EFFECTIVENESS EVALUATION OF FACILITIES PROTECTING FROM HYDROGEN-AIR EXPLOSION OVERPRESSURE

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ABSTRACT

The physical processes of the explosion of the hydrogen cloud which is formed as a result of the instantaneous destruction of high-pressure cylinder in the fueling station are investigated. To simulate the formation of hydrogen-air mixture and its combustion a three-dimensional model of an instantaneous explosion of the gas mixture based on the Euler equations supplemented by the conservation laws of mixture components solved by Godunov method is used. To reduce the influence of the overpressure effects in the shock wave on the surrounding environment it is proposed to use a number of protective measures. An estimation of the efficiency of safety devices is carried out by monitoring the overpressure changes in several critical points. To reduce the pressure load on the construction of protective devices a range of constructive measures is also offered.

INTRODUCTION

The level of safety at the 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.

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 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. 1). 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).

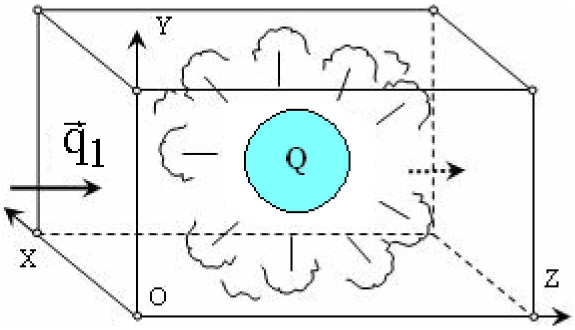

Fig. 1. A computer model of the hydrogen-air cloud explosion

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 [12].

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 [14]. 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 «Expert-2» (Scientific Center of Risk Investigations «Rizikon») is used.

2.0 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 one 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 m and ambient temperature 293 K (fig. 2). 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. 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. The computer has the following characteristics: 1 Intel® Celeron® CPU PCs (2.4 GHz), 0.75 Gb RAM, Windows XP. CPU time is about 1 h.

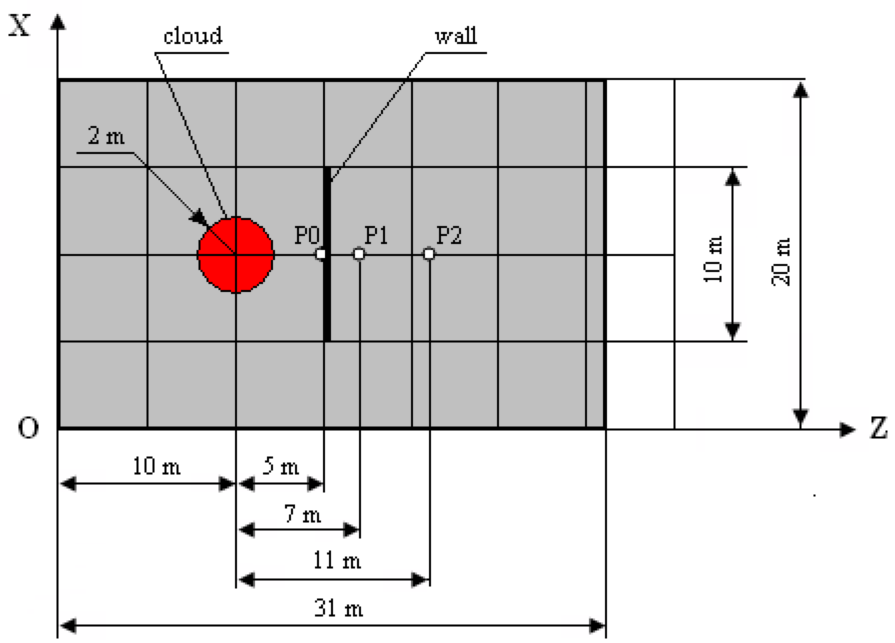

Fig. 2. Layout of hydrogen cloud, protection structure and control points

It is assumed that some protective structures would include individual elements the location of which would be below the level of the earth's surface, so the lower part of the computational domain will occupy a layer of the ground 2 m deep (fig. 3).

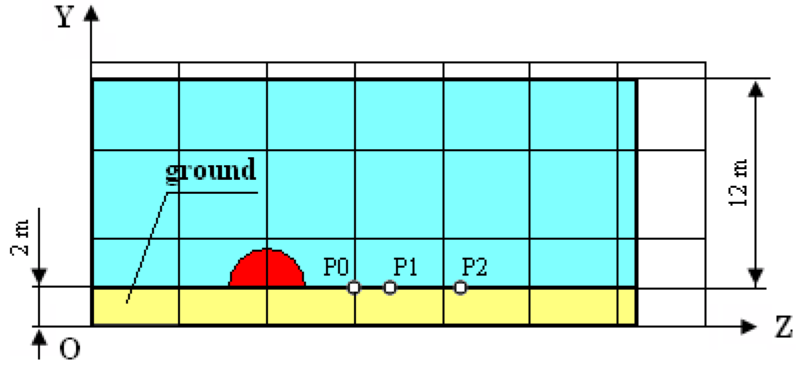

Fig. 3. Vertical geometrical characteristics of the computational domain

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. 2, 3). In addition, the maximum excessive pressure on the surface of the protection structure is analyzed to assess maximum loads from the explosion.

2.1 Hydrogen explosion without protective equipment (case 0)

This version of the numerical simulation corresponds to the most pessimistic accident scenario (fig. 2) when the control points are as fully as possible exposed to the influence of the blast wave in comparison to any other protection construction option (fig. 4-6).

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 this case the absence of any possible obstacles between the explosion epicenter and operational staff causes that the shock wave does not generate any cumulative effect. Lack of some deepening in the earth's surface doesn’t help to improve the level of safety at the control points P1 and P2, potential locations of the personnel and service equipment.

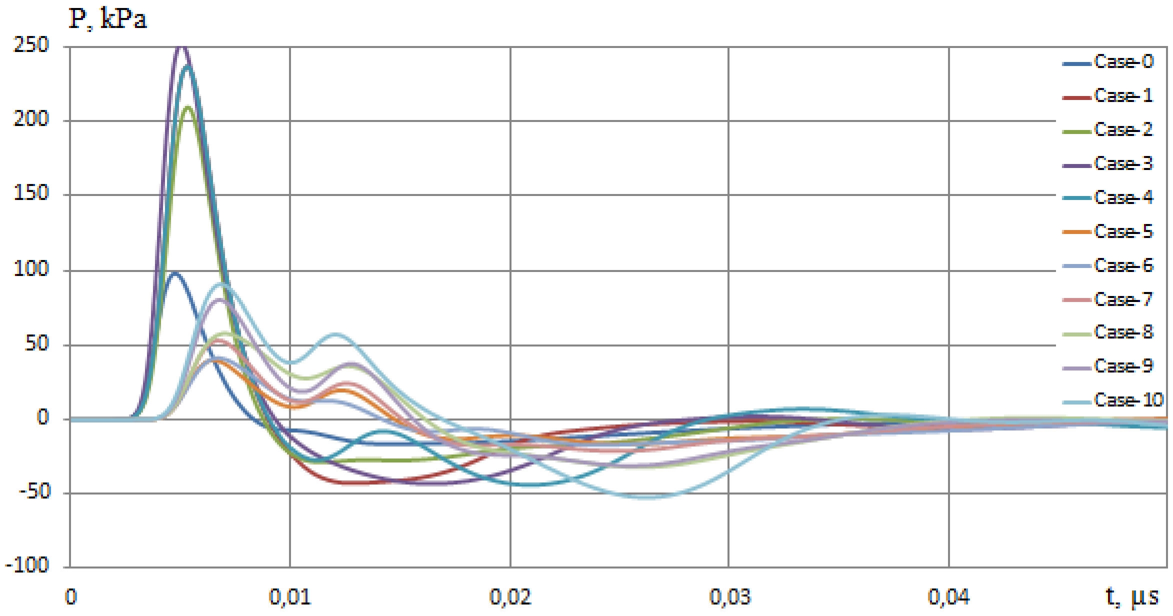

Fig. 4. Overpressure history in the control point P0

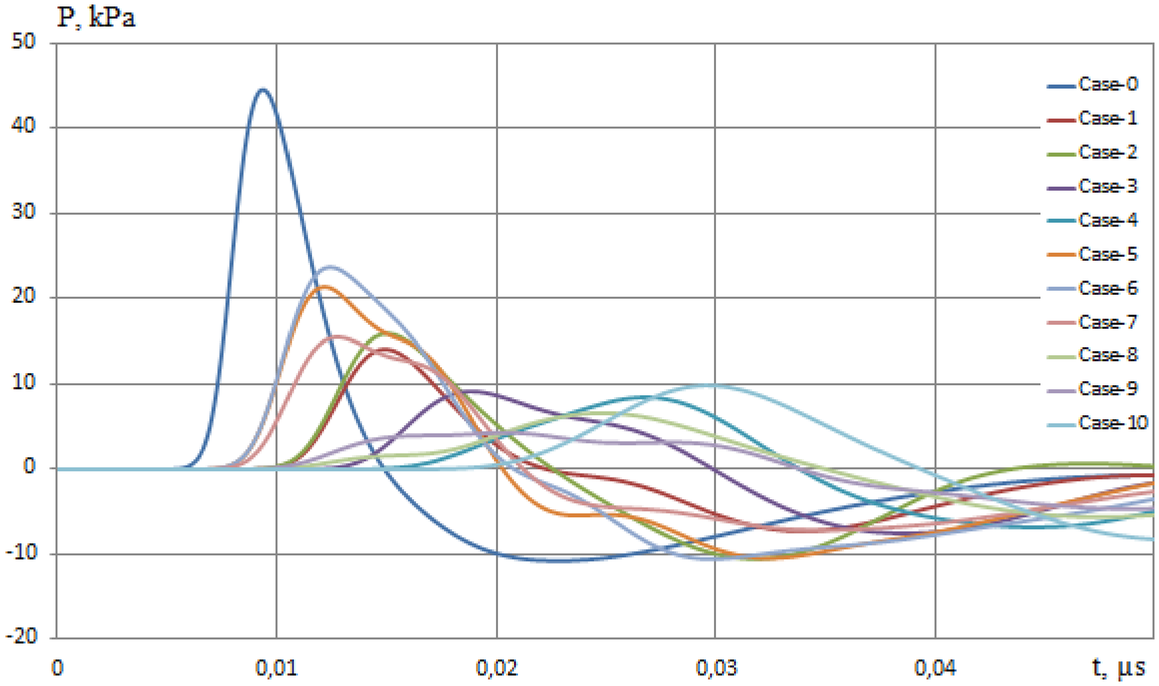

Fig. 5. Overpressure history in the control point P1

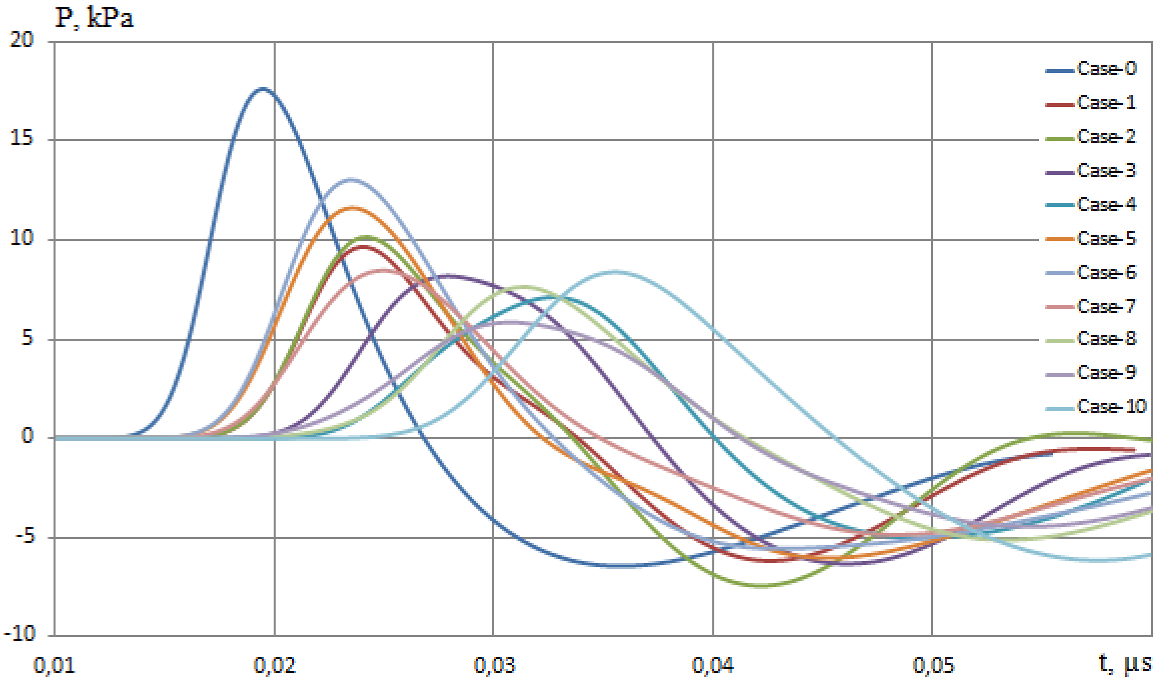

Fig. 6. Overpressure history in the control point P2

Naturally, in this case the excessive pressure in the control point P0 is smaller than the one in any other options, since there is no barrier, but higher than other values in the control points P1 and P2 because of the lack of protection.

2.2 Use of the solid protection wall (case 1)

Installation of the protection solid concrete wall 10 m wide, 0.2 m thick and 2 m high (fig. 2, 3) leads to a substantial rebuilding of the flow (fig. 7).

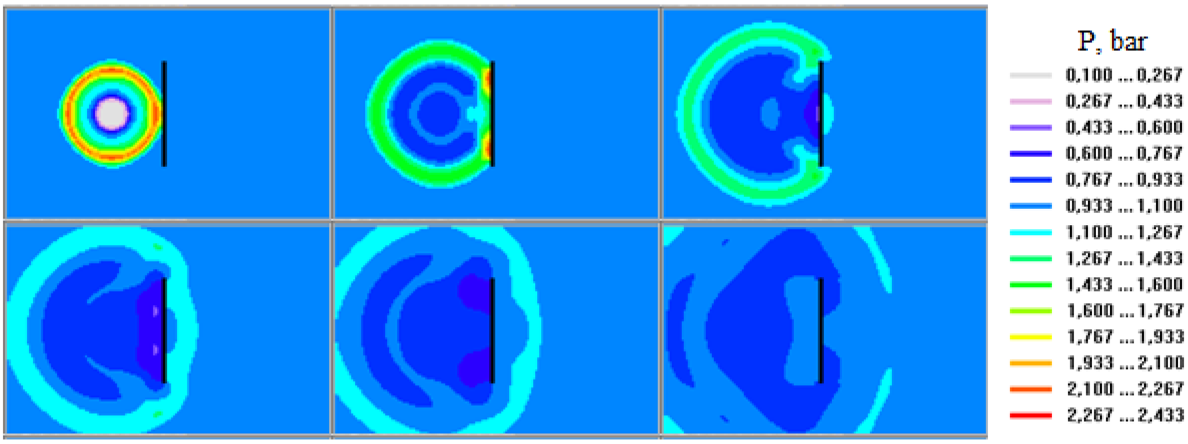

Fig. 7. Pressure distribution in the computational domain near the ground (case 1) at times: 0.004 µs, 0.008 µs, 0.012 µs, 0.016 µs, 0.020 µs and 0.028 µs

Accordingly, the overpressure in front of the wall at point P0 is substantially increased due to cumulative effect but declined at the points P1 and P2 (locations where the personnel may situate) (fig. 4-6). Pressure distribution on the surface of the wall indicates the loads that may lead to the formation of cracks [7] and the destruction of the wall (fig. 8).

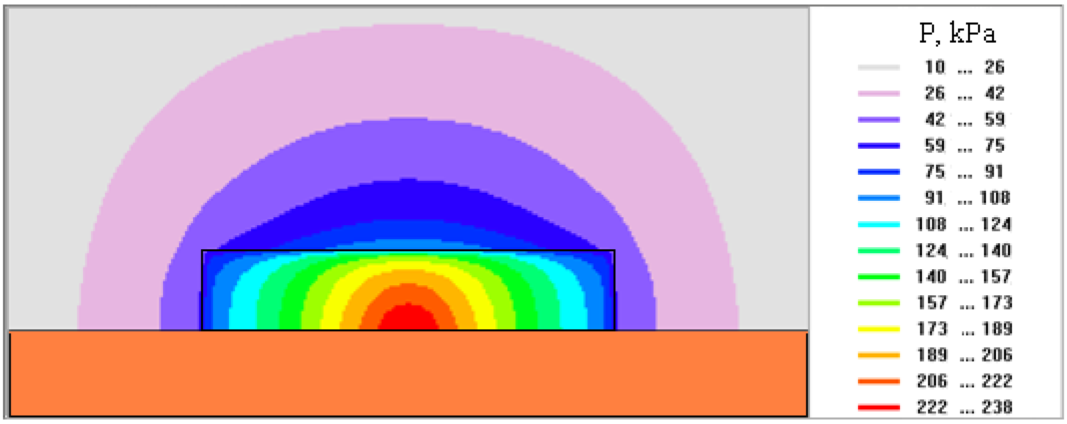

Fig. 8. Distribution of maximum pressure near the wall surface

In order to reduce the loads on the surface of the protective wall it is necessary to provide certain structural changes, some of which are discussed in this paper (cases 2, 7-9).

2.3 Use of the protective wall with bypass channel (case 2)

One of the measures, that reduce the maximum excessive pressure on the wall surface, is a bypass channel under the wall (fig. 9).

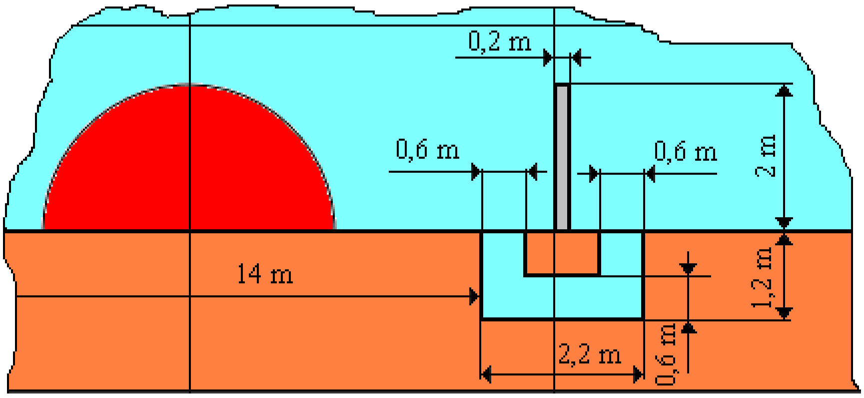

Fig. 9. Characteristic dimensions of the bypass channel under the wall

In this case, a decrease in the pressure peak load on the wall surface (fig. 10) with little effect on the excessive pressure at the control points P1 and P2 (fig. 5, 6) is observed.

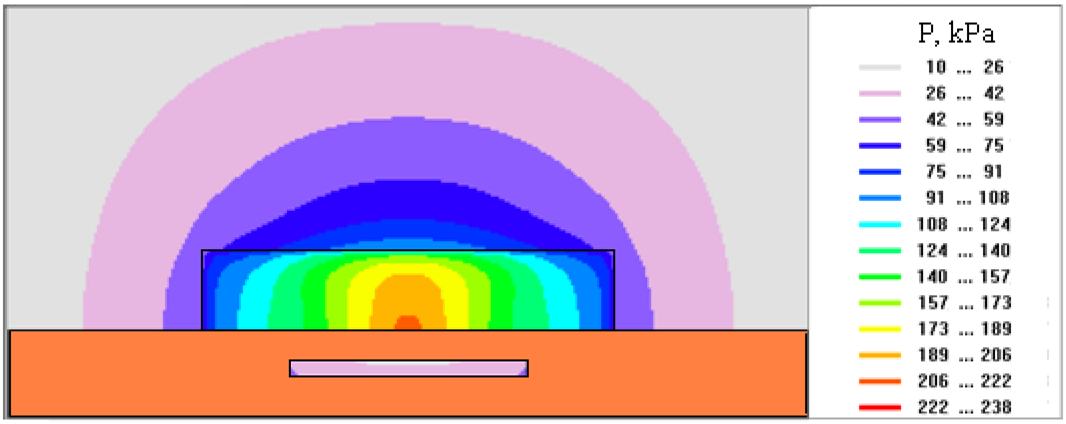

Fig. 10. Distribution of maximum overpressure near the wall with the bypass channel

Bypass channel connects the space with high pressure before the wall with the space behind the wall with low pressure that causes overflow beneath the wall and, to some extent, reduces the peak load on the wall surface.

2.4 Use of the higher protective wall (case 3)

One of the determining factors affecting the distribution of the overpressure at the control points P1 and P2 is the height of the wall. Naturally, the increased height of the wall (in this case up to 3 m) leads to a decrease in the peak of the overpressure behind the wall in contrast to case 1 (fig. 5, 6). Therefore, this height is chosen for the other protective devices (cases 7-10).

2.5 Use of a T-shaped protective wall (case 4)

The effectiveness of the protective wall for the case 3 can be improved by installing the “cap” on the top of the wall (T-shape) which appears up to 1 m on either side of the wall (fig. 11).

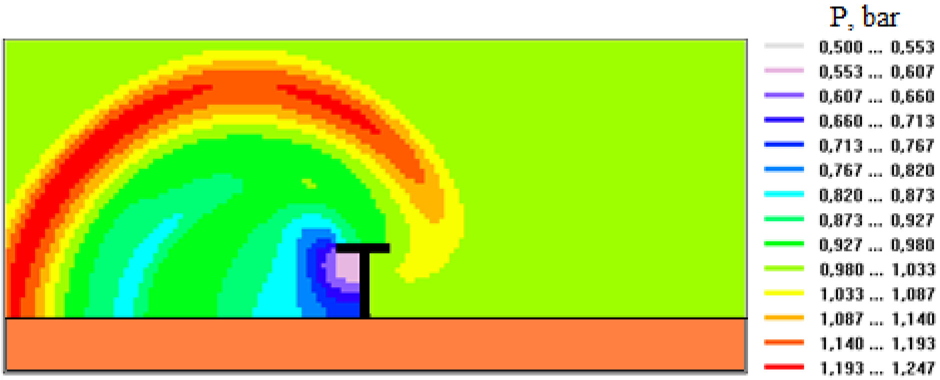

Fig. 11. Pressure distribution at time 0.0168 μs after the explosion (case 4)

According to [7], this form of the wall leads to an expansion of the flow on the edges of the visor that positively affects overpressure rates at the control points P1 and P2 (fig. 5, 6).

2.6 Use of deepening under the epicenter of the explosion (case 5)

Another undertaking to reduce the pressure at the control points is to deepen the subspace with a hydrogen cloud in relation to the earth's surface. We place a cloud in the square-form pit (3 m x 3 m) with a height of 2 m (fig. 12).

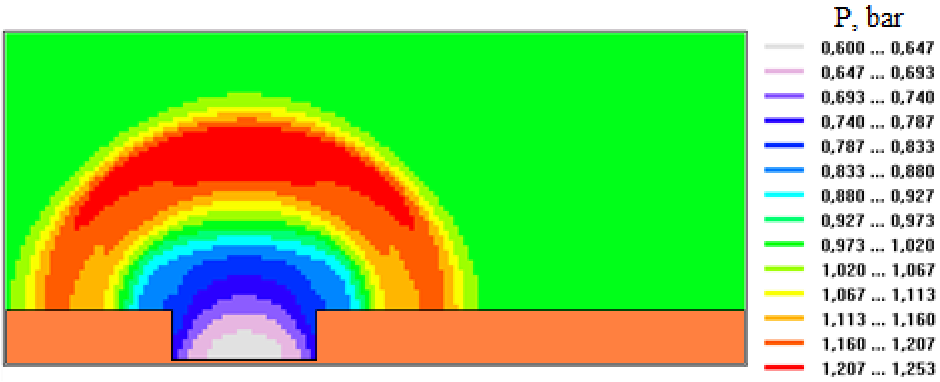

Fig. 12. Pressure distribution at the moment 0.0157 μs after the explosion (case 5)

During the explosion process the pit edges play the role of the visor on the wall in the case 4, and the pit itself performs a cumulative function, unloading the excess pressure in the vertical direction, which favorably affects the behavior of the pressure at the control points (fig.4-6).

2.7 Use of unloading passages in the pit (case 6)

The explosion in the pit (case 5) causes an increase in overpressure on the walls of the pit especially in the corners at the bottom. The peak pressure loads in these areas could be reduced by using the unloading passages around the pit perimeter (fig. 13).

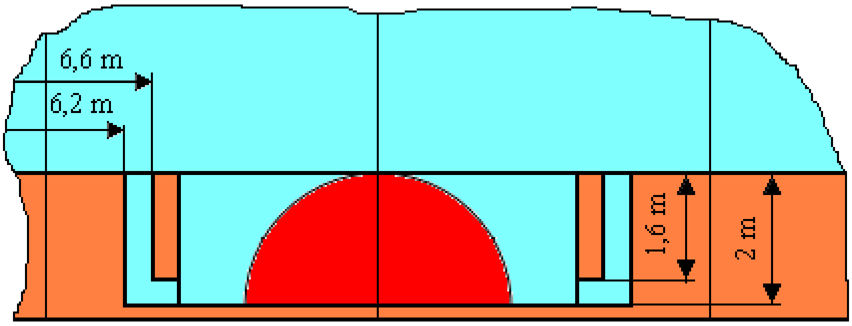

Fig. 13. Characteristic dimensions of unloading cavities (case 6)

Such a design of the pit causes some restructuring of the flow during the explosion (fig. 14), although it not significantly affects the excessive pressure at the control points (fig. 4-6).

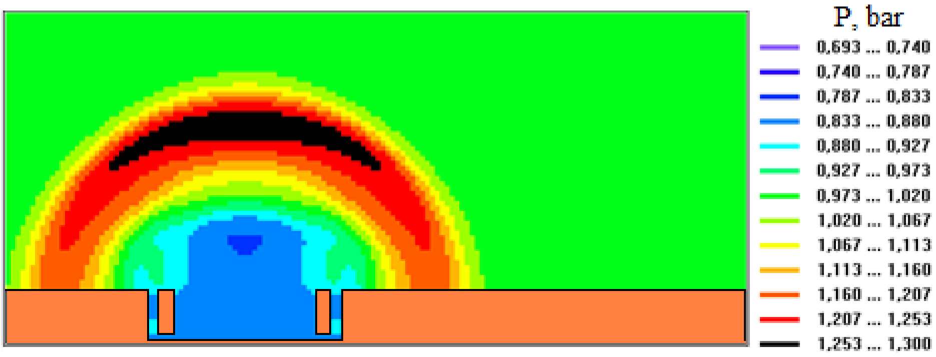

Fig. 14. Pressure distribution at the moment of 0.0158 µs after the explosion (case 6)

2.8 Use of the package of columns of template 1 (case 7)

Not only the use of individual safety devices but also their combination deserves an attention. In the case 7 we combine the deepening of the explosion (case 5) and a set of four rows of 3 m high concrete columns of square section (0.2 m x 0.2 m). The series of columns spaced apart from each other on a distance of 0.2 m (fig. 15) and installed instead of the solid wall.

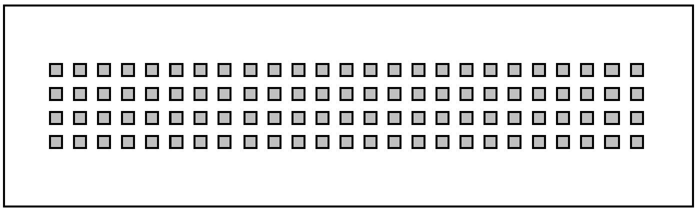

Fig. 15. Template 1 of the columns arrangement (case 7)

Such a design of protection device causes a partial loss of the shock wave intensity during the process of multiple reflections from the columns (fig. 16) and reduces the load on the protective obstacle.

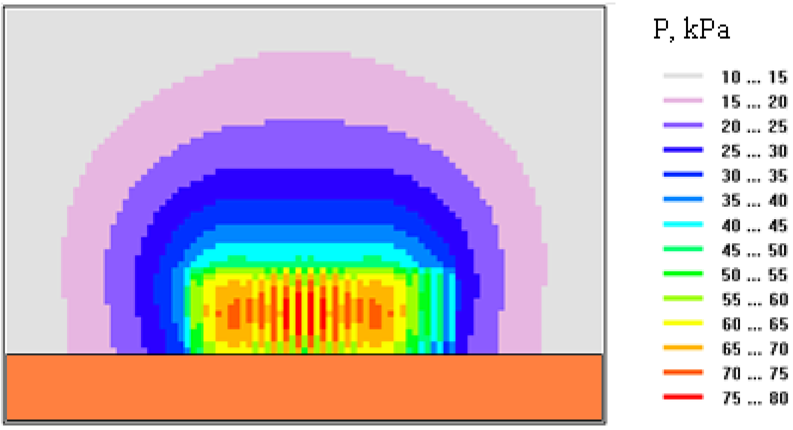

Fig. 16. Distribution of maximum pressure on the surface of obstacles (case 7)

2.9 Use of the package of columns of template 2 (case 8)

Let us change the protective devices for the case 7 by placing the columns according to the template 2 (fig. 17).

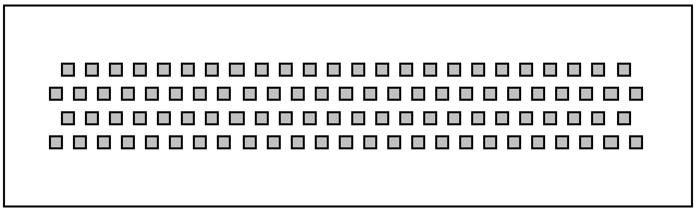

Fig. 17. Template 2 of the columns arrangement (case 8)

Such a construction leads to a greater degree of scattering of the shock wave during the passage between columns (fig. 18) and reduces the load on obstacle.

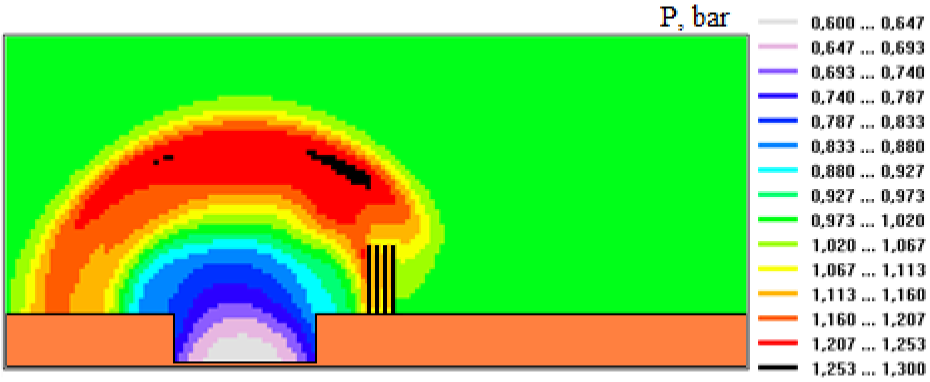

Fig. 18. Pressure distribution at the moment 0.0158 μs after the explosion (case 8)

2.10 Use of perforated walls (case 9)

The solid wall (case 3) gives a good protection from the shock wave but an explosion produces an excessive pressure load on the surface of the protective obstacle. Let us make discontinuous design of the wall that helps in reducing this pressure load and perform a barrier of two adjacent concrete walls (like in case 3) separated from each other on 0.4 m. Each of the walls is perforated by the set of square-form holes (0.2 m x 0.2 m) (fig. 19). Moreover, the holes on the one wall correspond to solid areas on the other wall.

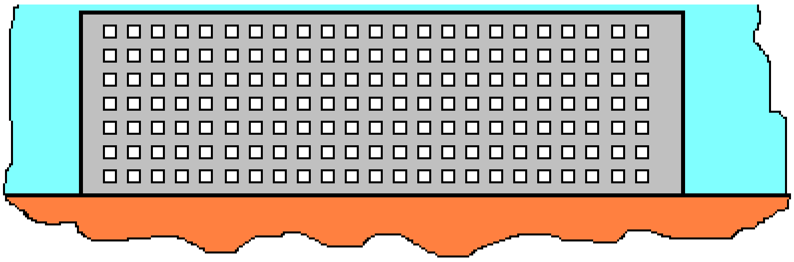

Fig. 19. A pattern of the wall perforation (case 9)

Such a protective design results in the combine effect: a partial unloading of the protective barrier due to the scattering of the shock wave while passing through the holes in the walls and effective blocking the path of the shock wave to the control points behind the obstacle (fig. 4-6).

2.11 Use of the pit with the T-shaped wall (case 10)

The T-shaped solid wall (case 4) and the pitted explosion zone (case 5) provide separatly one of the best protections from the exposure of the control points P1 and P2 to the explosion overpressure. Therefore the use of a combination of these devices must also provide effective protection (fig. 5, 6). The presence of these protective devices dramatically affects the shock wave and leads to a rearrangement of the flow (fig. 20).

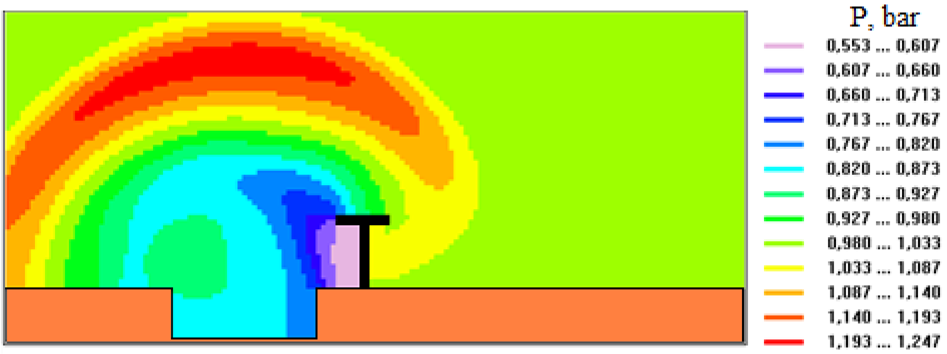

Fig. 20. Pressure distribution at the moment 0.023 µs after the explosion (case 10)

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 cylinder 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 at critical points and comparative analysis of three-dimensional distribution of the maximum excessive pressure in the computational domain it can be concluded that the most effective protection constructions are the obstacles in the form of the solid T-shape wall, the packages of columns arranged according to template 2, the package of two adjacent perforated walls in combination with the deepened explosion zone. Use of such protective measures improves the safety level of the fueling station operations.

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