NUMERICAL ASSESSMENT OF HYDROGEN EXPLOSION CONSEQUENCES IN MINE TUNNEL

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ABSTRACT

The aim of the work is a numerical estimation of the conditional probability of damage to the mine personnel during an emergency explosion of a hydrogen-air mixture. The methodology for determining the parameters of the gas-dynamic process of the explosion of a hydrogen-air cloud in an open and closed space, taking into account chemical interaction and space clutter, is presented. A computational method based on a probit analysis for determining the damage probability fields of a person exposed to an explosive shock wave has been developed. To automate the computational process, the tabular dependence “probit-function-damage probability” is replaced by a piecewise cubic spline. Numerical studies of the influence of the drift working space clutter by an electric locomotive on the distribution of the overpressure of the gaseous medium and the conditional probability of the eardrums rupture and lethal damage to personnel in the emergency zone of the coal mine have been carried out. It was obtained that the closed nature of the working space and its blockage significantly changes the shape and size of the danger zone and requires consideration by an expert at the stage of deciding on the safety level at the mine. The scientific novelty of the method proposed in the work consists in taking into account in the mathematical model of the movement of a multicomponent chemically reacting gas mixture the effect of compressibility of flow, complex terrain (space clutter with equipment), three-dimensional nature of the gas-air mixture dispersion process. The model allows obtaining the space-time distributions of the shock-impulse load of the blast wave, necessary for determining the non-stationary three-dimensional fields of the conditional probability of damage to the staff on the basis of probit analysis. The developed computational method allows analyzing and forecasting in time and space the conditional probability of damage of varying degrees of severity of personnel who are exposed to an explosive shock wave as an indicator of the safety level of a coal mine.

INTRODUCTION

Hydrogen, along with methane, is one of the most explosive gases that are present in layers of rock that is mined in the coal industry [1]. Therefore, coal mining occupies one of the highest places in terms of the risk of accidents, which lead to severe social and economic consequences [2]. Violations of safety, equipment failures, factors of natural origin often entail hydrogen emissions in mine workings and chambers, mixing of combustible gas with air to form an explosive gas mixture, the explosion of which is accompanied by the shock waves (SW) formation and propagation (Fg. 1) [3, 4].

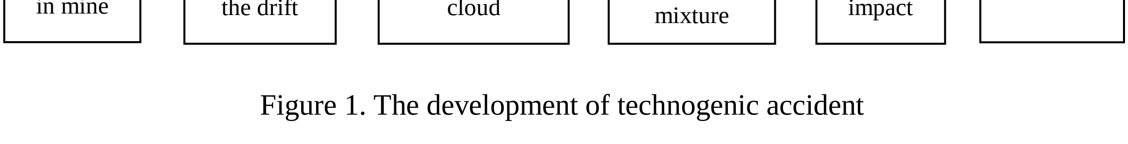


Figure 1. The development of technogenic accident

The SW exerts a shock-impulse load on the environment, threatening the life and health of the miners, destroying the mines and damaging the mining equipment located in them. As a result of such accidents, social, material and financial losses can reach catastrophic proportions.

In order to ensure the safety of working conditions in coal mines, it is necessary to develop and apply protective equipment that can prevent or reduce to an acceptable level the possible consequences caused by hydrogen-air explosion [3]. The effectiveness of protection methods can be tested experimentally [5]. However, a full-scale physical experiment in this case is difficult to implement, cumbersome and too expensive. Therefore, a computational experiment based on computer systems [6] implementing the considered emergency scenarios (Fig. 2) has been increasingly used recently. Thus, the engineering problem of mathematical modeling of physical processes of the considered emergency scenario is relevant.

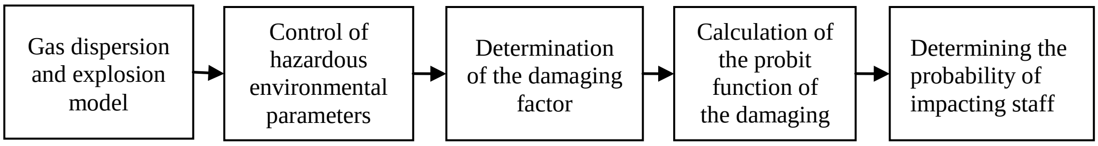


Figure 2. Probabilistic assessment scheme of the accident consequences

A mathematical model of the explosion of a hydrogen-air mixture cloud in a drift of a coal mine is considered in this paper. The analysis of the influence of the cluttering of space by a battery-electric locomotive on the formation of a shock-impulse load in an open and closed mine workings and the resulting fields of the conditional probability of damage to miners is analyzed. The state of the gas-air environment of mine workings can be described as a set of normal values of overpressure, temperature, velocity vector, chemical composition of the medium. During an emergency explosion, these parameters become a locally temporarily disturbed, the excess values of hazardous parameters form damaging factors that have a harmful effect on the human body. Some time after the accident, the environment returns to an unperturbed steady state.

The purpose of this work is to use an effective mathematical model of the explosion of a hydrogen-air mixture cloud resulting from an accidental hydrogen release at the coal mine’s drift footing, for spatial analysis and prediction of non-stationary fields of a damaging factor — a shock-impulse load and determining the fields of conditional probability of damage to a person based on probit analysis.

An adequate description of the physical processes of mixing chemically reacting gases with air and further spreading the mixture into the open space [6], tunnel [7] or closed ventilated space [8] is possible only using the Navier-Stokes system of non-stationary equations for compressible gas [9]. Currently, numerical simulation of turbulent flows is carried out by solving the Reynolds-Favre-averaged Navier-Stokes equations, supplemented by a model of turbulence [10]. However, most turbulence models do not describe with equal degree of adequacy the various types of flows that appear [11]. This is especially true for currents with intense flow breaks and / or large pressure and temperature gradients.

In [12] it is indicated that modern engineering methods for predicting the consequences of accidents on chemically hazardous objects (such as [13], [14]) implement the Gauss model or the analytical solution of the mass transfer equation and do not take into account the blockage of the calculated space by impenetrable objects. The use of numerical kinematic models [15] to assess territorial risk is also limited to cases of impurity dispersion over a flat surface. Some papers take into account the complex terrain in the process of solving the mass transfer equation by the finite-difference method [12, 14], but either there is no consideration for the three-dimensional nature of the flow around obstacles [12], or the effect of compressibility of the flow is not taken into account, which does not allow to use these mathematical models to calculate effects of all damaging factors (explosion shock wave load, thermal radiation, toxic dose), which may be present simultaneously during accidents.

In addition, modern techniques for assessing the technogenic impact on the environment are mainly based on a deterministic approach [16], and during probabilistic assessment of the consequences of damaging service personnel based on probit analysis, the dependence of probability on the probit function in a table view is used for expert analysis [17]. It is not possible to apply this approach automatically in a computer system to obtain non-stationary fields of damaging factors and probability of damage and it requires an improvement in computational methods.

Therefore, there is a need to build effective mathematical models and computational schemes for numerical modeling of three-dimensional flows of multicomponent gas mixtures, taking into account the space cluttering factor with impenetrable objects, compressibility and chemical interaction effects, which allow determining the full set of hazardous flow parameters for various scenarios of man-made accidents, calculate the damaging factors (including the shock-impulse load) and build a space-time fields of staff damage conditional probability needed to assess individual risk.

1.0 METHODS OF ASSESSING THE IMPACT CAUSED BY AN EXPLOSION WAVE

It is necessary to determine the peculiarities of the influence of space cluttering with mining equipment (battery locomotive) and the closed nature of the settlement zone on the spatial and temporal distribution of the shock-impulse load and the probability of personnel damaging during an accidental explosion of a hydrogen-air cloud in the drift of a coal mine based on a mathematical model of the considered process [18].

An emergency release of hydrogen in the drift of a coal mine is usually accompanied by the formation of a hydrogen-air mixture, which can explode under the influence of external factors. The resulting explosion SW spreads through the drift, exerting a shock-impulse load on the mine workers and leading to harmful consequences for their health (Fig. 1).

The damaging impact of the shock wave according a probabilistic approach is determined by the maximum overpressure ΔP_+ (relative to atmospheric pressure P_0) and compression phase impulse I_+ (Fig. 3).

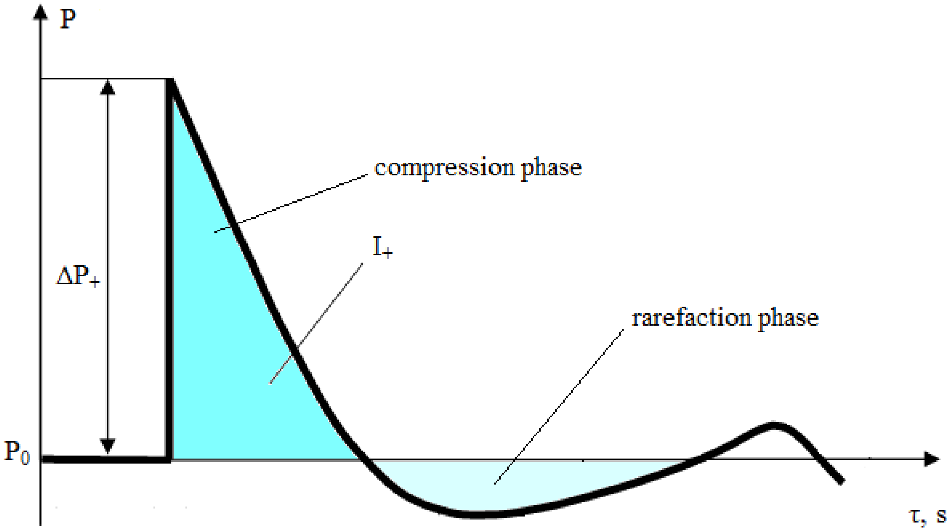


Figure 3. The typical profile of an explosion wave

The values of these indicators in each control point can be used to determine the individual risk of injury to personnel. The risk assessment of the harmful effects of damaging factors on the human body in the accident zone is one of the main stages of the safety analysis process and the magnitude of the overall risk of an industrial facility functioning (along with the identification of hazardous equipment, research of operational threats, assessment of the likelihood of an accident Risk assessment allows to draw conclusions about the acceptability of risk and evaluate the effectiveness of protective facilities and actions of personnel. The probability of a specific scenario for the development of an accident P_s depends on the statistical probability of the occurrence of such an accident P_a and the conditional damage probability of an affected person P_c which can be obtained by mathematical modeling.

The conditional probability P of harmful impact on a person that is under the influence of an explosion shock wave depends on the probit-function *Pr* – the upper limit of a definite integral of the normal distribution law with mathematical expectation 5 and variance 1

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\Pr} e^{-\frac{1}{2}(t-5)^2} dt, \tag{1}$$

where t is an integral degree of impact.

For example, the probability of human health lethal damage caused by overpressure can be estimated by the following ratio [19]

$$\Pr_1 = 5 - 0,26 \ln\left[\left(17500/\Delta P_+\right)^{8,4} + \left(290/I_+\right)^{9,3} \right]. \tag{2}$$

The probit-function for rupturing human eardrums depends on the level of overpressure and can be found by the formula [20]

$$\Pr_2 = -15,6 + 1,93 \ln \Delta P_+ . \tag{3}$$

Usually in engineering practice, safety experts operate on a table of discrete values of the integral (1) visually assessing the damage probability for a particular value of the probit function for a certain degree of damage.

In order to automate the computational process of analysis and prediction, the table of discrete values of the “probit-function-probability” dependence is replaced by a generalized piecewise cubic Hermitian spline [21]. The characteristics of such a spline allow you to avoid possible oscillations of the approximated function in the intervals.

2.0 EXPLOSION MATHEMATICAL MODEL AND CALCULATION ALGORITHM

For comparative computational experiments, in order to evaluate the effectiveness of protective measures against shock wave overpressure, we use a mathematical model of an instantaneous explosion of hydrogen-air mixture [11-13]. It is assumed that the main factor influencing the physical processes under consideration is the convective transfer of mass, momentum and energy. Therefore it is sufficient to use the simplified Navier-Stokes equations which are obtained by dropping the viscous terms in the mixture motion equations (Euler approach with source terms) [12].

The computational domain is a parallelepiped located in the right Cartesian coordinate system (Fig. 4). It is divided into spatial cells whose dimensions are determined by the scale of the characteristic features of the area (roughness of streamlined surface, dimensions of objects).

According to the explosion model it is assumed that the global instantaneous chemical reaction takes place in all elementary volumes of computational grid where the hydrogen concentration is in the limits of ignition ($Q_{\min} \le Q \le Q_{\max}$).This means that the parameters of the two-component mixture (air and fuel) in the control volume immediately get the new values of the parameters of three-component mixture (air, combustion products and residues of fuel). In other words, it is assumed that the flame front propagates with infinite velocity [16].

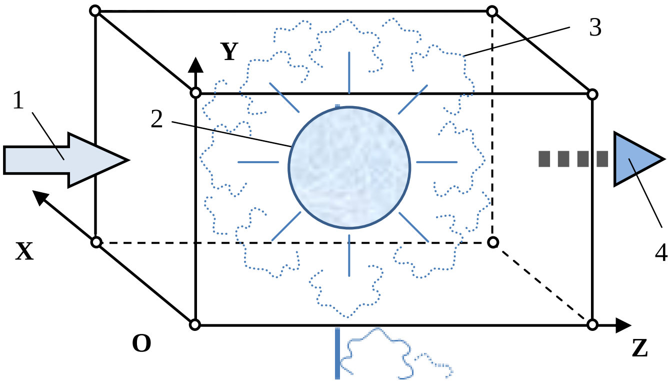


Figure 4. A computer model of the hydrogen-air cloud explosion:
1 – inlet air; 2 – cloud; 3 – combustion products; 4 – output mixture

Computer solution of the fundamental equations of gas dynamics for a mixture supplemented by the mass conservation laws of admixtures in the integral form is obtained using explicit Godunov method [22]. To approximate the Euler equations the first order finite-difference scheme is used. Central differences of second order are used for the diffusion source terms in the conservation equations of admixtures. Simple interpolation of the pressure is applied in the vertical direction. Godunov method is characterized by a robust algorithm that is resistant to large disturbances of the flow parameters (e.g. pressure) which allows obtaining a solution for modeling of large-scale explosions of gas mixtures.

A mathematical model was verified with respect to Fraunhofer ICT experimental data for hydrogen explosions and the explosion of propane [23].

To analyze the formation of hydrogen cloud, its explosion and dispersion of the combustion products in the atmosphere, as well as to forecast the pressure changes at the control points of the computational domain and to evaluate the difference between the various mine workings and the effect of space cluttering by an mine locomotive the computer system «Explosion Safety»® [24] is used. The software allows calculating the density, velocity, pressure, temperature of the mixture, the concentration of the mixture components (combustible gas, air, and combustion products), and the heat release rate within each control volume of the mixture at each discrete time step.

3.0 CALCULATION OF HYDROGEN CLOUD EXPLOSION

A computer simulation of the explosion of a cloud of hydrogen-air mixture resulting from an accidental release from a crack in the base of a drift of a coal mine is carried out. The calculated area is shown in Fig. 6. The computational experiment is carried out at an air velocity q = 0.5 m / s, temperature 293 K, pressure 101325 Pa at the entrance to the considered area. The dimensions of the computational domain are: length L_z = 11.0 m (determined by computer resource limitations), height L_y = 2.33 m, width L_x = 3.37 m, radius of circle R_2 = 1.65 m, the center of which is at a height of Y_1 = 0.65 m.

The cloud of the hydrogen-air stoichiometric mixture is located at a distance of Z_1 = 5.03 m from the input of the computational domain, the radius of the cloud is R_1 = 0.8 m (see Fig. 1a). At a distance of Z_2 = 6.33 m, a battery-electric locomotive is located, the main dimensions of which correspond to the ARP8S model (H_X = 1.4 m, H_z = 4.5 m, H_y = 1.67 m, D_x = 0.76 m, D_y = 0.1 m, D_z = 1.17 m). The control points P0-P4 are located in the characteristic places of the emergency zone, in which the change in overpressure with time is monitored (point P4 at a height of 1.82 m).

In order to assess the influence of the closed nature of the flow in the drift and the space clutter effects caused by an electric locomotive on the resulting fields of overpressure and the damage probability, six options of the design scheme are considered (table 1): V1 – an open space without a locomotive; V2 – an open space with a locomotive; V3 – a round-ceiling drift without a locomotive; V4 – a round-ceiling drift with a locomotive; V5 – a rectangular-ceiling drift without a locomotive; V6 – a rectangular-ceiling drift with a locomotive.

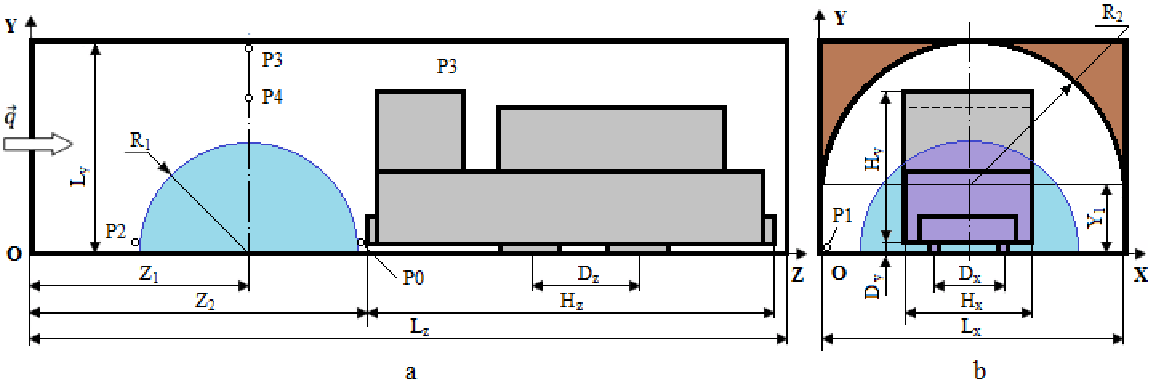
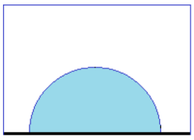
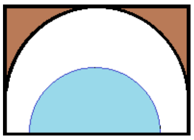
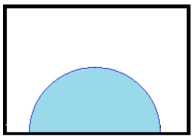
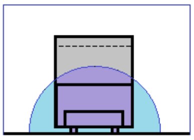
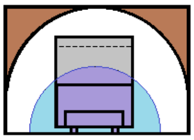
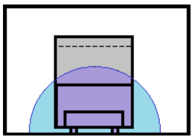


Figure 5. The scheme of the calculated area

Table 1. Types of calculation scheme.

No.	Scheme	No.	Scheme	No.	Scheme
V1		V3		V5	
V2		V4		V6	

At the initial moment of time, as a result of the explosion of a hydrogen-air mixture, a cloud of combustion products with a high pressure and temperature is formed. Further, the process of dispersion of combustion products is realized, accompanied by convective transfer and turbulent scattering of gas mixture along the drift and movement of shock wave from an explosion epicenter. During calculation process, it is possible to derive pressure fields in any point of time in all three planes of the calculation domain (Fig. 6) in order to collect all the needed information to calculate conditional probability fields for personnel damage and gather overpressure collections.

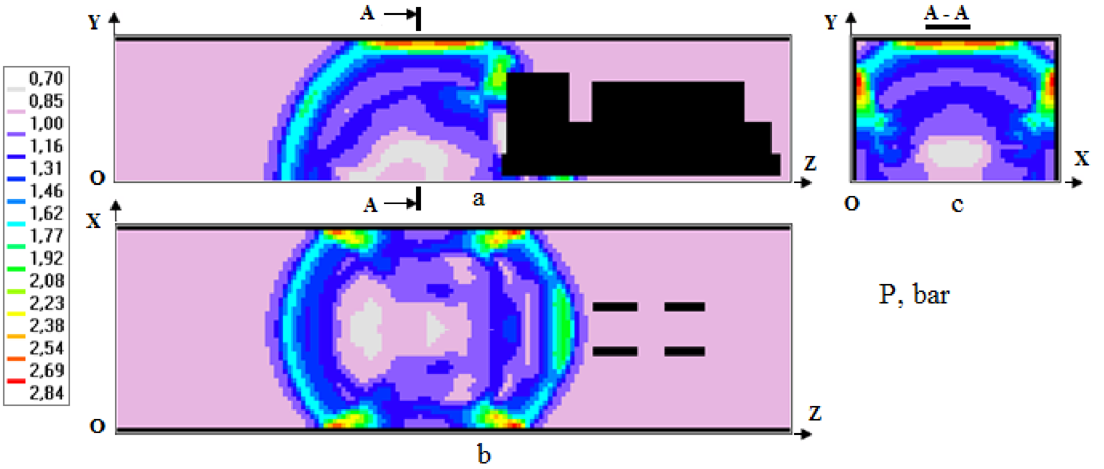
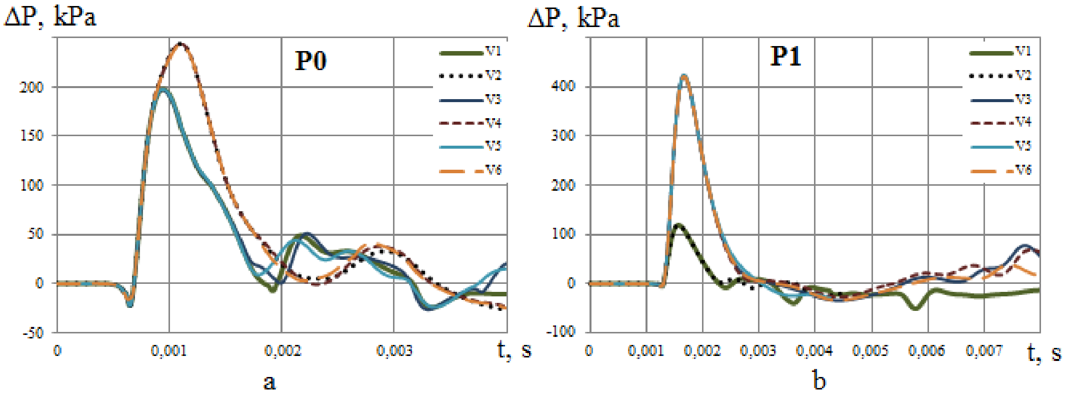


Figure 6. Pressure distribution for option V6 at t = 0,003 c: a – plane YOZ; b – XOZ; c – XOY

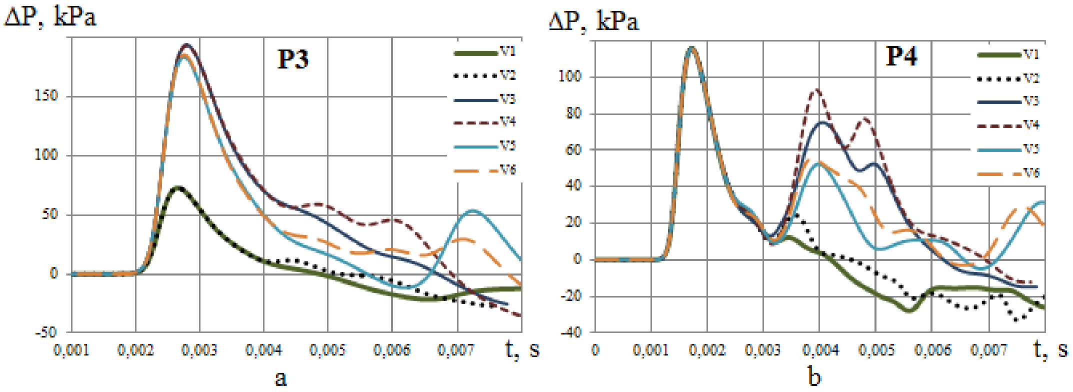
The overpressure history at the control points P0-P4 for different scheme options V1-V6 of calculating is presented in Fig. 7-8.



a

b

Figure 7. Overpressure history at the control points P0 (a) and P1 (b)



a

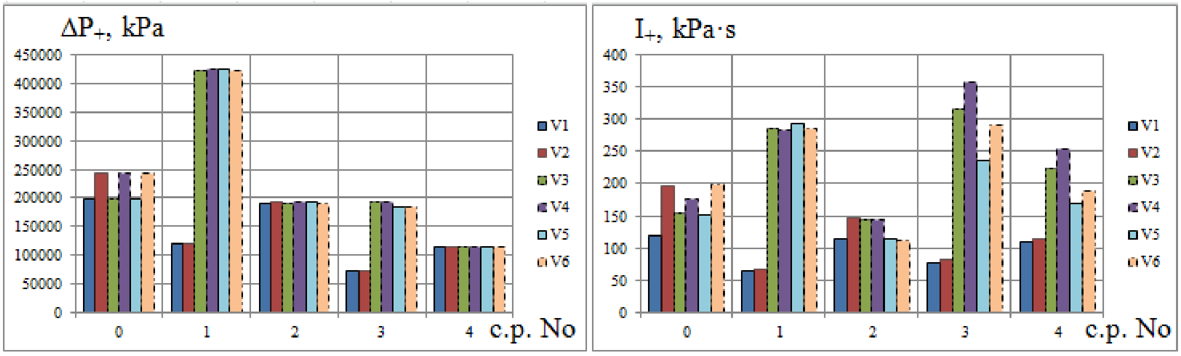
b

Figure 8. Overpressure history at the control points P3 (a) and P4 (b)

From an analysis of the overpressure behavior (Figs. 7-8, 9a), it can be seen that the presence of a closed area (V3-V6) leads to a significant increase in the maximum overpressure at points P1 and P3 compared to open space (V1, V2) due to effect of SW reflection from the drift walls. In the remaining points, the influence of the drift walls is insignificant. On the other hand, at the point P0, the space clutter with a locomotive (V2, V4, V6) significantly affects the overpressure. From the point of view of the impulse load (Fig. 9b), a similar behavior is seen compared to the shock component, with the exception of points P2, P4, in which the drift walls effect increases markedly due to the secondary pressure peak from the reflected pressure wave.

Collected data allow us to extract the damaging factors of the shock wave (maximum overpressure and compression phase impulse) (Fig. 9) and calculate the values of the conditional probability of a lethal outcome (Fig. 10a) and eardrum rupture (Fig. 10b) at control points.

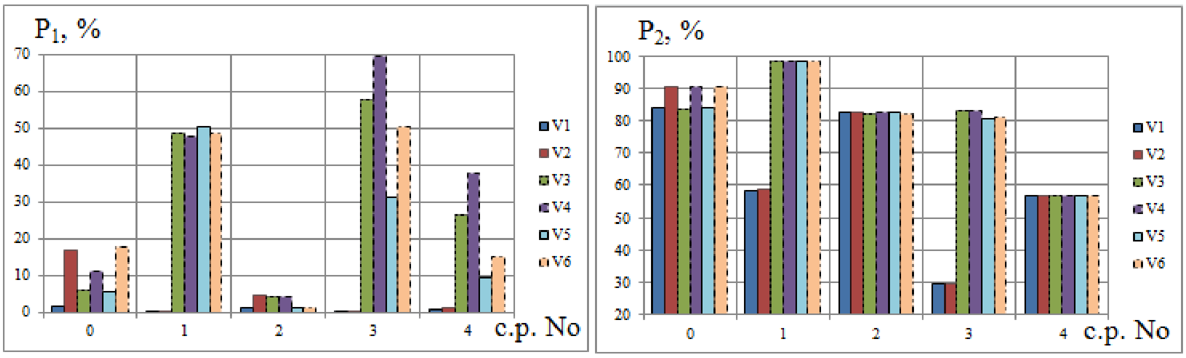
In accordance with the behavior of maximum overpressure (Fig. 9a) the conditional probability of rupture of the eardrum (Fig. 10b) behaves at the control points, which is logical, since there is only a shock component in the formula (3). It is seen that the maximum probabilities correspond to the points P1 and P3 for the options with a drift and at the point P0 due to the presence of a locomotive. A value of less than 50% probability has only at point P3 in open space. The behavior of lethal probability is more complex (Fig. 10a) due to the presence of the impulse component of the SW load in the formula (2). For control points P1-P4, the presence of drift walls is decisive for the generation of high values of the lethal probability, whereas in open space, the probability value is insignificant. For point P0, the probability of lethal damage increases slightly due to the presence of a locomotive.



a

b

Figure 9. Hazardous parameters at test points: a – overpressure; b – impulse



a

b

Figure 10. Lethal (a) and eardrum rupture (b) probabilities in control points P0-P4 for options V1-V6

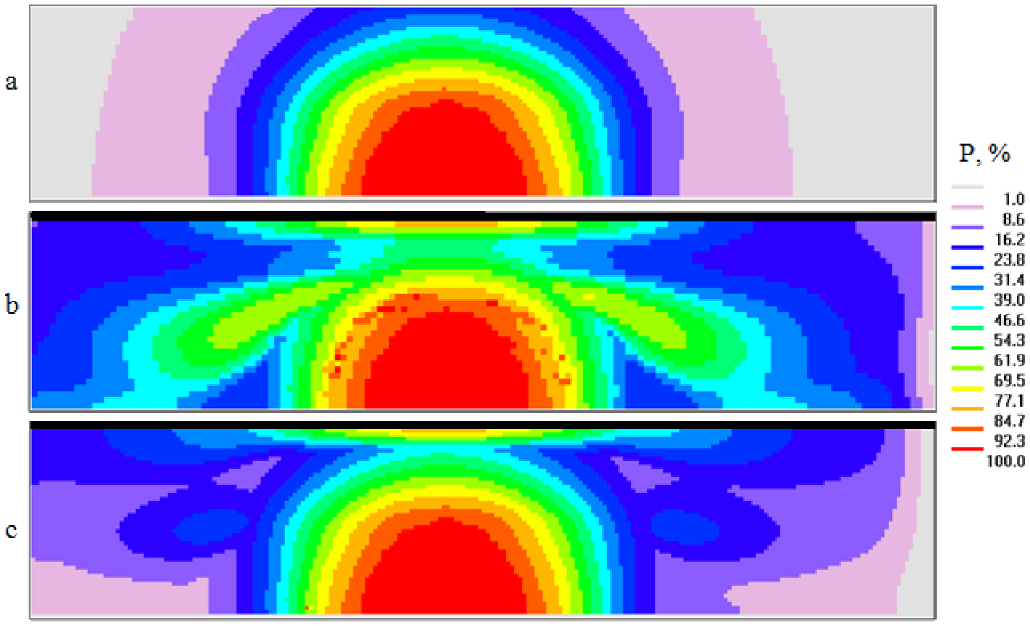


Figure 11. Eardrums rupture probability in plane YOZ for options V1 (a), V3 (b) and V5 (c)

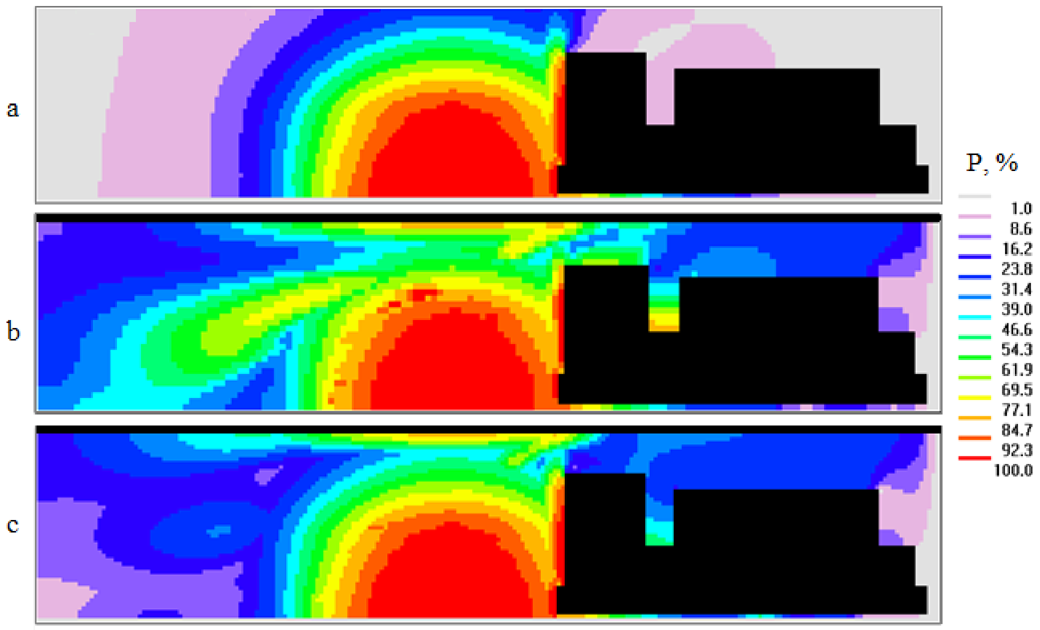


Figure 12. Eardrums rupture probability in plane YOZ for options V2 (a), V4 (b) and V6 (c)

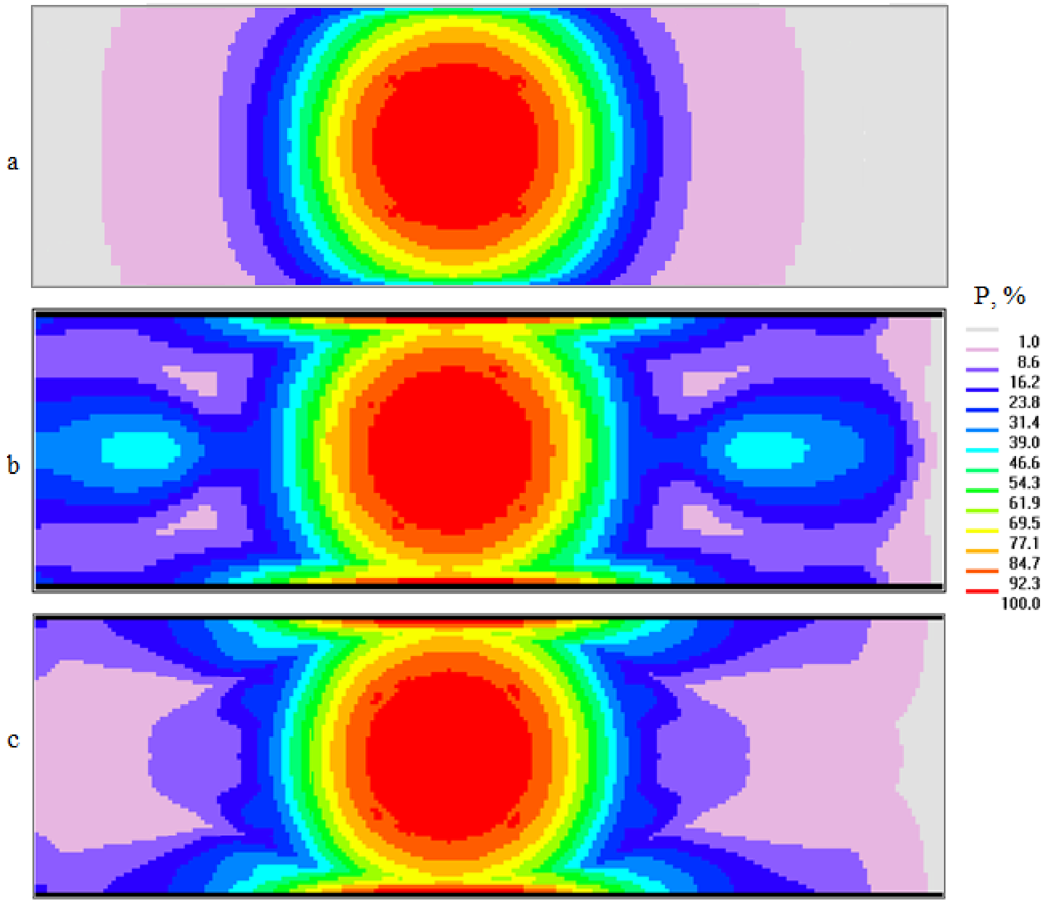


Figure 13. Eardrums rupture probability in plane XOZ for options V1 (a), V3 (b) and V5 (c)

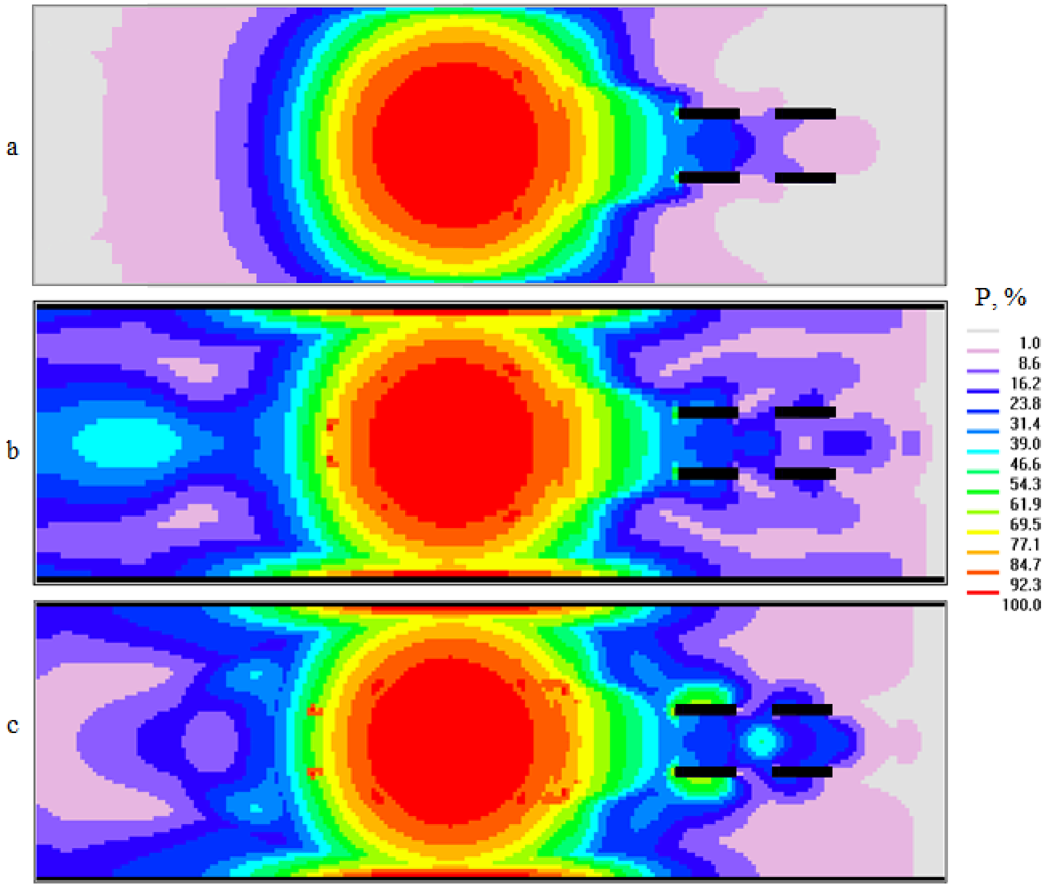


Figure 14. Eardrums rupture probability in plane XOZ for options V2 (a), V4 (b) and V6 (c)

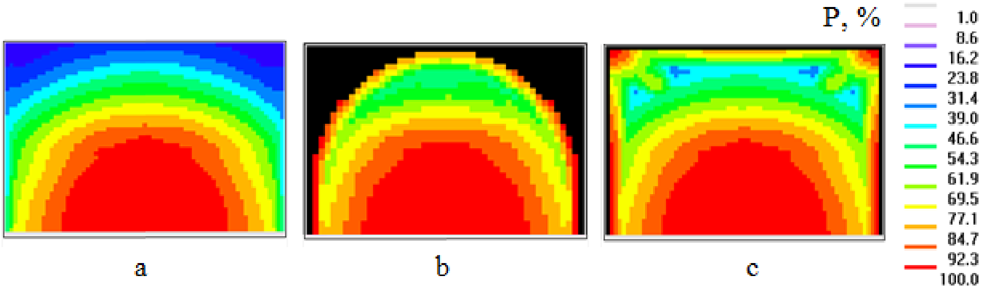


Fig. 15. Eardrums rupture probability in plane XOY for options V1 (a), V3 (b) and V5 (c)

Analysis of the spatial distribution of damage conditional probability in the computational domain (Fig. 11-15) makes it possible to visually trace the complication of the flow pattern caused by the presence of a drift walls (Fig. 11-15 b, c) as compared with open space (Fig. 11-15 a). Cluttering the working area with an electric locomotive leads to an additional pressure perturbation due to the reflection of the shock wave from the walls of the locomotive in plane YOZ (Fig. 12, a, b, c) and in plane XOZ (Fig. 15, a, b, c). Such an influence in plane XOY is insignificant (Fig. 15). Rectangular-ceiling tunnel has less shock-impulse loaded state in the mine drift without locomotive (Fig. 11, c and Fig. 13, c) and with locomotive (Fig. 12, c and Fig. 14, c) comparing with round-ceiling tunnel option without locomotive (Fig. 11, b and Fig. 13, b) and with locomotive (Fig. 12, b and Fig. 14, b) what can be explained by greater unloading due to the top of the tunnel (Fig. 15, b, c).

The presence of a drift walls increases the area S_{50} of dangerously high values (> 50%) of the conditional damage probability (Fig. 16) especially for the round ceiling tunnel option. the presence of an electric locomotive does not greatly change the value of this parameter, which may indicate a redistribution of this danger zone along the tunnel (Fig. 11, 12).

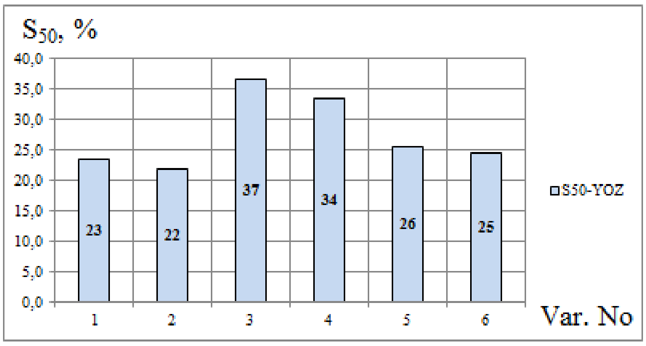


Figure 16. Danger zone relative area S_{50} in the plane YOZ

CONCLUSIONS

The paper presents a methodology for the probabilistic assessment of the damage of the coal mine service personnel located in the zone of an accidental release of a cloud of an explosive chemical substance (hydrogen) under conditions of open or closed (drift) coal mining. The methodology is based on a three-dimensional mathematical model of the explosion of a cloud of hydrogen-air gas mixture formed as a result of an accidental release of hydrogen from a crack in the foot of the mine drift.

The model allows obtaining fields of maximum overpressure and compression phase impulse of the explosion wave and using the probit-analysis procedure numerically estimate the conditional probability of damage to miners who are exposed to explosion wave shock-impulse loading as an indicator of the safety of an industrial object. The features of the formation of zones hazardous to human health and life and the influence of cluttering the drift area by an electric locomotive and the open / closed nature of the working space on their size and shape are revealed. The obtained results can be used by safety experts to develop measures to reduce the risk of such accidents at the mine and to analyze their effectiveness. Further improvement of this methodology is possible in the direction of considering a combination of emergency scenarios with various damaging factors (SW, toxic dose, thermal radiation).

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