QUANTITATIVE RISK ASSESSMENT OF MINERS INJURY DURING EXPLOSIONS OF METHANE-DUST-AIR MIXTURES IN UNDERGROUND WORKINGS

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ABSTRACT

This article proposes a solution to the problem of methodological support of injury to coal mine personnel probability quantification during explosions of methane-dust-air mixtures. The relevance of using a risk-based approach, due to the need to implement targeted preventive measures to protect personnel from explosions, is justified. The data on causes of damage to miners during explosions of methane and dust in coal mines in Russia distribution are provided. The analysis of factors affecting the size of injury to personnel by air shock waves zone during methane and dust explosions was carried out, during which quantitative dependencies were established that allow to probabilistically assess the injury to mine personnel during explosions, considering the distance from the explosion zone, initial composition and volume of explosive mixture, aerodynamic, geometric and topological parameters of mine workings, workings with air provision. The principles of using the index of explosive mixture effective energy reserve are justified. A probit model is presented to determine the probability of fatal injury to a person when exposed to a blast shock wave overpressure. For the purpose of testing the proposed method, an example of determining the injury to a person probability during explosion of a methane-dust-air mixture in the development face is given depending on the distance from explosion zone border, and the size of danger zone is also determined. It was concluded about the possibility of the proposed method of occupational risk quantification application...
in order to ensure the safety of underground mining facilities and other hazardous production facilities.

**Key words:** coal mine, occupational safety, methane explosion, dust explosion, risk-based approach, occupational risk, shock wave, probit model

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=10&IType=3

1. **INTRODUCTION**

   Mining and geological conditions of underground mining in coal mines in Russia are characterized by high gas content rates: more than 90% of mines are dangerous due to methane explosions and about 64% work under conditions of natural gas content over 10 m$^3$/t. In addition, 90% of mines work on reservoirs that are dangerous due to coal dust explosions.

   Over the last decades, as a result of the coal industry restructuring and occupational safety and coal mines industrial safety systems improvement, the overall level of fatal injuries in underground mining has decreased. However, the injury rates during methane and coal dust explosions are still at an extremely high level: for example, since 2004, more than 550 people have been injured in explosions, of whom more than 330 people died, which makes up 33% of all fatal injuries in Russian coal mines for the period under review. At the same time, the super serious social and economic consequences of this type of accidents make the problem of their prevention under the conditions of loads increase on the mining face and gas content increase in underground workings particularly relevant. [5,6,11,16,17]

   To timely take actions in order to prevent explosions and ensure the safety of operations in coal mines, the principles of a risk-based approach are currently implemented [9]. The risk-based approach implementation is based on the use of risk assessment methods considering the range of risk factors and allowing identify hazardous situations and hazardous zones for taking protective measures in advance. To date, there are various approaches to assess the risk of methane explosions in coal mines [3, 7, 10, 15, 22 and etc.], including the methods for risk quantification [12, 14, 18 and etc.], which allow assessing the probability of methane and dust explosion in underground workings – $P_e$ %. The results of such an analysis can be used to study the probability of various explosion scenarios implementation in order to ensure the emergency tolerance of a coal producer. On the other hand, to implement targeted measures to protect personnel from the methane-dust-air mixture explosions, it is also necessary to take into account the risk of injury to a person during explosion – $P_t$ %, which is determined by such factors as: distance from explosion zone border, initial composition and volume of explosive mixture, aerodynamic, geometric and topological parameters of mine workings. Whereby, the quantitative index of occupational risk of miner's injury during explosion – $R_t$ % will allow to make a prediction of both dangerous situations and dangerous zones caused by the impact of injurious effects on a person, and can be found in accordance with the following expression:

\[
R_t = P_e \cdot P_t
\]  

(1)

A study [19] is known, during which the following distribution of miners death causes under the influence of hazards as a result of methane and dust explosions was established:

1. The factors physically affecting the human body – shock waves of the air environment (53%) and thermal radiation from combustion zones and flame front (1%);
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2. The factor chemically affecting the human body – gaseous toxic (poisonous) substances formed during combustion (46 %).

These data indicate that the vast majority of analyzed cases of fatal injuries to coal mine personnel during underground explosions occurred as a result of air shock waves, and therefore in this study this hazard is considered as the main adverse factor determining the damage range in assessing and forecasting an occupational risk. In accordance with what, the aim of this work is to create a method for quantifying the probability of fatal injury to coal mine workers when exposed to shock waves of methane-dust-air mixture explosions in underground workings. The main objective of the study is to determine the principles of considering the factors affecting \( P_t \) injury probability index, for which an analysis of mixtures of different composition effective energy supply, as well as air shock waves distribution processes through the network of underground mine workings, was made.

2. RESEARCH METHODS

According to [8], the damaging effect of shock waves is determined by overpressure in a wave front – \( \Delta P_f \), MPa and time of its impact (compression phase) – \( \tau \), s. In this case, \( \Delta P_f \) value at the design point depends on:

- shock front overpressure in explosion zone – \( \Delta P \), MPa;
- length of shock wave propagation path along straight sections of workings – \( x_l \), m;
- parameters of shock wave motion straight sections: perimeter – \( P \), m and sectional area – \( S \), \( m^2 \) workings; value of workings aerodynamic drag factor – \( \alpha_a \), kgF·s\(^2\)/m\(^4\);
- local resistance parameters: type of resistance; value of rotational angle or conjugation \( \gamma \), degree; cross sections of workings areas ratios – \( \delta \), %.

The analysis of data given in [1, 20 and etc.] indicates the possibility to achieve the overpressure level in the shock front of underground mine explosion zone \( \Delta P = 5.0 \) MPa or more. At the same time, there is a relationship between the overpressure level and initial parameters of explosive air mixture, which can be established taking into account the amount of mixture effective energy supply – \( E \), J. Thus, the use of \( E \) indicator makes it possible to take into account the volume of an explosive air mixture and methane and coal dust concentration in it when determining the overpressure level \( \Delta P \) [2]:

\[
\Delta P = P_0 \cdot \exp(-1.124 - 1.66 \cdot \ln(R_i) + 0.260 \cdot \ln(R_i)^2),
\]

\[
R_i = \frac{R_i}{(E/P_0)^{1/3}},
\]

\[
E = \sum_{i=1}^{2} (E_i \cdot m_i),
\]

\[
m_{CH_4} = \begin{cases} V_e \cdot \rho_{CH_4} \cdot C_{CH_4}, & C_{CH_4} \leq C_{CH_4}^{cm} \\ V_e \cdot \rho_{CH_4} \cdot C_{CH_4}^{cm} / C_{CH_4}, & C_{CH_4} > C_{CH_4}^{cm} \end{cases},
\]

\[
m_c = \begin{cases} V_e \cdot C_c^{cm} / 1000 \cdot C, & (C_{\text{max}} \cdot C_c) \leq C_c^{cm} \\ V_e \cdot C_c^{cm} \cdot C / 1000, & (C_{\text{max}} \cdot C_c) > C_c^{cm} \end{cases},
\]
where: \( P_0 \) – atmospheric pressure, Pa; \( R \) – dimensionless distance from the center of explosive mixture; \( R_i \) – actual distance from the center of explosive mixture, m; \( E_i \) – specific heat of \( i \)-th substance, J/kg; \( m_i \) – mass of \( i \)-th substance in the mixture (\( m_{CH4} \) and \( m_C \) – methane and dust mass in terms of carbon respectively), kg; \( V_c \) – explosive mixture volume, m\(^3\); \( \rho_{CH4} \) – methane density, kg/m\(^3\); \( C_{CH4} \) – methane concentration in the mixture, % vol.; \( C_{st}^{CH4} \) – stoichiometric methane concentration, % vol.; \( C_{dust} \) – dust concentration in the mixture, g/m\(^3\); \( C_C \) – carbon content in a dust, fr. unit; \( C_{st}^{dust} \) – stoichiometric dust concentration, g/m\(^3\).

To determine the amount of methane and dust that may be involved in a potential explosion; the concentration limits of air mixtures explosivity are analyzed. So, it is known that the methane-air mixture becomes dangerous due to inflammation within 5,0 % < \( C_{CH4} < 16,0 \% \) and within 6,3 % < \( C_{CH4} < 13,5 \% \) by detonation. At that this explosion occurs according to one of the main stoichiometric combustion reactions:

\[
CH_4 + 2O_2 = CO_2 + 2H_2O ,
\]

(7)

\[
2CH_4 + 3O_2 = 2CO + 4H_2O ,
\]

(8)

\[
3CH_4 + 5O_2 = CO_2 + 2CO + 6H_2O.
\]

(9)

When analyzing the equations of reactions (7-9) [1], the lower stoichiometric explosion limit of methane was found at the level of \( C_{CH4} = 9.5 \% \) (corresponding to the reaction (7)), at which the maximum explosion force was observed [4], as well as the upper stoichiometric explosion limit at the level of \( C_{CH4} = 12.28 \% \) (corresponding to the reaction (9)). The dust-air mixture explosiveness depends on the coal dust concentration in the air, its dispersion composition, volatile-matter content and non-combustible mineral substances content [1]. Absolute values of DAM explosive limits are within the range from 10 g/m\(^3\) to 2000 g/m\(^3\) and more [13]. The main stoichiometric reactions of coal dust carbon combustion during DAM explosions are:

\[
C + O_2 = CO_2 ,
\]

(10)

\[
2C + O_2 = 2CO .
\]

(11)

Thus, the upper stoichiometric explosive limit of pure carbon \([C]=178.25\) g/m\(^3\) corresponds to reaction (10), taking place in case of its complete oxidation under excess oxygen conditions, to reaction (11) – the lower stoichiometric explosive limit \([C]=96.25\) g/m\(^3\), at which the carbon not oxidized at full while forming carbon monoxide [1]. The use of the above values of concentrations makes it possible to bring the studied mixtures to conditional stoichiometric composition, which allows predicting the most negative scenario, accompanied by an explosion of the greatest force. In this case, the explosive component stoichiometric concentration accepted value makes it possible to determine the volume of a potential explosive mixture arising when decreasing the intensity of ventilation and dilution conditions violation. Wherefore, the necessary proportions of dilution to a safe concentration should be considered: for example, to dilute the air mixture in outgoing jet to permissible concentration of methane \( C_{CH4} = 0.75 \% \), 133 m\(^3\) of clean air must be supplied per 1 m\(^3\) of released methane. The chosen approach allows to take into account the intensity of methane release and to assume that the amount of undiluted methane, reduced to stoichiometric concentration, is directly proportional to the amount of ventilation intensity decrease. In actual practice, the undiluted volume of methane can accumulate in the form of local and
stratified accumulations, and in case of a serious violation of ventilation, in the form of general gasification of the entire working site volume.

Thus, using expressions (2-6) and the results of stoichiometric analysis of mixtures combustion reactions (7-9, 10-11), the dependence of excess pressure in a shock wave front in \( \Delta P \) explosion zone on \( E \) mixture effective energy reserve, presented in Figure 1, as well as \( \Delta P \) dependence on \( m_{CH4} \) methane and \( m_C \) dust content in the air mixture, is presented in Figure 2.

Considered the obtained \( \Delta P \) value, the change in overpressure in the shock wave front during its propagation along workings’ straight sections at \( x_l \) distance from explosion zone – \( \Delta P_x \), MPa, and with local resistances propagation – \( \Delta P_R \), MPa [8]:

\[
\Delta P_x = \Delta P_f \cdot \exp \left( -k_z \cdot \frac{I}{S} \cdot x \right), \quad (12)
\]

where: \( \Delta P_f \) – overpressure in the shock wave front at the beginning of straight section, MPa; \( k_z \) – dimensionless attenuation coefficient:

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

The change in overpressure in \( \Delta P_R \) shock wave front, MPa after rotation (conjugation, contraction) is determined by the formula:

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

where: \( A \) – value determined depending on the type of local resistance according to [8].

**Figure 1** The effect of effective energy reserve of mixture on the overpressure magnitude in the shock wave front at explosion zone border
3. RESULTS AND DISCUSSION

The proposed method of $\Delta P$ index calculation application at design points located at various points in the coal mine underground workings network allows estimating the probability of a person’s death at given points under shock wave baric impact using the probit model [6, 21]:

$$\text{Pr} = 5 - 5.74 \cdot \ln \left( \frac{4.2}{1 + \frac{\Delta P}{P_0}} \cdot \frac{1.3 \cdot P_0^{0.5} \cdot m^{0.33}}{I_x} \right),$$

where: $m$ – person weight, kg; $I_x$ – compression phase pulse, Pa·s:

$$I_x = P_0^{0.67} \cdot E^{0.33} \cdot \frac{\exp(-3.4217 - 0.898 \cdot \ln(R_s) - 0.009 \cdot \ln(R_s)^2)}{C_0},$$

where: $C_0$ – sound speed in air, m/s.

The use of probit models has found wide application in determining the effects of various harmful and dangerous factors on the human body and allows to quantitively assess the probability of injury depending on the negative impact intensity. Thus, the use of expressions (15-16) made it possible to establish a connection between the determined indicator of $P_t$, fatal injury probability and shock wave dynamic impact intensity during the methane-dust-air mixture explosion, which is shown in Figure 3.

Thus, the relationships obtained in the course of this study allow to quantitively assess the probability of injury to a person, considering the distance from explosion zone border, initial composition and explosive mixture volume, and aerodynamic, geometric and topological parameters of mine workings.

![Figure 2](image-url)
Quantitative Risk Assessment of Miners Injury During Explosions of Methane-Dust-Air Mixtures in Underground Workings

In order to evaluate the method, we consider the case of a methane-dust-air mixture occurrence at the development face of rectangular cross section with sides equal to 2 m site, and aerodynamic drag factor of 0.0009 kgF·s²/m⁴ value as a result of ventilation intensity reduction by 20% below the calculated value of 70 m³/min for a period of 1 hour. Whereby, the intensity of methane emission at the site is set at the level of 0.5 m³/min, and the concentration of suspended explosive coal dust released during the heading machine operation reaches 1.5 g/m³ in terms of pure carbon. In these conditions, there is a danger of an undiluted part of methane with a volume of 6 m³ accumulation, which is equivalent to 63.15 m³ of a methane-dust-air mixture with a stoichiometric concentration of 9.5%. Thus, the most negative variant of the explosive methane-dust-air mixture formation containing 0.656 kg of methane and 0.095 kg of explosive coal dust in terms of pure carbon is considered. Using expressions (2-6), the effective energy reserve of this mixture was calculated, based on which the value of shock wave overpressure at the zone of possible explosion boundary was determined at the level of 0.241 MPa. Using expressions (12-13) allows to determine the change in the shock wave overpressure magnitude while moving away from explosion zone in a straight section, based on which the probability of fatal injury to a person is estimated using the dependence shown in Figure 3:

- at a distance of 100 m from the explosion zone, the probability of person’s death is 98%;
- at a distance of 200 m – 69 %;
- at a distance of 300 m – 12 %.

In this case, the conditionally safe zone border, due to the probability of injury to personnel less than 1%, is located at a distance of 370 m from the potential explosion zone.

4. CONCLUSIONS
The proposed method implementation allowed carrying out a probabilistic assessment of injuries to personnel during methane and dust explosions, considering the predicted parameters of the methane-dust-air mixture, ventilation rate, geometric parameters and workings topology. The results of a probabilistic assessment make it possible to predict the occurrence of hazardous zones caused by air shock waves dynamic effect when conducting a quantitative assessment and forecast of occupational risks associated with methane and dust explosions in coal mines.
This approach also allows taking into account the propagation of shock waves during various local resistances passage, which makes it possible to identify potentially hazardous zones in the underground workings network with a complex topology, and to make a choice of preventive targeted measures to protect personnel from explosions in underground workings. In addition, the proposed method can also be used in assessing the destruction potential of explosive mixtures of different composition explosions at industrial facilities for various purposes.

ACKNOWLEDGMENT

This study was performed as part of improving results of research work «Development of science-based proposals for assessment of accidents risk in coal mines taking into account the specific mining and geological conditions», which was implemented by Industrial Safety Department of Saint-Petersburg Mining University. Authors express their appreciation to members of Industrial Safety Department for assistance in research.

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