EVALUATION OF THE PROTECTION EFFECTIVENESS AGAINST OVERPRESSURE FROM HYDROGEN-AIR EXPLOSION

Skob Y.A.[1], Ugryumov M.L.[1], Granovskiy E.A.[2]

[1] National Aerospace University "Kharkov Aviation Institute",17 Chkalov Street, Kharkov, 61070, Ukraine, yuriy.skob@gmail.com
[2] Scientific Center of Risk Investigations "Rizikon", 33-b Sovetsky prospect, (P.B. 44), Severodonetsk, Lugansk region, 93411, Ukraine, gran@rizikon.lg.ua

ABSTRACT

The aim of this study is to assess the probability of the damage to hydrogen fueling station personnel exposed to the hydrogen explosion shock wave. A three-dimensional mathematical model of the explosion of hydrogen-air cloud formed after the destruction of the high-pressure storage cylinders is developed. A computer technology how to define the personnel damage probability field on the basis of probit analysis of the generated shock wave is developed. To automate the process of computing the "probit function-damage probability" tabular dependence is replaced by a piecewise cubic spline. The results of calculations of overpressure fields, impulse loading, and the probability of damage to fueling station personnel exposed to the shock wave are obtained. The mathematical model takes into account the complex terrain and three-dimensional non-stationary nature of the shock wave propagation process. The model allows to obtain time-spatial distribution of damaging factors (overpressure in the shock wave front and the compression phase impulse) required to determine the three-dimensional non-stationary damage probability fields based on probit analysis. The developed computer technology allows to carry out an automated analysis of the safety situation at the fueling station and to conduct a comparative analysis of the effectiveness of different types of protective facilities

INTRODUCTION

The level of safety at the industrial enterprises which use hydrogen (such as fueling stations) depends on reliable operation of the equipment and efficient safety measures protecting the staff and surrounding buildings from the effects of emergencies that arise when malfunctions of equipment take place: hydrogen leaks of varying intensity on pipes joints, evaporation of the liquid hydrogen spilled from storage tanks, large-scale releases of compressed gaseous hydrogen from destroyed high-pressure vessels [1]. The most dangerous scenario of an emergency situation is an explosion of the hydrogen-air cloud generating a shock wave that spreads rapidly from the epicenter and has a negative impact on the environment. The major damaging factor in this case is the maximal overpressure in the shock wave front and impulse.

The effectiveness of protective measures is usually checked by field tests [2-4]. However, the unpredictable nature of the hydrogen (due to such properties as low density, high-energy combustion and rapid transition of deflagration to detonation) requires replacement of expensive physical experiments by computer simulations based on adequate mathematical models of the physical processes of the release, dispersion and explosion of hydrogen in the atmosphere [5-13]. Modern computer systems allow carrying out a three-dimensional analysis of gas-dynamic flow parameters in the computational domain, including the protective measures, and to forecast changes in pressure at typical control points in space and draw conclusions about the effectiveness of each protective device.

1.0 METHODS OF ASSESSING THE IMPACT CAUSED BY AN EXPLOSION WAVE

Technogenic accidents are usually accompanied by a sudden release or leakage of the hydrogen into the atmosphere, the formation of explosive hydrogen-air mixtures followed by their explosion and fire. As a result of such accidents the compression wave in the atmosphere is formed and propagated, the impact-pulse effect of explosion may cause a dangerous consequences to the personnel health state (Fig. 1).

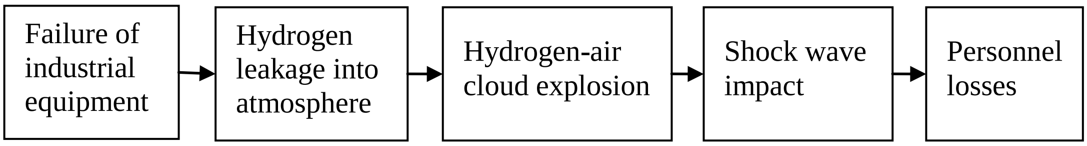


Figure 1. Development scheme of technogenic accident

In general a shock wave has a characteristic profile (Fig. 2) and is determined by the following parameters: τ_a – time of arrival; τ_+ – the duration of the positive phase; τ_- – duration of negative phase; ΔP_+ – overpressure; P_0 – atmosphere pressure; ΔP_- – underpressure of the rarefaction phase; I_+ – compression phase impulse; I_- – impulse of the rarefaction phase; ΔP_2 and τ_2 – secondary pressure rise and its duration.

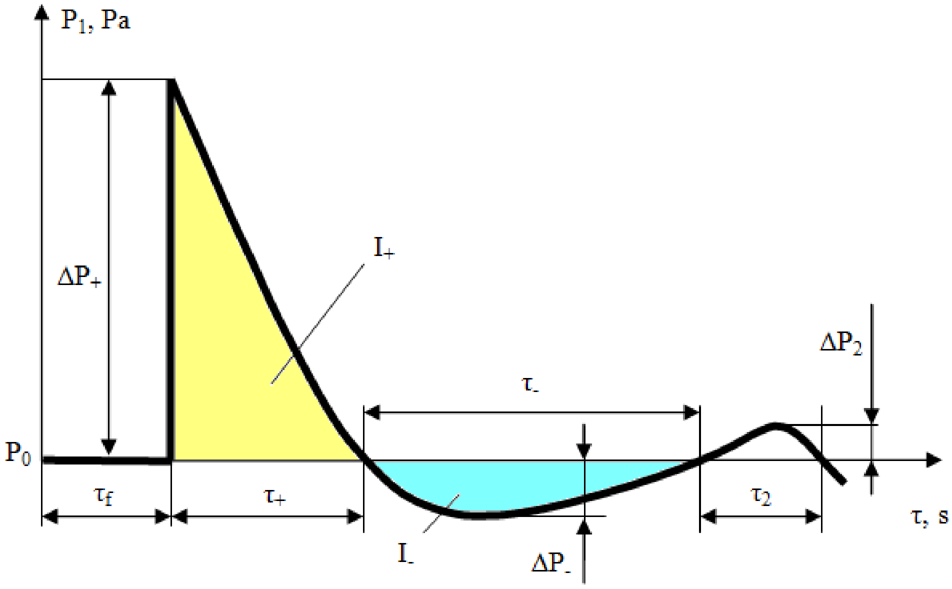


Figure 2. The typical profile of an explosion wave

In engineering practice the prediction of the consequences of the explosions is to determine the size of the zones of possible losses, the degree of human impact by one of the factors (excessive pressure or momentum) and the level of objects destruction. For this purpose, as a rule, one of two prediction methods is used: deterministic (simplified) or probabilistic.

With the deterministic method of forecasting, the damaging effect of the shock wave is determined by the overpressure ΔP_+ in the front of the shock wave. Comparison of overpressure with threshold values allows to determine the extent of human impact (table 1) [14].

Table 1. Overpressure thresholds.

ΔP_+, kPa	Less than 10	10…40	40…60	60…100	More than 100
Degree of impact on people	Safe overpressure	Light (bruises, hearing loss)	Average (bleeding, dislocation)	Heavy (concussion)	Lethal effect

However, a more complete probabilistic approach takes into account both pressure factors: the maximum overpressure ΔP_+ and momentum I_+ of the shock wave compression phase. Assessment of the risk of harmful impact to service personnel in case of an industrial accident is one of the main stages of the hazard analysis and assessment of the overall risk of functioning of a technogenic object (along with identification of hazardous facilities, research of operational hazards, assessment of the probability of an accident development). Risk assessment allows to draw conclusions about the acceptability of risk and assess the effectiveness of protection systems and personnel actions.

The risk for a specific scenario of an anthropogenic accident R depends on the statistical probability of the occurrence of the accident P_a and the simulated conditional probability P of human impact

$$R = P_a \cdot P. \quad (1)$$

As a result of numerical simulation of the hydrogen explosion it is possible to obtain the time and space distribution of the main damaging factors: the maximum overpressure in the front of the shock wave

$$\Delta P_+ = P_1 - P_0, \quad (2)$$

where ΔP_+, P_1, P_0, Pa – maximum overpressure, current and atmospheric pressure at a given point in space and impulse I_+ – momentum of the shock wave compression phase, Pa·s:

$$I_+ = \int_{\tau_a}^{\tau_a+\tau_+} \Delta P \, dt, \quad (3)$$

where τ_a, τ_+, s – start time and length of the shock wave compression phase.

On the base of these functions the probit functions for the damaging shock wave factors and the conditional probability of damages [15] as the main characteristics of the negative impact of the shock wave on the operating personnel.

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

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{Pr}} e^{-\frac{1}{2}(t-5)^2} dt, \quad (4)$$

where t – integral degree of impact.

For example, the probability of human health lethal damage caused by overpressure can be estimated by the following ratio [16]:

$$\mathrm{Pr}_1 = 5 - 0,26 \ln\left[\left(17500/\Delta P_+\right)^{8,4} + \left(290/I_+\right)^{9,3} \right]. \quad (5)$$

The probit-function for rupturing human eardrums depends on the level of overpressure and can be found by the formula [17, 18]

$$\mathrm{Pr}_2 = -15,6 + 1,93 \ln \Delta P_+. \quad (6)$$

Usually experts use the table of discrete values of the definite integral (4) visually evaluating the probability of the impact on the base of the value of the probit-function (table 2).

To automate the computational process the table is replaced by a generalized piecewise cubic Hermitian spline [19]. This spline has characteristics that allow eliminating the oscillations of the approximated function in the gaps (Fig. 3).

Table 2. Tabular dependence of probability on probit function.

P, %	0	1	2	3	4	5	6	7	8	9
0		2,67	2,95	3,12	3,25	3,38	3,45	3,52	3,59	3,66
10	3,72	3,77	3,82	3,86	3,92	3,96	4,01	4,05	4,08	4,12
20	4,16	4,19	4,23	4,26	4,29	4,33	4,36	4,39	4,42	4,45
30	4,48	4,50	4,53	4,56	4,59	4,61	4,64	4,67	4,69	4,72
40	4,75	4,77	4,80	4,82	4,85	4,87	4,90	4,92	4,95	4,97
50	5,00	5,03	5,05	5,08	5,10	5,13	5,15	5,18	5,20	5,23
60	5,25	5,28	5,31	5,33	5,36	5,39	5,41	5,44	5,47	5,50
70	5,52	5,55	5,58	5,61	5,64	5,67	5,71	5,74	5,77	5,81
80	5,84	5,88	5,92	5,95	5,99	6,04	6,08	6,13	6,18	6,23
90	6,28	6,34	6,41	6,48	6,55	6,64	6,75	6,88	7,05	7,33
99	7,33	7,37	7,41	7,46	7,51	7,58	7,65	7,75	7,88	8,09

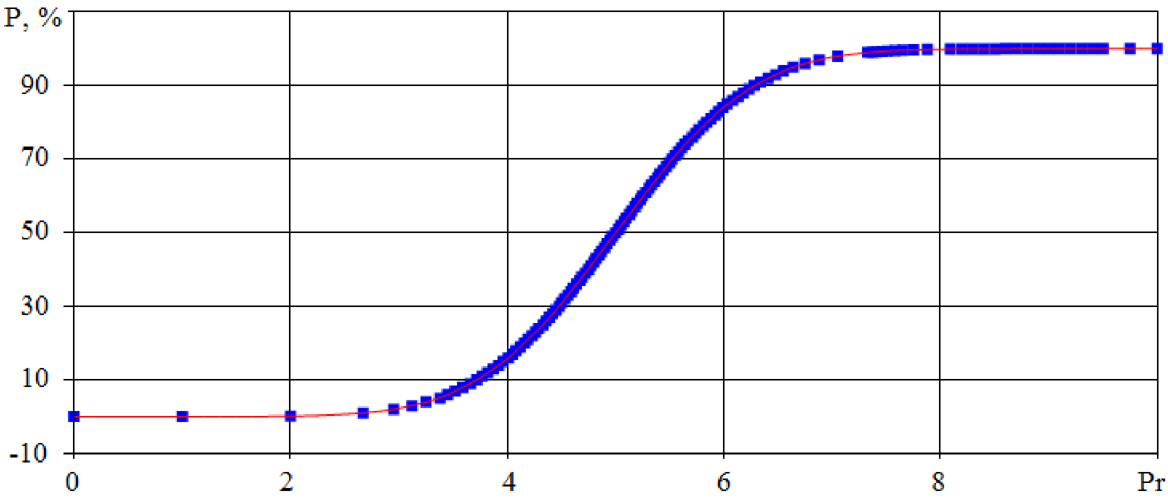


Figure 3. Interpolating tabular dependency of probability on probit-function

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 [10-12]. 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) [11].

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 threecomponent mixture (air, combustion products and residues of fuel). In other words, it is assumed that the flame front propagates with infinite velocity [12].

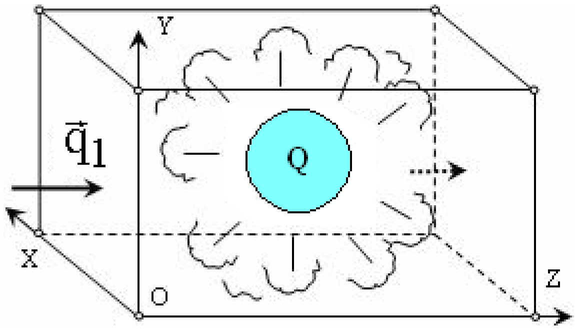


Figure 4. A computer model of the hydrogen-air cloud explosion

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 [20]. 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 [13].

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 effectiveness of protective measures the computer system «Fire» [21] is used.

3.0 CALCULATION OF HYDROGEN CLOUD EXPLOSION

A typical station to refuel hydrogen vehicles [1] is considered. The station contains a cryogenic storage tank of liquid hydrogen (5.7 m^3) which supplies high-pressure (6500 psi ≈ 44.8 MPa) cylinders dispensing compressed gas hydrogen. The volume of each cylinder is about 0.51 m^3.

Assume that three of the high-pressure dispensing cylinders is instantly destroyed, resulting in the release of compressed hydrogen into the atmosphere near the ground, expansion of it to atmospheric pressure and formation of a hemispherical stoichiometric hydrogen-air cloud with radius of about 2,88 m and ambient temperature 293 K (Fig. 5). Consider an instantaneous explosion of this hydrogen cloud that causes the formation in the control volume of the combustion products with the following parameters: temperature 3450 K, pressure 901 kPa, molar mass 0.02441 kg/mol and adiabatic coefficient 1.24.

The computation space has the following dimensions: the length – 31 m; the width – 20 m, the height – 14 m (including the ground 2 m deep). All sides of the computational cells have the same size – 0.2 m, so the computational grid has 155 x 100 x 70 cells respectively. The time step is calculated in order to keep the stability of explicit finite-difference Godunov method.

To analyze the effectiveness of protective measures the excessive pressure is controlled, similar to [5, 7, 12, and 13], in several critical points near the ground: P0 – in close proximity to a protection structure, P1 and P2 – at some distances from it (Fig. 5). In order to increase the level of safety at the control points P0 and P1 (human locations), several protective devices were considered (table 1).

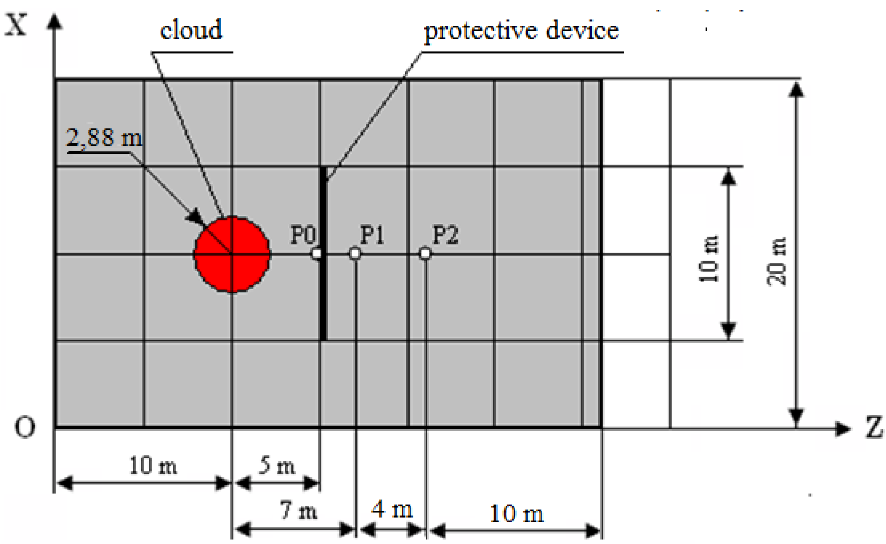
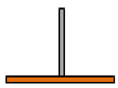
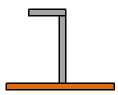
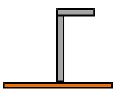
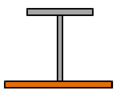
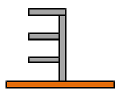
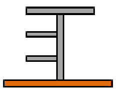
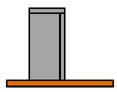
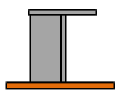
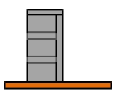
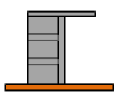
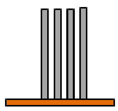


Figure 5. Layout of hydrogen cloud, protection structure and control points

Variant Case-0 does not contain a protective device. A solid wall 0,2 m thick, 10 m long and 2,2 m high is the Case-1 variant. Variants Case-2, Case-3 and Case-4 in contrast to Case-1 contain different types of top visor. Variants of the Case-5 and Case-6 devices are the development of variants of Case-2 and Case-4. Both are complemented by two horizontal internal visors. Variants of the Case-7, Case-8, Case-9 and Case-10 devices are the development of variants of Case-2, Case-4, Case-5 and Case-6. All of them are supplemented by seven vertical ribs with a thickness of 0.2 m. The Case-11 device is a package of four rows of vertical 23 columns with a height of 3 m and a square section of 0.2 x 0.2 m [22].

Table 3. Variants of protective devices.

№ of device	Device	№ of device	Device	№ of device	Device
Case-0		Case-1		Case-2	
Case-3		Case-4		Case-5	
Case-6		Case-7		Case-8	
Case-9		Case-10		Case-11	

3.1 Hydrogen explosion without protective equipment

Lack of protective devices (Case 0) corresponds to the most pessimistic accident scenario (Fig. 6) when the control points are openely exposed to the influence of the explosion wave in comparison to variant of solid wall (Case-1) (Fig. 7-9) as well as to any other protection option. The resulting shock wave is rapidly spreading along the computational domain losing its intensity with the distance from the epicenter of a hydrogen-air explosion. Naturally, the maximum overpressure is at the control point P0 and the minimum is at the point P2, the farthest from the blast epicenter. In the Case-1 of protective device the presence of the obstacle (wall) between the explosion epicenter and operational staff causes the generation of pressure cumulative effect (Fig. 7) in front of the wall and accordingly increases the probability of harmful impact (Fig. 8, 9) on the human.

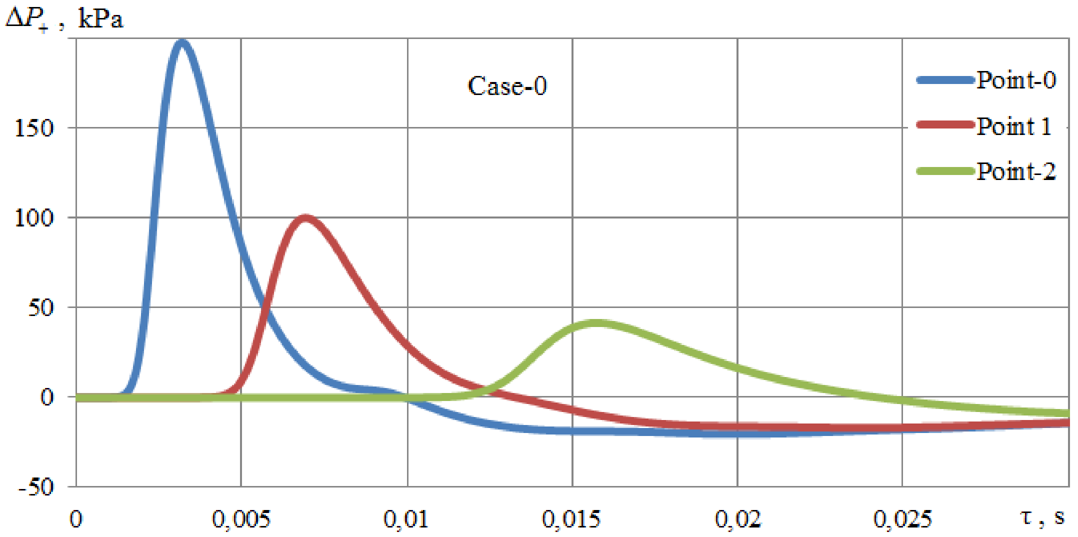


Figure 6. Overpressure history in the control points P0, P1, P2 without protection

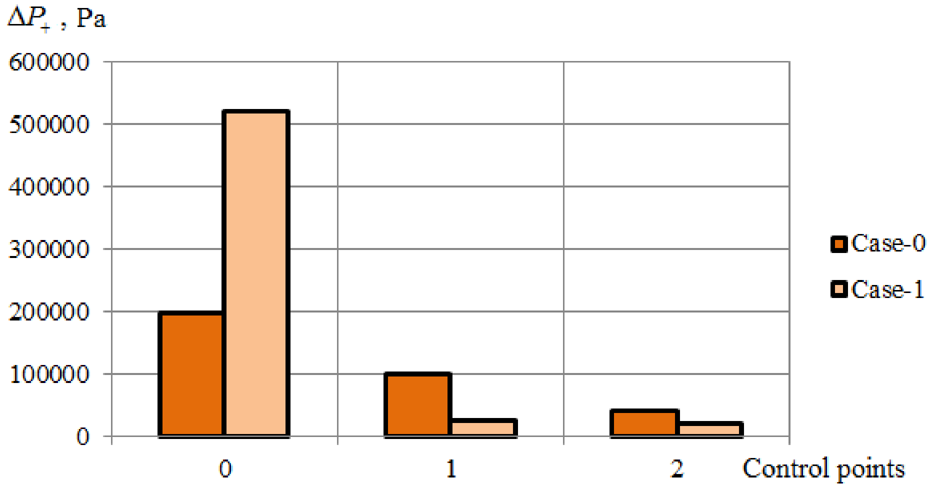


Figure 7. Overpressure in the control points without protection and with the wall

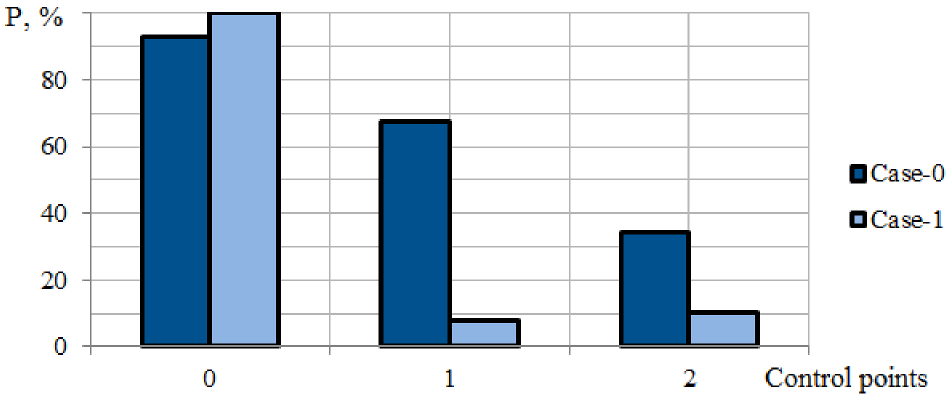


Figure 8. The conditional probability of lethal damage (5) caused by the shock wave overpressure

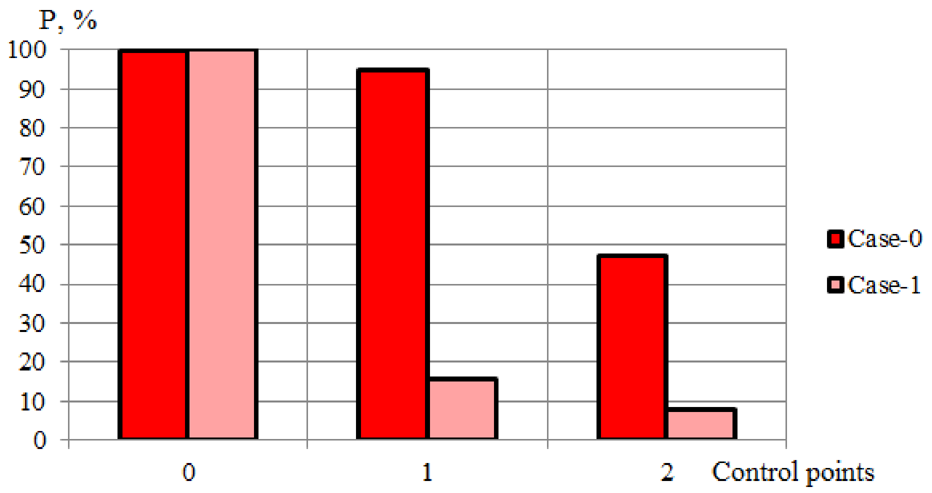


Figure 9. Conditional probability of eardrums rupture (6) caused by overpressure in the control points without protection (case 0) and with the wall (case 1)

3.2 Use of the protection devices

Installation of any type of protection devices, for example solid concrete wall, leads to a substantial rebuilding of the flow (Fig. 10, 11).

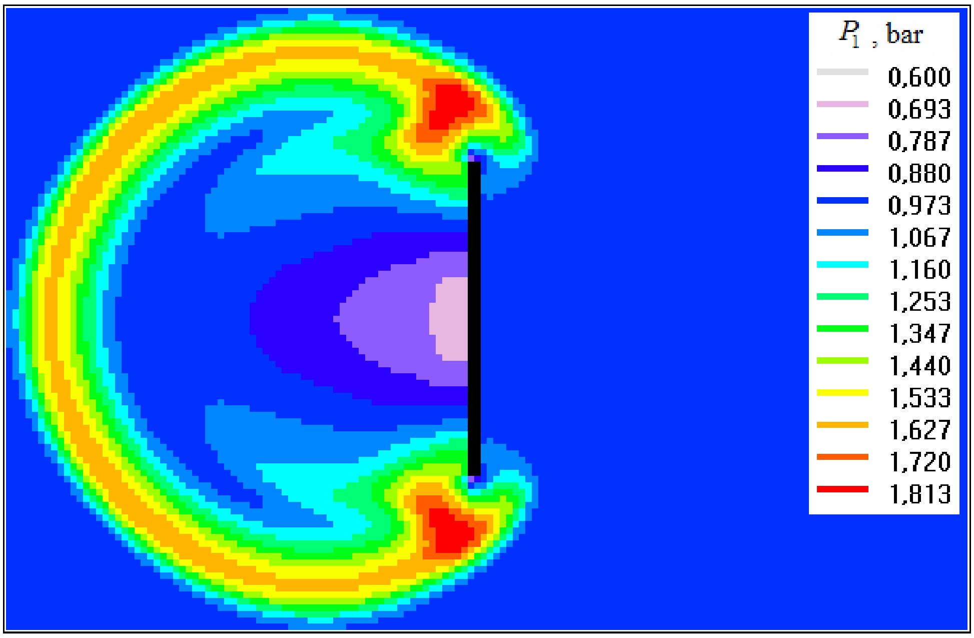


Figure 10. Pressure distribution near the ground (case 4) at 0.0107 s

Respectively, the overpressure in front of the device at point P0 is substantially increased due to cumulative effect but decreased at the points P1 and P2 (locations where the personnel may present) (Fig. 7).

According to [7], any type of the wall causes an expansion of the flow on the edges that positively affects overpressure rates at the control points P1 and P2 (Fig. 11). This effect is reflected in the distribution of the probability of harmful effects (Fig. 12, 13).

Naturally, in the Case-11 the values of overpressure (Fig. 14, 15) in the control points P1 and P2 and damage probability (Fig. 16, 17) are much less than in the any other protective options.

Figure 11. Pressure distribution in vertical section (case 4) at 0.0107 s

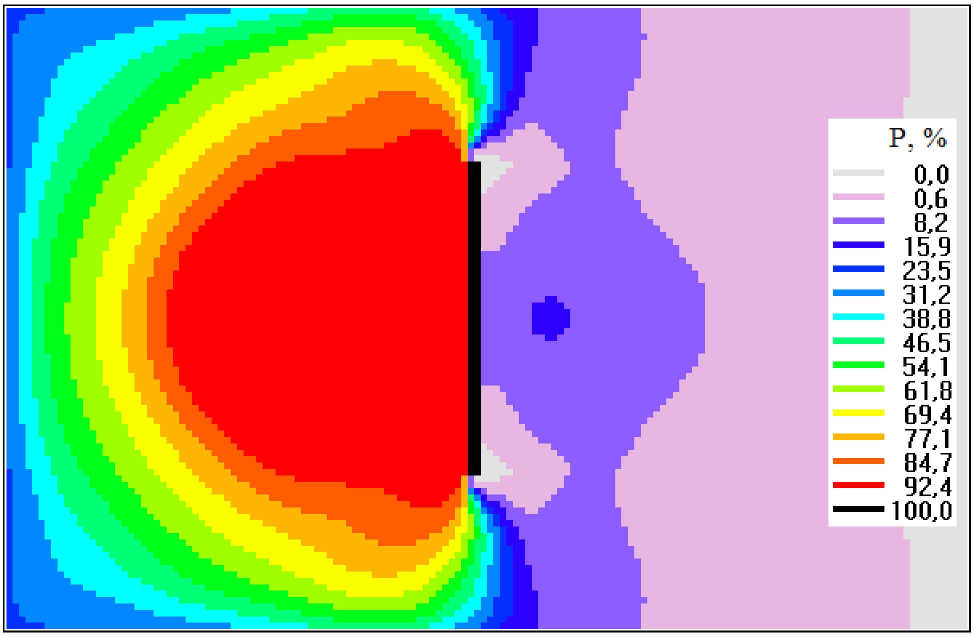


Figure 12. Damage probability (5) caused by the shock wave near the ground (case 4)

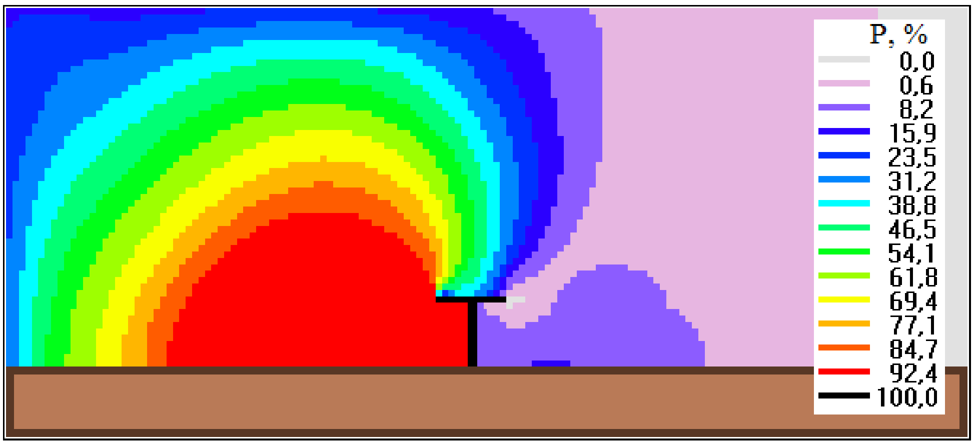


Figure 13. Damage probability (5) caused by the shock wave near the ground (case 4)

Thus, the developed computing technology of probit analysis based on three-dimensional modeling of shock wave propagation in the atmosphere makes it possible to evaluate the effectiveness of protective devices and construct fields of conditional probability of negative impact on a person.

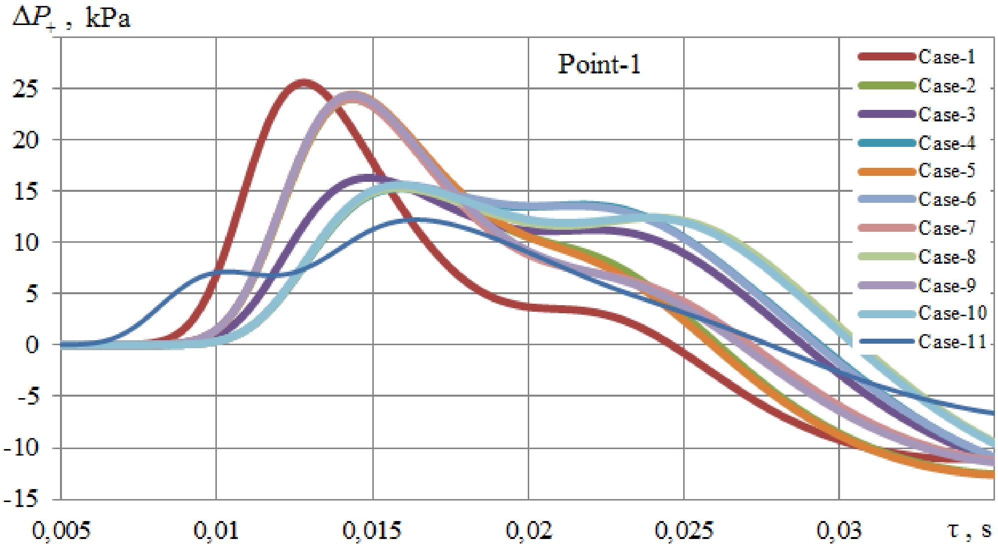


Figure 14. Overpressure history in the control point P1

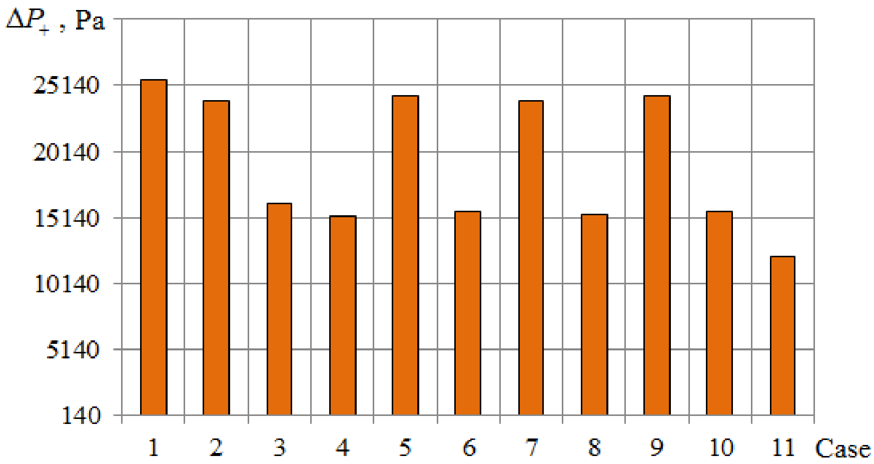


Figure 15. Overpressure in the control point P1 for different protection cases

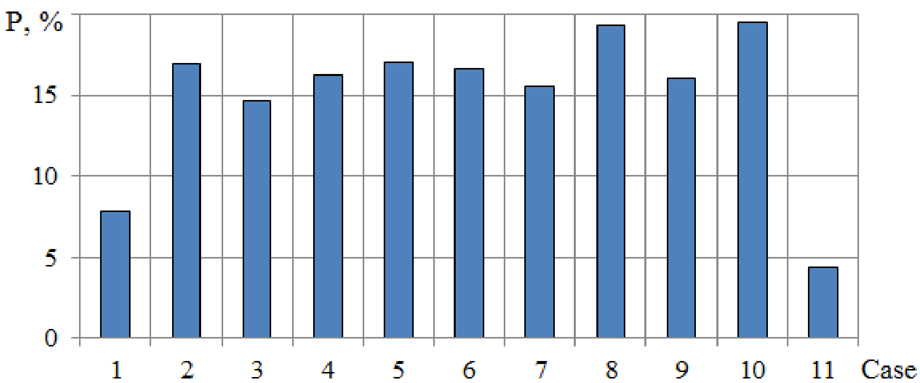


Figure 16. Conditional damage probability (5) in the control point P1
for different protection cases

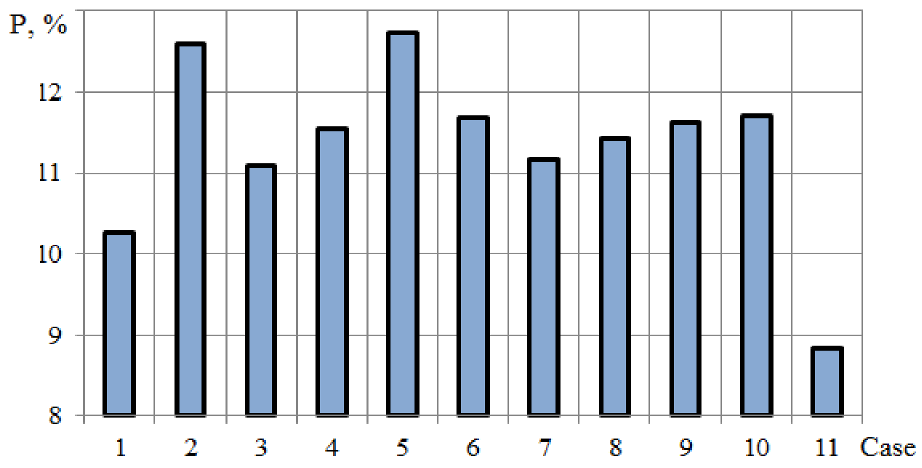


Figure17. Conditional damage probability (5) in the control point P2
for different protection cases

CONCLUSIONS

The physical processes of the explosion of the hemispherical hydrogen cloud formed as a result of the instantaneous destruction of the high-pressure dispensing cylinders in the fueling station are investigated. A three-dimensional model of instantaneous explosion of the hydrogen-air mixture based on the Euler equations solved by Godunov method is used. A comparative analysis of the effectiveness of different safety measures that protect surrounding environment from the shock wave overpressure effects is carried out. Based on overpressure control and conditional damage probability at critical points and comparative analysis of three-dimensional distribution of the maximum excessive pressure and impulse in the computational domain it can be concluded that the most effective protection construction is the obstacle in the form of package of staggered solid columns. Use of such protective measures may improve the safety level of the fueling station operations.

REFERENCES

1. Safety and Security Analysis: Investigative Report by NASA on Proposed EPA Hydrogen-Powered Vehicle Fueling Station. Assessment and Standards Division Office of Transportation and Air Quality U.S. Environment Protection Agency, EPA420-R-04-016 October 2004. – 45 p.
2. Large Scale Experiments: Deflagration and Deflagration to Detonation within a partial Confinement similar to a lane / Schneider, H. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 120018)
3. Experimental study on hydrogen explosions in a full-scale hydrogen filling station model / Tanaka, T., Azuma, T., Evans, J.A., Cronin, P.M., Johnson, D.M., Cleaver, R.P. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 120036)
4. Hydrogen detection: visualization of hydrogen using noninvasive optical schlieren technique BOS / Keβler, A., Ehrhardt, W., Langer, G. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 110127)
5. An Intercomparison Exercise on the Capabilities of CFD Models to Predict Deflagration of a Large-Scale H2-Air Mixture in Open Atmosphere / E. Gallego, J. Garcia, E. Migoya, A. Crespo, A. Kotchourko, J. Yanez, A. Beccantini, O.R. Hansen, D.Baraldi, S. Hoiset, M.M. Voort, V. Molkov // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 120003)
6. Analysis methodology for hydrogen behaviour in accident scenarios / Breitung W. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 120009)

7. Numerical Simulation of Hydrogen Explosion Tests with a Barier Wall for Blast Mitigation / Nozu, T., Tanaka, R., Ogawa, T., Hibi, K., Sakai, Y. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 130028)
8. Phenomena of Dispersion and Explosion of High Pressurized Hydrogen / Takeno, K., Okabayashi, K., Ichinose, T., Kouchi, A., Nonaka, T., Hashiguchi, K. and Chitose, K. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 100044)
9. Evaluation of safety distances related to unconfined hydrogen explosions / Dorofeev, S.B. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 100129)
10. Validation of FLACS-hydrogen CFD consequence prediction model against large scale H2 explosion experiments in the flame facility / Hansen, O.R., Renoult, J., Sherman, M.P., Tieszen, S.R. // CD–ROM Proceedings the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. (ICHS Paper No. 120075)
11. Numerical Modeling of Hydrogen Release, Mixture and Dispersion in Atmosphere / E.A. Granovskiy, V. A. Lyfar, Yu. A. Skob, M. L. Ugryumov // Abstracts Book and CD–ROM Proceedings of the International Conference on Hydrogen Safety. – Pisa (Italy). – 2005. – 10 p. (ICHS Paper No. 110021)
12. Computational Modeling of Pressure Effects from Hydrogen Deflagrations / E.A. Granovskiy, V.A. Lyfar, Yu.A. Skob, M.L. Ugryumov // Abstracts Book and CD–ROM Proceedings of the 2-nd International Conference on Hydrogen Safety. – San Sebastian (Spain). – 2007. – 15 p. (ICHS Paper No. 1.3.52)
13. Numerical Modeling of Hydrogen Deflagration Dynamics in Enclosed Space / Yu.A. Skob, M.L. Ugryumov, K.P. Korobchynskiy, V.V. Shentsov, E.A. Granovskiy, V.A. Lyfar // Abstracts Book and CD–ROM Proceedings of the 3-nd International Conference on Hydrogen Safety. – Ajaccio-Corsica (France). – 2009. – 12 p. (ICHS Paper No. ID 182)
14. Trushkin, V. P., Andreev, A. I. Protection of the population in peacetime emergency situations: textbook. Khabarovsk: Far Eastern State Transport University, 2010. – 96 p. (in Russian)
15. Methodology for assessing the consequences of accidental explosions of fuel and air mixtures ("Toksi"). Collection of documents. Vol. 27., No. 2. – M.: Scientific and Technical Center "Industrial Safety", 2010. – 208 p. (in Russian)
16. Definition of categories of premises, buildings and external installations for explosion and fire hazard : Norms of fire safety – Moscow: Federal State Institution "All-Russian Scientific Research Institute of Fire Protection" of Emergency Situations Ministry of Russia, 2003. – 400 p. (in Russian)
17. Methods for the determination of possible damage. Green book / CPR 16E, 1989.
18. Pietersen, C.M.. Consequences of accidental releases of hazardous material (in J. Loss Prev. Process Ind., 1990, Vol. 3, January
19. Chernyshev, Ju. K. Vypuklye vektornye splajny v primenenii k profilirovaniju lopatok GTD [The convex splines vector applied to the profiling blade]. Kharkiv, Aerospace technic and technology, 2000, no. 21, pp. 16-18. (in Russian)
20. Numerical solution of multidimensional problems of gas dynamics / S. K. Godunov, A. V. Zabrodin, M. Ya. Ivanov, A. N. Krayko, G. P. Prokopov. – Moscow.: Science, 1976. – 400 p. (in Russian)
21. Korobchynskyi, K.P. Skob, Y.A. and Ugryumov, M.L. (2009), “The computer program "Computer interactive system of engineering analysis and forecasting of movement of chemically reacting gas mixture in the problems of industrial aerodynamics and ecology of atmosphere ”FIRE””, Official bulletin of copyrights, no. 19, p. 488.
22. Skob, Yu.A. Effectiveness evaluation of facilities protecting from hydrogen-air explosion overpressure / Yu.A. Skob, M.L. Ugryumov, E.A. Granovskiy, V.A. Lyfar // Abstracts Book and CD–ROM Proceedings of the 4 International Conference on Hydrogen Safety “Enabling Progress and Opportunities”. – San Francisco, California-USA. – 2011. – 10 p. (ICHS Paper No. ID 179)