration of 9.5 %. Therefore, the most negative variant of generation of explosive methane/coal dust/air mixture containing 0.656 kg of methane and 0.095 kg of explosive coal dust as per pure carbon is considered. Using Eqs. (2–6), the effective energy content of this mixture is predicted as well as the respective excessive pressure of shockwave at the boundary of possible explosion equaling to 0.241 MPa. Using Eqs. (12–13), it is possible to determine variation of shockwave excessive pressure with the distance to explosion area at straight segment applied for assessment of probability of fatal injuries using the dependence illustrated in Fig. 3:

- at the distance of 100 m from explosion area fatality probability is 98 %;
- at the distance of 200 m: 69 %;
- at the distance of 300 m: 12 %.

Herewith, the boundary of conventionally safe area stipulated by probability of miners' injury below 1 % is at the distance of 370 m from the area of potential explosion.

It should be noted that the limitations of using the proposed calculation model are determined by the real conditions of the production environment of coal mines. At the same time, the proposed model can be adapted for other production facilities (other combustible substances), provided that the algorithms are used that take into account additional specific conditions.

4. Conclusion

The proposed method makes it possible to assess probability of miners' injury upon methane and dust explosion with consideration for forecasted parameters of methane/coal dust/air mixture, ventilation intensity and excavation topology, which indicates that the research objective has been achieved. The obtained results make it possible to implement and justify the forecast of occurrence of hazardous areas stipulated by dynamic impact during quantitative assessment, as well as the forecast of professional risks, including in networks of mine excavations with complex topology.

The obtained calculated values allow accurately determining the parameters of protective measures: safe distance from the area of potential explosion, the parameters of barrier protection means (explosion-proof enclosures), means of preventing explosions, etc. The obtained results, which consist in increasing the information content of the professional risk assessment, allow increasing the degree of detail in the development of targeted protective measures, which improves the quality of management decisions taken and increases the efficiency of the professional risk management system.

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