Selection of Material and Thickness of the Protective Wall in the Conditions of a Hydrogen Explosion of Various Power

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Abstract. The main purpose of this study is a numerical assessment of the consequences of an explosion of a hydrogen-air cloud on the personnel of a hydrogen fueling station and the strength of a protective solid wall of certain dimensions. An explosive gas mixture is formed as a result of the destruction of high-pressure cylinders, the number of which determines the size of the cloud, the power of the explosion, and the scale of the consequences of environmental impact. To obtain the spatio-temporal distribution of the maximum overpressure and the impulse of the shock wave compression phase, a mathematical model of the dispersion of an active gaseous admixture is used, taking into account the chemical interaction with air oxygen. The probable consequences of the shock-impulse impact on the personnel at the control point are carried out using probit analysis. The values of the maximum bending moment and stress at the base of the protective wall, which result from the impact of the blast wave, are used to deterministically estimate the minimum wall thickness necessary for the safe operation of the protective device. The mathematical model takes into account the complex terrain and the three-dimensional non-stationary nature of the shock wave propagation process, and it is a source of data necessary to solve the problem of the strength of solid objects located in the area of baric perturbation of the gaseous medium. The developed methodology makes it possible to carry out a comparative analysis of the effectiveness of protective structures in relation to the power of the explosion.

1 Introduction

Reliable operation of such high-risk man-made facilities as vehicle fueling stations depends not only on the uninterrupted and trouble-free operation of process equipment but also on a sufficient degree of protection of the operating personnel of the technogenic object, which are provided by protection devices in case of accidents [1]. Hydrogen, as the most environmentally friendly type of fuel in terms of toxicity of its combustion products, increasingly replaces traditional hydrocarbons in all spheres of human activity, especially in transport, because hydrocarbons have such a negative impact on the surface layer of the atmosphere that leads to air pollution and global warming. However, hydrogen is an extremely explosive light gas with unpredictable nature: low density, high-energy combustion, rapid transition from deflagration to detonation, wide flammability limits, and a high calorific value. Even a slight accidental release of it into the atmosphere leads to the formation of an explosive gas-air mixture, and chemical interaction with atmospheric oxygen. The combustion of hydrogen can proceed in a deflagration or even in a detonation mode [2] and causes an explosion pressure wave that quickly propagates from the epicenter of the accident, has a shock-impulse effect on process equipment and harms (even fatally) the health of service personnel. In this regard, the following complex scientific problems arise: mathematical modeling of actual physical processes that take place during an accidental hydrogen explosion at a man-made object; numerical assessment of the probable consequences of the impact of shock-impulse loads of an explosion pressure wave on a human; an installation of rationally designed protective equipment (such as a solid wall) that provides an adequate level of safety for personnel in the workplace without destruction (Fig. 1).

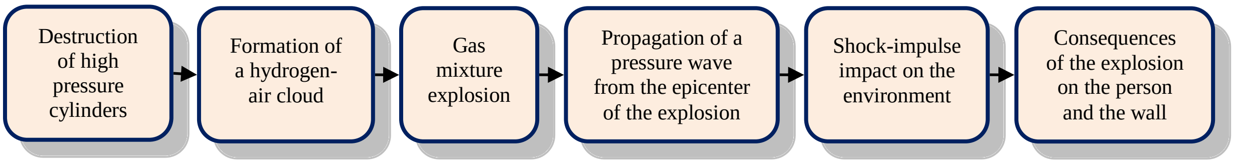


Fig. 1. Block diagram of the development of an accident

Of course, the most reliable results of solving this scientific and applied problem can be obtained experimentally [3]. Use of such highly specialized computer information systems as ANSYS [4] or LIRA [5] makes it possible to numerically estimate the stress state of the structural elements of the equipment. If we consider the undisturbed state of atmospheric air, the main influence on the characteristics of protective devices is exerted only by the climatic parameters of the environment [6]. However, under conditions of an accidental release and explosion of a gas-air mixture, additional excessive thermal disturbances and loads arise [7], and can have a significant effect on the strength properties of the protective devices material resistance [8] to the shock-impulse effect of the blast wave and lead to their premature destruction [9]. Thus, a comprehensive analysis of the effectiveness of protective devices should include not only a gas-dynamic calculation of spatio-temporal pressure fields in the accident zone to assess the consequences of an explosion on a human, taking into account the installation of a protective device of a rational design [11], but also the choice of its material, the resistance of which to the bending moment due to the action of explosion pressure forces will not lead to its destruction [12]. Such an analysis is possible on the basis of a joint solution of a non-stationary three-dimensional problem of the explosion of a hydrogen-air mixture and the problem of the strength of a protective wall under conditions of shock-impulse perturbation of atmospheric air. Moreover, it should be taken into account that the power of a hydrogen explosion at a fueling station can vary depending on the number of accidentally destroyed high-pressure gas tanks. Modeling of such a multifactorial physical process is possible only on the basis of adequate mathematical models of the spatial internal or external gas flow [13], physical processes of emission of gas impurities into the atmosphere and their dispersion [14], chemical interaction with atmospheric oxygen [15]. The model makes it possible to extract the necessary information about the gas-dynamic characteristics of the disturbed atmospheric medium in the accident zone, use it to conduct a probit analysis of the effects of the explosion on personnel and the strength of the protective device [16].

2 Main part

Wall strength evaluation. As a result of the accidental destruction of the N high-pressure dispensing cylinders for storing gaseous hydrogen, a hydrogen-air cloud is formed and explodes (Fig. 2). The blast pressure wave propagates in all directions from the epicenter of the accidental explosion, moving around solid obstacles such as protection wall, and gradually loses the intensity of its impact on the surrounding environment. The pressure forces form a total bending moment M, the action of which causes the occurrence of a bending resistance stress at the base of the protecting wall [16].

Actually, the power of the hydrogen-air explosion and the corresponding possible consequences of the shock-impulse impact of the explosion wave on the fueling station equipment and service personnel depend on the total amount of released hydrogen, that is the number of accidentally destroyed high-pressure dispensing cylinders provide the hydrogen-air cloud of definite sizes.

Consider the hydrogen fuelling station. It has the large cryogenic tank (5.7 m^3) for storing hydrogen in liquid state [3] (Fig. 2), and feeds a set of three packages of high pressure cylinders (each package consists of twelve cylinders) in total amount 799.2 m^3. The volume of each cylinder is about 0.51 m^3. Highly pressurized (6500 psi $\approx$ 44.8 MPa) gaseous hydrogen is stored at ambient temperature in each cylinder ready to be used to refuel the vehicles. The hydrogen under pressure is dispensed to vehicles' tanks. Thus, the varying number of accidentally destroyed cylinders makes it possible to simulate the release and explosion of hydrogen of various scales.

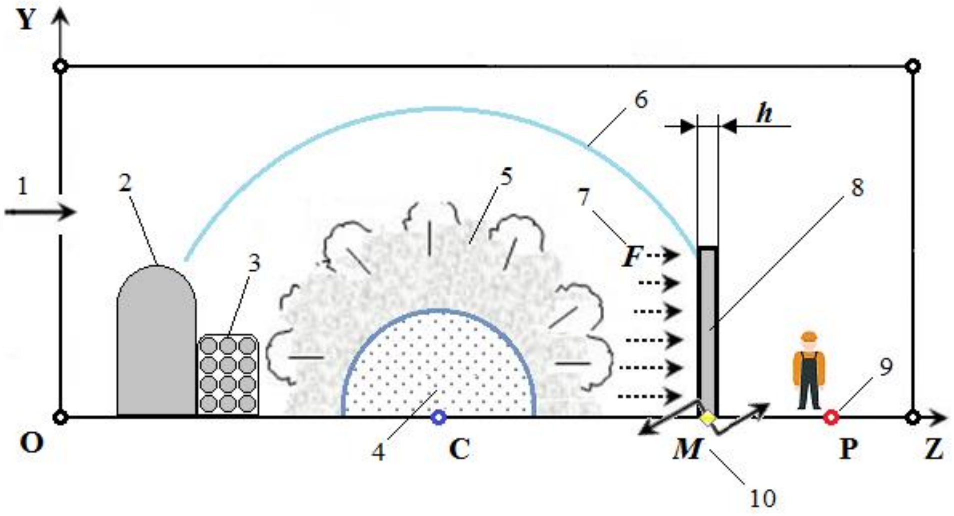


Fig. 2. Map of objects: 1 – incoming air; 2 – tank of liquefied gas; 3 – high pressure cylinders; 4 – explosive mixture cloud; 5 – combustion products; 6 – blast wave; 7 – overpressure forces; 8 – protective wall; 9 – control point (working place); 10 – moment of resistance to bending

During the process of modelling an accident situation, a non-stationary three-dimensional pressure field of the gaseous medium is controlled in the entire computational domain [16]. This makes it possible to sequentially extract the distribution of the maximum overpressure ΔP_+ on the surface of a solid protection wall, obtain a discrete field of overpressure forces F, and estimate the total torsional force on the wall M_Σ resulting from the explosion. Further, considering the scheme of the cantilever beam scheme, it is possible to determine the minimum allowable design momentum of resistance to bending W at the base of the wall. Finally, taking into account the allowable value of the bending stress [σ] for a particular wall construction material [16], it is possible to estimate the minimum allowable wall thickness h (Fig. 3).

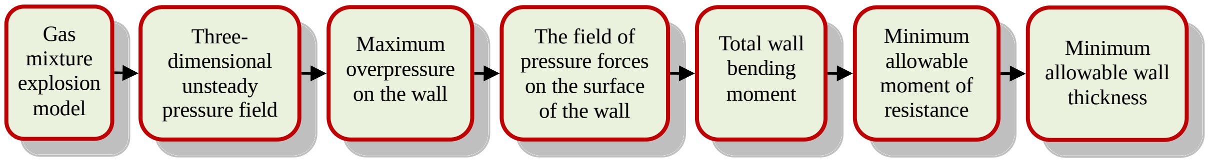


Fig. 3. Wall strength analysis algorithm

Explosion model. A model of an instantaneous explosion of a hydrogen-air mixture is used to numerically estimate the effect of the power of an accidental hydrogen explosion on the consequences of the impact of a shock-impulse load on the personnel of a fueling station, that is protected by a solid wall of a given height and width, and assess the bending stability of a wall made of different materials. The model is based on the assumption that the main factor influencing the physical processes of impurity dispersion is the convective transfer of mass, impulse, and energy of the mixture. Therefore, it is considered sufficient to use the system of simplified Euler equations with source terms for the motion of the gas mixture.

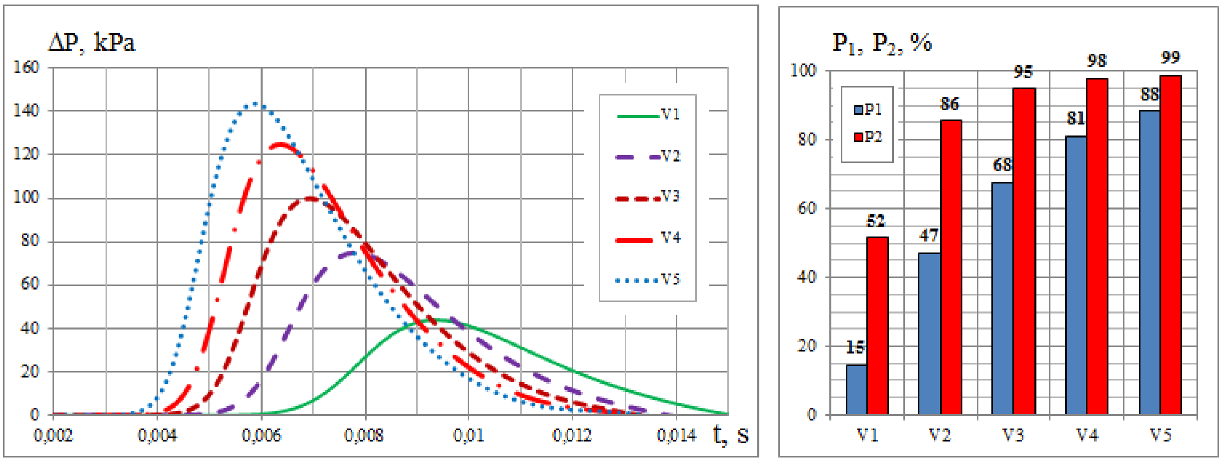
Explosion consequences evaluation. Consider an accident at a vehicle hydrogen fueling station [3] where several high-pressure distribution cylinders are simultaneously destroyed. The scale of the accident depends on the N number of failed hydrogen gas storage cylinders. Consider several options of the explosion power for $N = \{1, 2, ..., 5\}$. Let us assume that as a result of the release of compressed hydrogen into the atmosphere near the earth, its expansion to atmospheric pressure, a hemispherical stoichiometric hydrogen-air cloud of radius R and an ambient temperature of 293 K is formed (Fig. 2). The instantaneous explosion of this cloud leads to the formation of combustion products with the following parameters: temperature 3450 K, pressure 901 kPa, molar mass 0.02441 kg/mol, and adiabatic coefficient 1.24 [11].

Options of the computational experiment differ in the amount of hydrogen released into the atmosphere. The volume of a hemispherical cloud (radius R) of a hydrogen-air mixture is determined by the number N of destroyed high-pressure gas cylinders (Table 1).

Table 1. Accident scale options.

Option	V1	V2	V3	V4	V5
Number of cylinders, N	1	2	3	4	5
Cloud radius, R [m]	2.00	2.52	2.88	3.17	3.42

At the control point P for the initial variant without personnel protection (there is no wall) overpressure distributions ΔP of the blast wave compression phase (Fig. 4a) and the values of the conditional probability of fatal injury P_1 and the probability of eardrum rupture P_2 (Fig. 4б) of a personnel are obtained for all explosion power options. Almost all of them are unacceptable from the point of view of human safety.



a

b

Fig. 4. The state of safety at the control point P for different options of the accident scale in the absence of a wall: a – overpressure history; b – the impact probability

Installation of a protection solid wall 10.0 m wide and 2.2 m high at a distance of 5.0 m from the explosion epicenter C (Fig. 2) significantly affects the pressure field in the computational domain (Fig. 5). For all options of the explosion power at the control point P, the distributions of overpressure ΔP (Fig. 6), the maximum overpressure in the blast wave front ΔP_+ (Fig. 7a), the impulse of the compression phase I_+ (Fig. 7b) and the values of the conditional probabilities of fatal injury P_1 and eardrum rupture P_2 (Fig. 7c) are obtained. The installation of the wall significantly improved the safety of the gas station personnel.

To assess the resistance of the wall to the gas forces of the blast wave, an instantaneous impact of the explosion on the wall is assumed. This makes it possible to assume that the wall maximum bending force is caused by the distribution of the maximum overpressure on its surface (Fig. 8).

According to the strength analysis algorithm (Fig. 3) on the wall surface, discrete fields of overpressure forces F (Fig. 9), tourque forces M (Fig. 10), the total tourque force M_Σ (Fig. 11a), and the moment of resistance to bending at the base of the wall W (Fig. 11b) are estimated. Finally, the dependences of the minimum allowable wall thickness *h* for different construction materials of its manufacture are obtained (Fig. 11c).

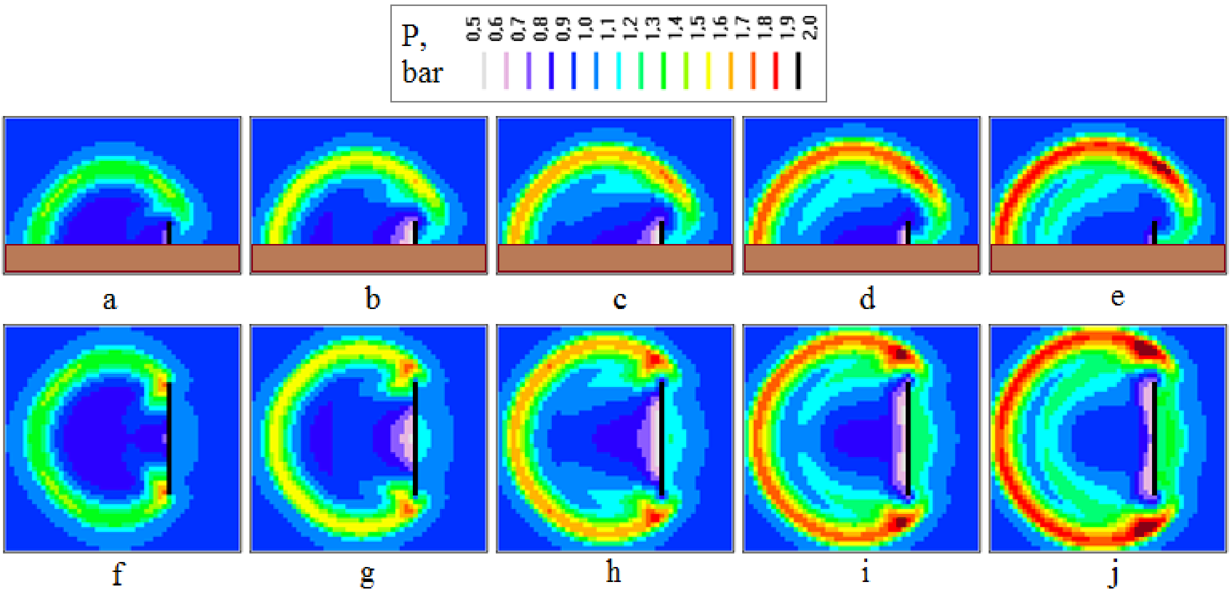


Fig. 5. Pressure fields for explosion options V1-V5 since 0.0107 s

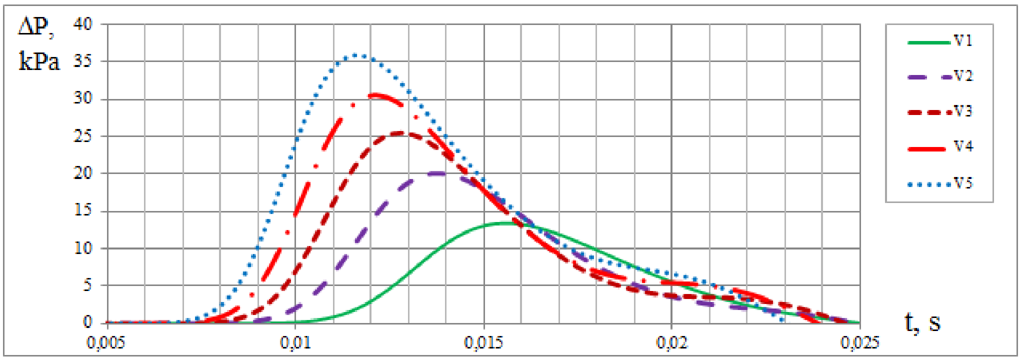


Fig. 6. Overpressure history at the control point P for the different scale of the accident with wall

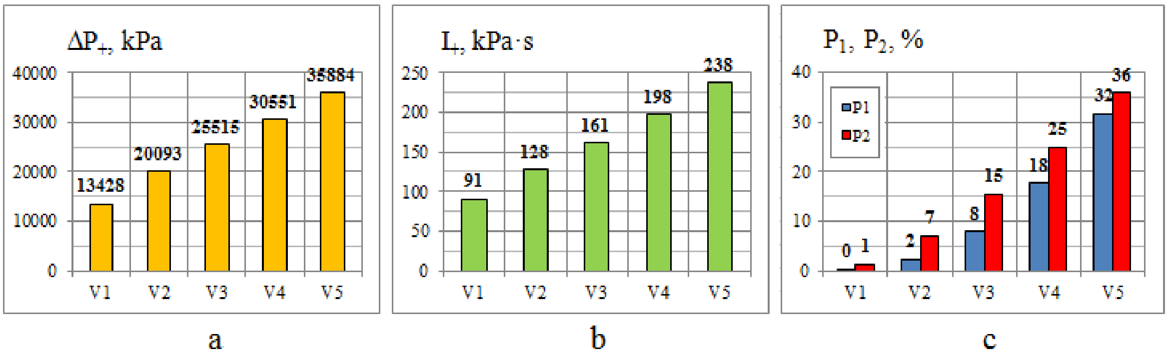


Fig. 7. Shock-impulse loads and consequences at point P for options V1-V5 with wall: a –overpressure; b – impulse; c – conditional probability of fatal injury and ruptured eardrums

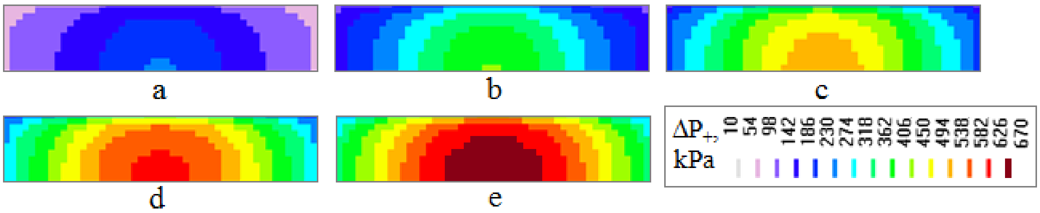


Fig. 8. Maximum overpressure on the wall: a, b, c, d, e – options V1-V5 of the accident scale

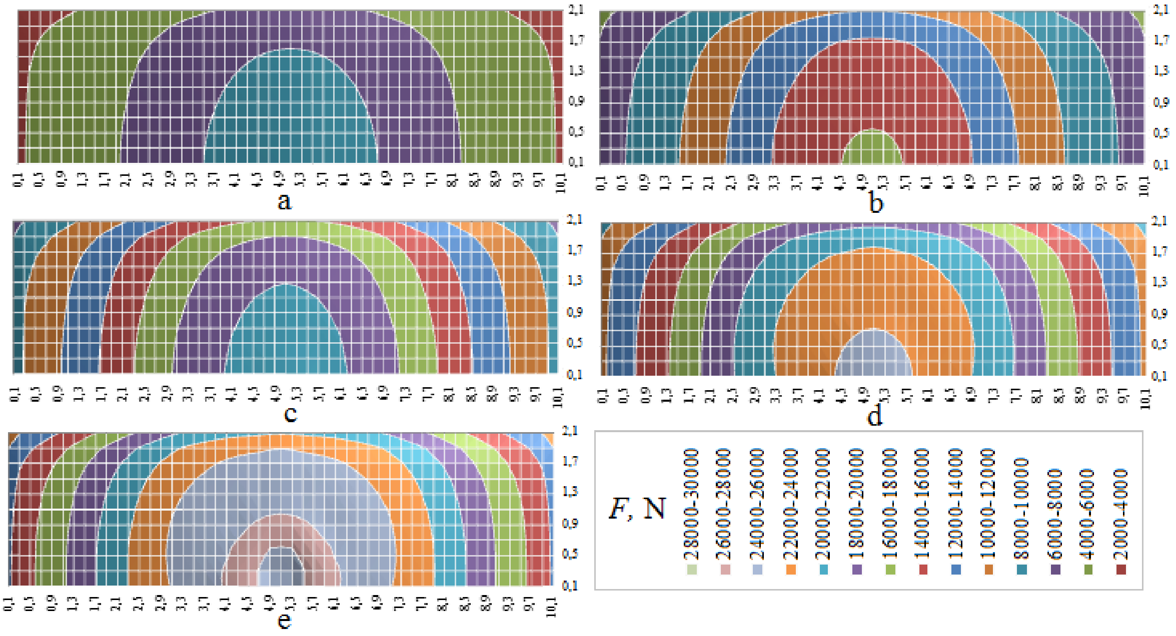


Fig. 9. Pressure forces on the wall: a, b, c, d, e – options V1-V5 of the accident scale

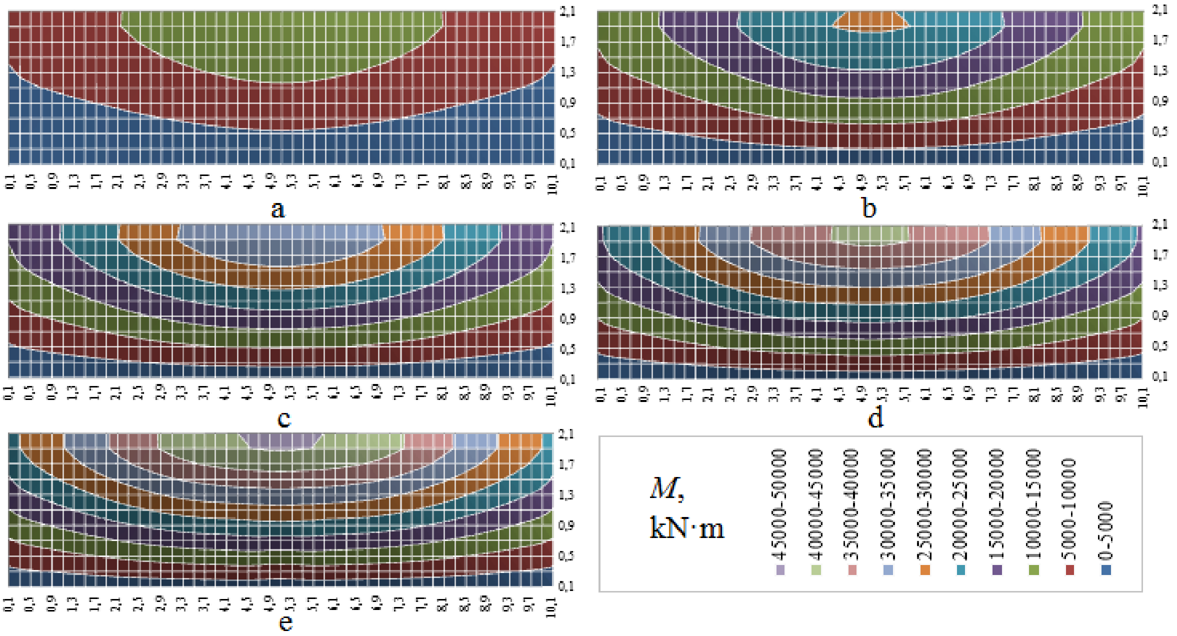
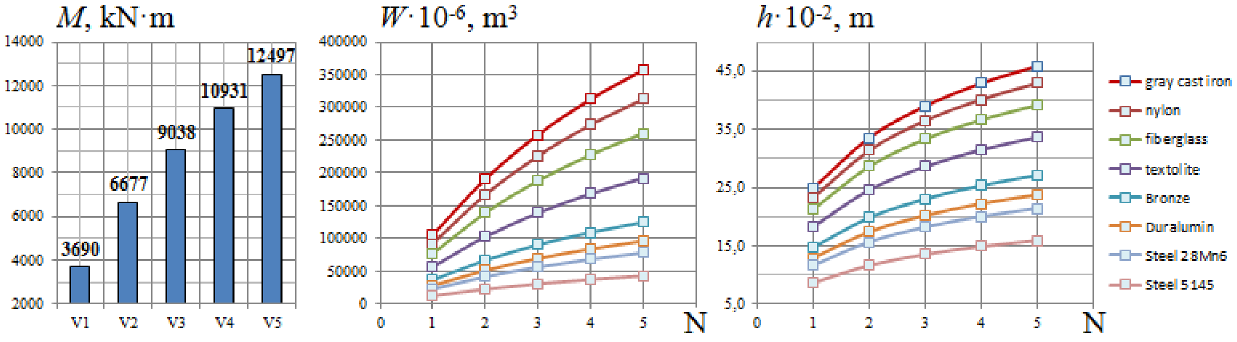


Fig. 10. Fields of torque forces on the wall: a, b, c, d, e – options V1-V5 of the accident

Results discussion. The surface distributions of overpressure (Fig. 8), pressure forces (Fig. 9), and wall bending torque (Fig. 10) reveal the main features of the influence of the hydrogen explosion power on the consequences of its impact on personnel and the protective wall. The values of the conditional probability of fatal injury and ruptured eardrums (Fig. 4b) significantly exceed the critical value of 50 %, which makes the option without a protective wall unacceptable. Installing a wall between the epicenter of the explosion and the workplace significantly reduces the shock-impulse load on a person and the probable consequences for him (Fig. 7c). However, with an increase in the power of the explosion, the maximum overpressure on the side of the wall facing the epicenter of the explosion increases (Fig. 8), the effects of pressure forces influence (Fig. 9) and the bending torque of the protective wall (Fig. 10) intensify. This leads to an increase in the minimum momentum of resistance to bending at the base of the wall (Fig. 11b). Choosing the specific material for the protective wall manufacture, one can estimate its minimum allowable thickness from the point of view of the non-destruction condition (Fig. 11c). Taking into account the characteristics of a particular material, it is obvious that the minimum allowable wall thickness increases for options with more powerful hydrogen explosion.



a b c

Fig. 11. Strength characteristics of the wall for different materials: a – total bending momentum; b – the minimum required momentum resistance; c – minimum safe wall thickness

3 Conclusion

The influence of the power of an explosion of a hydrogen-air mixture on the consequences of a shock-impulse effect on the personnel of a fueling station and the strength of a protective solid wall has been studied. The volume of released hydrogen is determined by the number of the accidentally destroyed high-pressure dispensing gas tanks. A three-dimensional non-stationary mathematical model of a gas mixture explosion is used to obtain spatio-temporal overpressure fields in the calculated volume which are required for probit analysis of the consequences of the impact of a blast wave on a human and strength analysis of the safe operation of a protective wall in order to select the necessary structural material for the manufacture of the wall and assess its minimum thickness, which satisfies the condition of sufficient resistance to bending by pressure forces.The bending stress state in the foot of the wall is assessed using a cantilever beam calculation scheme under the assumption that maximum overpressure force field influences the wall at the same time to assess the worst possible scenario. The represented methodology resolves a coupled problem of gas dynamics during an explosion of various intensities and protection wall foot strength. It allows assessing the effectiveness of the wall from the personnel safety point of view, and the wall material functionality without its destruction.

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