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Numerical Evaluation of Safety Wall Bending Strength during Hydrogen Explosion

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Abstract. The main aims of this study are to assess numerically the stress state of a solid wall which is installed at the hydrogen fueling station in order to protect personnel from the consequences of the accidental hydrogen explosion, define the bending stress values in the foot of the wall exposed to explosion wave pressure forces and located at different distances from explosion epicenter in order to choose appropriate construction material of the wall and assess the minimum thickness of the wall satisfying bending strength condition. A three-dimensional mathematical model of hydrogen-air mixture explosion is used to define the distribution of the maximum overpressure on the wall surface. To assess the bending stress state at the foot of the wall, the design scheme of a cantilever beam is considered. It is assumed that the maximum overpressure force field influences the wall at the same time to assess the worst possible scenario. Actually, the computer-based methodology of how to resolve a coupled problem of explosion gas dynamics and defense wall strength is suggested. This technique allows evaluating of the construction parameters of the wall, which protects the personnel against consequences of the explosion wave exposure, without the destruction of the wall.

Introduction

Safety is a complex interdisciplinary and cross-sectoral phenomenon. Consequently, ensuring safety in all spheres of public relations is essential for the state of protection of vital interests of the individual, the state, and society as a whole [1]. That is why, ecological issues, technical conditions, and means of ensuring safety are especially important on industrial objects in which explosive, and toxic substances are stored and used.

Intensification of hydrogen use in transport requires the installation of a huge amount of fueling stations across the European continent. Taking into account that hydrogen is so dangerously explosive gas, it is required to keep high safety level at fueling stations during the equipment operation, and properly installing reliable protective devices such as safety walls which have to be one of the efficient measures defending fueling station personnel and surrounding environment from dangerous consequences of accidentally released hydrogen explosions [2] (Fig. 1).

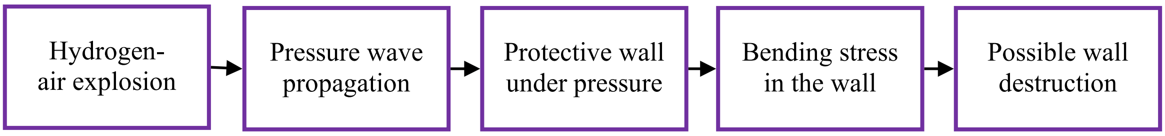


Fig. 1. A development scheme of the "wall-explosion wave" interaction.

Typically, the results of experimental studies [3] or modeling by means of narrowly specialized complexes, such as LIRA [4] or ANSYS [5], are used to assess the stress state of structural elements. During the non-accidental condition at the site the protective structures are only under the influence of climatic factors [6], while during the explosion high thermal load is added [7], which can significantly change the strength characteristics of the structural materials [8], moreover, shock-impulse impact [9] can quickly lead to the destruction of the structure. The effectiveness of the protective wall depends on not only the proper dimensions and location of the installment [10] but the construction material of the wall that has to be resistant to bending stress in the foot of the wall under the explosion overpressure forces impact. It can be reached by resolving the coupled problem of hydrogen-air mixture explosion gas dynamics and wall bending strength condition satisfaction. Experimental measuring of the overpressure on the wall surface [11] can be considered as a good way to validate mathematical models because only using adequate mathematical models of the physical processes of gas admixture release, dispersion [12], and explosion [13] in the atmosphere can give the opportunity to obtain all the detailed information of chemical, overpressure, and thermal disturbances of the airflow at the fueling station and make conclusions about effectiveness and strength resistance of the protective devices.

Evaluation of the Wall Bending Stress

As a result of the accidental explosion of hydrogen at the fueling station, the explosion wave is formed and propagated trying to bend the wall at the foot section (Fig. 2).

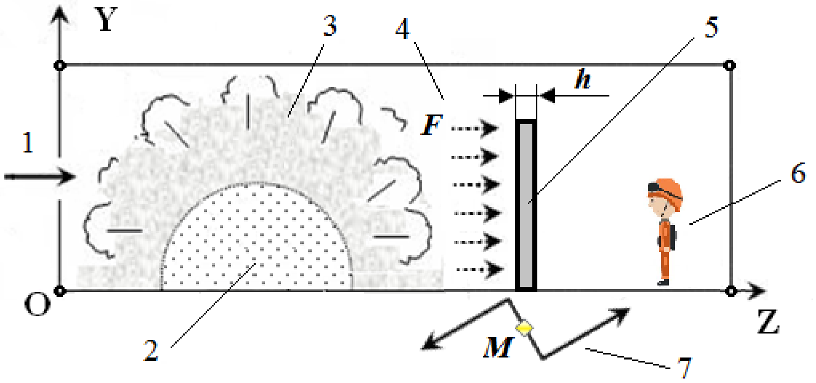


Fig. 2. Wall bending stress evaluation scheme: 1 – air; 2 – hydrogen-air mixture; 3 – explosion products; 4 – overpressure forces; 5 – wall; 6 – personnel; 7 – bending stress momentum

Extracting from the mathematical model maximum overpressure field on the wall surface, it can be evaluated the field of the discrete overpressure forces *F*, and an overall momentum effort *M* to bend the wall at its foot, consequently. A cantilever beam scheme is considered. It is known from the materials stress theory that the minimum required design moment of resistance *W* of the wall foot section can be found from this formula

$$W = \frac{bh^2}{6} \geq \frac{M}{[\sigma]}, \tag{1}$$

where *b* is a width, *h* is a thickness of the wall, and σ is acceptable bending stress for the wall construction material (Table 1).

From formula (1) it is followed that the depth of the wall *h* has to be greater than this minimum value to satisfy the bending strength condition

$$h \geq \sqrt{\frac{6W}{b}}. \tag{2}$$

At different locations relative to the epicenter of the explosion the wall is exposed to different bending momentum stress and can be constructed with different thicknesses.

Table 1. Acceptable bending stress values for different wall materials.

Type number	Material designation	Wall material	Acceptable bending stress, [MPa]
1	M1	Gray cast iron GG 15 (DIN)	35
2	M2	Nylon	40
3	M3	Fiberglass	48
4	M4	Textolite	65
5	M5	Bronze	100
6	M6	Duralumin	130
7	M7	Steel 28Mn6 (DIN)	160
8	M8	Alloy steel 5145 (ASME)	290

Explosion Mathematical Model and Calculation Algorithm

In order to evaluate the effectiveness of an overpressure protective wall, it is used a mathematical model of an instantaneous explosion of hydrogen-air mixture [14]. 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 without viscous terms in the mixture motion equations (Euler approach with sources).

Calculation of Hydrogen Cloud Explosion

An explosion of the hemispherical stoichiometric hydrogen-air cloud with a radius of 1.5 m and ambient temperature 293 K is considered [10]. Some options of the wall location with different distances Z_w relative to the epicenter of the explosion (Table 2).

Table 2. Options of the wall location

Option number	V1	V2	V3	V4	V5
Z_w [m]	4.0	5.0	6.0	7.0	8.0

The combustion products with temperature 3450 K, pressure 901 kPa, molar mass 0.02441 kg/mol and adiabatic coefficient 1.24 generate an explosion wave which creates the maximum overpressure field on the surface of the wall with the length 10.0 m, width 0.2 m, and height 2.2 m (Fig. 3). It is assumed here that the explosion wave has an instant maximum impact at the same time instantly, which corresponds to the worst scenario of maximum loading.

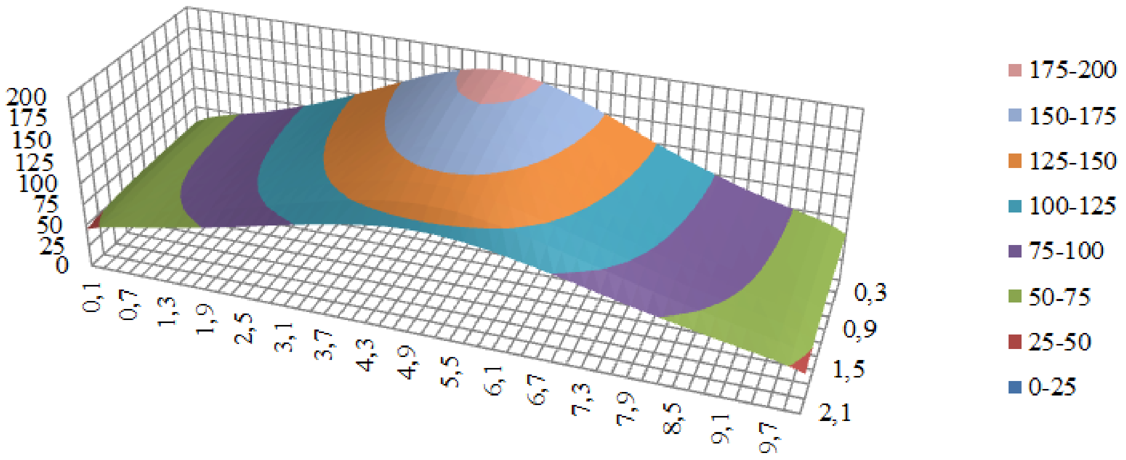


Fig. 3. Overpressure (kPa) distribution on the wall surface (option V1)

It is clear that with a more distantly located wall the influence of the explosion wave is weaker and the overpressure on the wall surface is less tense. It is followed by less intense overpressure force distribution, and corresponding discrete bending momentum field. Respectively, total bending momentum stress values decrease with a distance from the explosion epicenter. It is reflected on the values of the minimum required moment of resistance (1) of the stressed foot section of the bent wall, and, finally, on the values of the minimum safe thickness of the wall (2).

The overpressure field (Fig. 3) makes the pressure force distribution on the wall surface for mostly exposed option V1 (Fig. 4).

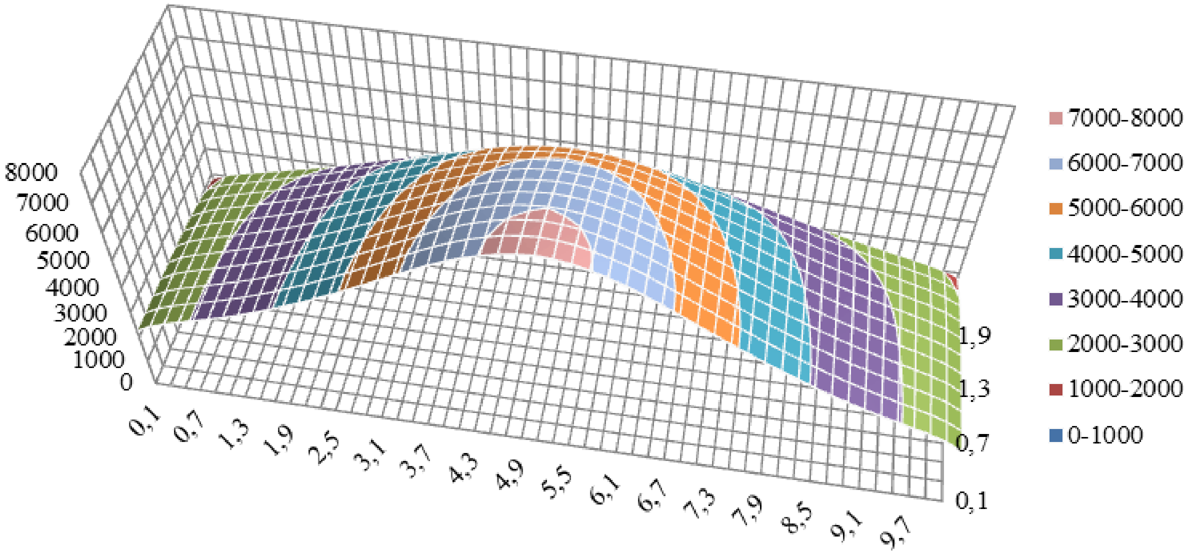


Fig. 4. Pressure force (N) distribution on the wall surface (option V1)

The discrete overpressure forces (Fig. 4) bend the wall in the foot cross-section creating the bending momentum distribution on the wall surface (Fig. 5). Middle wall distribution for all options shows the difference of loading (Fig. 6).

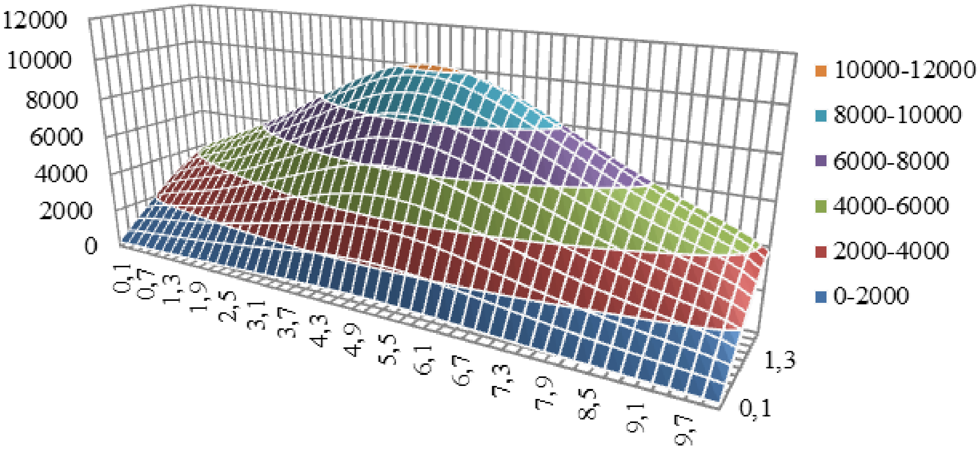
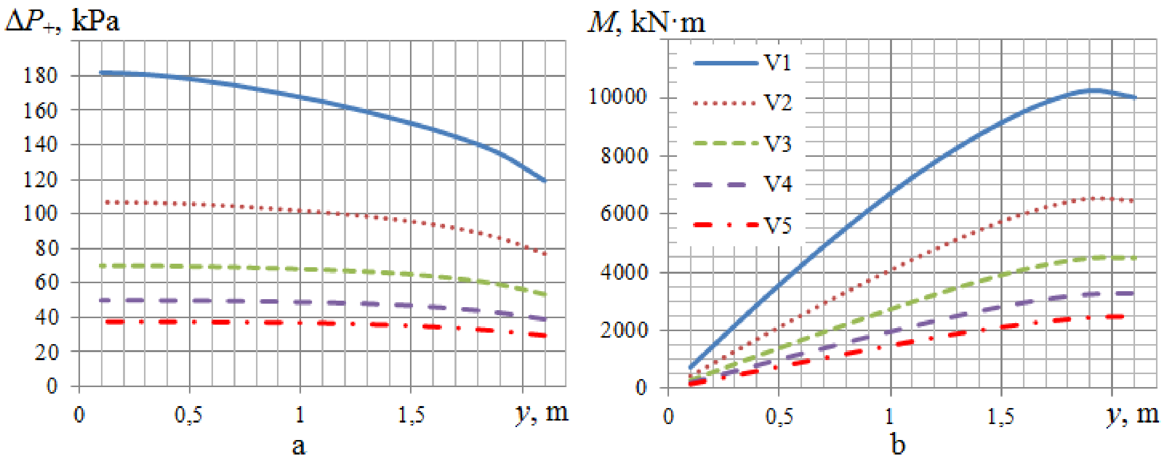


Fig. 5. Bending momentum (kN·m) distribution on the wall surface (option V1)

The sum of all wall surface discrete momentums gives the value of the total bending momentum on the wall surface for each option of the wall location relative to the epicenter of the hydrogen explosion (Fig. 7).

Using the formula (1) and acceptable bending stress values for different wall materials M1-M8 (Table 1), the minimum required moments of resistance of the foot section of the wall with different wall locations can be calculated (Fig. 8).

And finally, using the formula (2), the minimum safe thickness of the bent wall made of different materials M1-M8 for different wall locations V1-V5 can be evaluated (Fig. 9).



a

b

Fig. 6. Overpressure (a) and momentum (b) distribution in the middle of the wall (option V1)

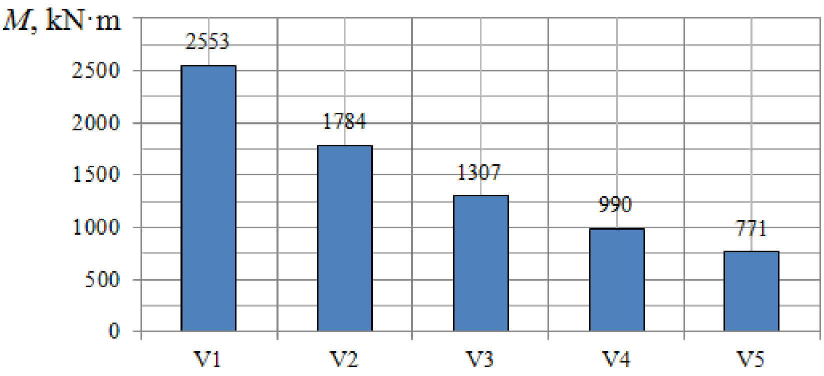


Fig. 7. Total bending momentum on the wall surface (options V1-V5)

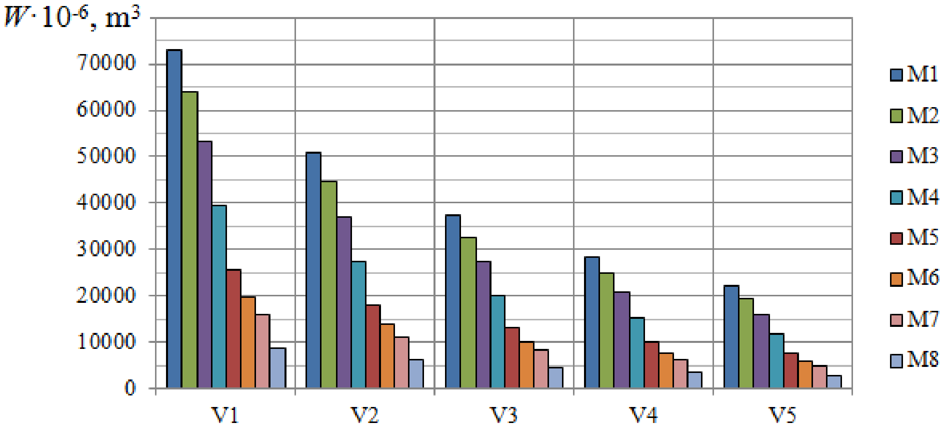


Fig. 8. Minimum required moment of resistance (m^3) of the foot section of the wall made of different materials M1-M8 for different wall location (V1-V5)

Results Discussion

Overpressure (Fig. 3) and pressure force (Fig. 4) distributions on the wall surface reveals the main features of wall bending loading from hydrogen explosion (Fig. 5): the bending loading depends not only on the value of the overpressure force, which is greater in the bottom center place on the wall (Fig. 6, a), but from the radius of the momentum (Fig. 6, b). That is why the distribution of the bending momentum is not so plain (Fig. 5). All in all, the closer the wall to the explosion epicenter the greater value of the total bending momentum (Fig. 8), and not only the distance from the explosion, but the type of the wall material can define the minimum required moment of resistance (Fig. 9) of the foot section of the wall, and provide the required information about the minimum safe thickness (Fig. 10) of the wall made of different materials and located differently.

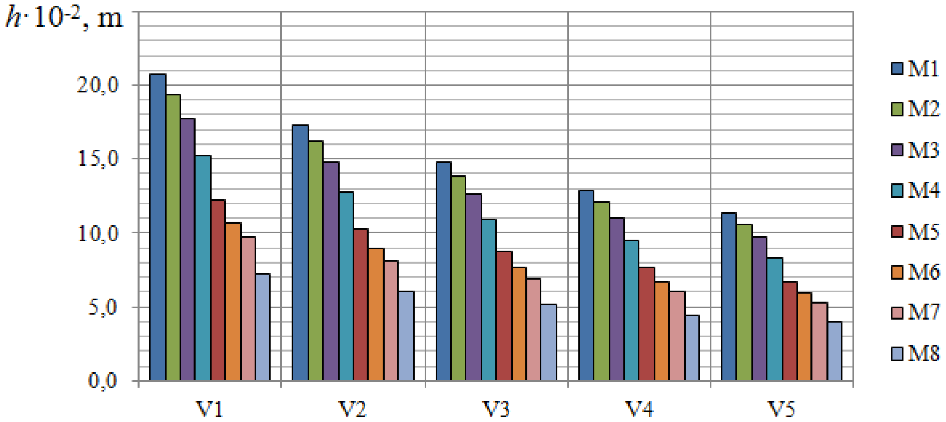


Fig. 9. Minimum safe thickness (m) of the wall made of different materials M1-M8 for different wall locations (V1-V5)

Summary

An explosion of accidentally released hydrogen at the fueling station is numerically evaluated. A three-dimensional mathematical model of instantaneous gas mixture explosion based on the Euler equations solved by the Godunov method is used to obtain the maximum overpressure distribution on the protection wall installed at different distances from an explosion epicenter in order to choose appropriate construction material of the wall and assess the minimum thickness of the wall satisfying bending strength condition. The bending stress state in the foot of the wall is assessed using a cantilever beam calculated scheme under the assumption that maximum overpressure force field influences the wall at the same time to assess the worst possible scenario. The developed methodology resolves a coupled problem of explosion gas dynamics and defense wall strength and allows evaluating the construction parameters of the protection wall keeping on the personnel safe, and the wall without destruction.

References

[1] Y. Dreval, V. Loboichenko, A. Malko, A. Morozov, S. Zaika, V. Kis. The Problem of Comprehensive Analysis of Organic Agriculture as a Factor of Environmental Safety, J. Environ. Clim. Technol. 24 (2020) 58–71.

[2] 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.

[3] A. Kovalov, Y. Otrosh, O. Ostroverkh, O. Hrushovinchuk, O. Savchenko. Fire resistance evaluation of reinforced concrete floors with fire-retardant coating by calculation and experimental method. E3S Web of Conferences. 60, 00003 (2018). https://doi.org/10.1051/e3sconf/20186000003.

[4] Y. Otrosh, A. Kovalov, O. Semkiv, I. Rudeshko, V. Diven. Methodology remaining lifetime determination of the building structures. MATEC Web of Conferences. 230, 02023 (2018). https://doi.org/10.1051/matecconf/201823002023.

[5] A. Kovalov, Y. Otrosh, M. Surianinov, T. Kovalevska. Experimental and Computer Researches of Ferroconcrete Floor Slabs at High-Temperature Influences. Materials Science Forum. 968 (2019) 361-367.

[6] A. Kovalov, Y. Otrosh, S. Vedula, O. Danilin, T. Kovalevska. Parameters of fire-retardant coatings of steel constructions under the influence of climatic factors. Scientific Bulletin of National Mining University. 3 (2019) 46-53. DOI: 10.29202/nvngu/2019-3/9.

[7] Y. Otrosh, M. Surianinov, A. Golodnov, O. Starova. Experimental and Computer Researches of Ferroconcrete Beams at High-Temperature Influences. Materials Science Forum. 968 (2019) 355-360.

[8] Y. Otrosh, O. Semkiv, E. Rybka, A. Kovalov. About need of calculations for the steel framework building in temperature influences conditions. Materials Science and Engineering. 708 (2019) 012065.

[9] M. Surianinov, V. Andronov, Y. Otrosh, T. Makovkina, S. Vasiukov. Concrete and Fiber Concrete Impact Strength. In Materials Science Forum. Trans Tech Publications Ltd. 1006 (2020) 101-106.

[10] Y. Skob, M. Ugryumov, Y. Dreval. Numerical Modelling of Gas Explosion Overpressure Mitigation Effects. Materials Science Forum. 1006 (2020) 117-122.

[11] H. Schneider. Large Scale Experiments: Deflagration and Deflagration to Detonation within a partial Confinement similar to a lane. Proc. of International Conference on Hydrogen Safety. Pisa (Italy). 2005. 10 p.

[12] Y. Skob, M. Ugryumov, E. Granovskiy, Numerical Evaluation of Probability of Harmful Impact Caused by Toxic Spill Emergencies, J. Environ. Clim. Technol. 23 (2019) 1-14.

[13] Y. Skob, M. Ugryumov, E. Granovskiy. Numerical assessment of hydrogen explosion consequences in a mine tunnel, Int. J. Hydrog. Energy. 2020. https://doi.org/10.1016/j.ijhydene.2020.09.067

[14] E. A. Granovskiy, V. A. Lyfar, Yu. A. Skob, M. L. Ugryumov, Computational Modeling of Pressure Effects from Hydrogen Deflagrations // Proc. of 2-nd International Conference on Hydrogen Safety. San Sebastian (Spain). 2007. 15 p.