INFLUENCE OF OBSTACLES ON THE DEVELOPMENT OF GAS EXPLOSION IN ROOM

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Abstract. *It is considered that the obstacles lead to turbulence in the flow during the gas explosion. This leads to an increased flow of combustion products that increases the pressure explosion. But in some cases, the pressure is reduced when installing obstacles. Numerical experiments confirm these results. Mathematical model consisted of a classical system equations of conservation in the form of Euler's ideal compressible gas supplemented with flame propagation conditions for a stoichiometric mixture, filling the entire treated area. The system of equations are solved by large particles (Belotserkovskii and Davydov). Investigated area is divided into cells in which there is a calculation. The calculation was performed in the room (0.5x0.5x0.5m) with a vent (0.3x0.2m). Obstacle (0.5x0.03x0.03m) was installed in a room space on the axis at a distance from the wall is 1.4 m and 0.7 m. Ignition was made against the back wall. Explosion pressure increases more than two times when installing obstacles in the room. Moving obstacles along the axis away from the walls of the room have little effect on the results. However, the location of the obstacles against the wall reduces the pressure and makes an explosion like an explosion in an empty room.*

1 INTRODUCTION

As is well known, the dynamics of development of gas explosion depends on the nature state of the initial explosive mixture, including composition, initial pressure and temperature, and on the vessel characteristics, including dimension and shape, position of the ignition source, location, size, strength and shape of the vent [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The main hazard in the gas explosion in the premises of almost all these authors believe the explosion pressure, and the primary means of reducing this risk - a window (panel or other element) through which in the case of an explosion in the explosion of gases emitted from the room because they give it two parameters the center of interest Standards of the United States and the European Union in its "weighted" approach, borrowed from W. Bartknecht and Swift [14], based on the results of many experimental studies, which are described by algebraic equations. It is clear that this approximation of dynamic processes can be valid only in those circumstances in which the experiments were conducted. Therefore, the equations describing the received communications are relevant to a certain static state property which has burst in the "zero" approach. It should be recognized that the physical connection between the main parameters of the process are presented too simple, does not reflect the fullness of influence on the development of all the above mentioned parameters. Thus, in NFPA 68 and EN 14994, it is proposed for understanding the linkages with the explosion of options based on the type of equation

$$m_b = A_s S_и \rho = C_d \varepsilon A_v (2\rho P_{red})^{0,5} \quad (1)$$

where m_b – mass rate of burning, kg/s; A_s – total surface area of the vessel, m^2; C_d – orifice discharge coefficient; A_v – vent area, m^2; P_{red} – reduced maximum pressure [i.e., maximum pressure actually developed during a vented deflagration, *bar*; ε – expansibility factor; ρ – unburnt gas density, kg/m^3; $S_и$ – laminar burning velocity, m/s.

According to this equation, it is possible, by setting the appropriate value P_{red}, calculate the value of the vent area A_v. However, serious arguments in favor of the values of the area of the combustion front, equal to total surface area is not given. Obviously, it is believed that this is the most unfavorable situation.

V.V. Molkov [1], W. Bartknecht [2] (in later works) and a number of other authors [13, 14, 15] made an attempt to go to the description of the dynamics of the process, using a first order differential equation, for example, R. Blanchard [15]:

$$dm/dt = m_b - m_v \quad (2)$$

where m_b – mass burning rate, kg/s; m_v – mass flow of gases through the window, kg/s.

$$m_b = M_w \cdot V/(RT_E)\ dp/dt \tag{3}$$

where M_w – the mean molar mass (*kg/mol*); V – the volume of the room, m^3; R = 8.314 J/(*mol*·*K*); T_E – temperature of the outflow of gases, *K*.

This takes into account only the maximum value of the derivative of pressure with respect to time:

$$(dp/dt)_{max} = K_g \cdot V^{-1/3} \cdot A_T \tag{4}$$

therefore, the maximum value of the mass burning rate will be determined as:

$$m_{rmax} = M_w \cdot V/(RT_E) \cdot K_g \cdot V^{-1/3} \cdot A_T \tag{5}$$

where K_g – designation rate of pressure rise; A_T – a factor which is used to account for the turbulence generation developed during venting.

The value of the gas flow through the window when the pressure in the room determined by the formula:

$$m_v = \alpha \cdot F \cdot \Psi \cdot p_1 [2M_w/(RT_E)]^{0,5} \tag{6}$$

where α – accounts for the effective fraction of the area; F – the venting area (m^2); Ψ – the efflux function; p_1 – the pressure inside the vessel.

In the analysis of these equations can only agree with one statement that pressure throughout the volume space is equally, if not take into account the acoustic oscillations, hydraulic resistance and buoyancy forces. When using other parameters difficult questions arise. An insurmountable barrier to both methods of calculation is indeterminacy in every moment the area of the combustion front, this most important factor affecting the dynamics of the whole process.

It is clear that this issue can be solved only with the use of equations describing the dynamics of the process and take into account the parameters distributed throughout the volume in which there is an explosion, it is possible to use methods of CFD. Of course, in this case there are a significant number of problems with the description of the explosion, but these problems have a more acceptable level.

2 THE WORKING HYPOTHESIS

Possible position of the obstacles in the volume in which there is an explosion, so diverse that distribute experimental results obtained in one case, on the other sometimes leads to the opposite result. Taking into account the fact that the position of obstacles within the volume can only be described in three-dimensional space (in a two-dimensional space), the system of equations must be correspondingly. Given the dynamics of the process, we come to the need for a well-known equations describing the fundamental laws of conservation in relation to gas dynamics in their differential form, that is, the methods of CFD, one of the most common versions of which is FLACS. Visualization solutions of such systems and the dynamics of explosions sometimes creates the illusion of physical experiment. Obviously, therefore, carry out such calculations are often called numerical experiments.

However, we were alerted by the fact that the simulation using FLACS gas explosion [8], conducted by other authors [7], it was not possible to describe the fluctuations that have occurred in the field experiments, and caused serious divergence between the numerical and physical experiments. Therefore, we used a different method for solving systems of equations CFD, called the method of large particles [12], and the original mechanism of the flame, with which managed to describe more fully the physical process of the explosion, including a description and the low-frequency oscillations [11] affecting the process.

When planning the experiment, we noticed that in certain publications, focuses on the study of the influence on the development of the explosion of the fact of the presence of obstacles, as well as the number and shape. We decided to add the results of the study places the provisions of the obstacles in the process of explosion. From a practical point of view, this program is interesting, for example, that it will respond to the question of correctness in terms of the explosion of arrangement of furniture in the kitchen, where the gas is used.

2.1 The original system of equations

In the original system of equations included known in gas dynamics differential equations in the form of Euler, expressing the basic laws of conservation (continuity equation, momentum and energy) relative to the ideal compressible discrepancy environment. The equation of conservation of momentum, in turn, is given in the form of three scalar equations.

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + div\left(\rho \overline{U}\right) = 0 \\ \dfrac{\partial \rho U_x}{\partial t} + div\left(U_x \rho \overline{U}\right) + \dfrac{\partial p}{\partial x} = 0 \\ \dfrac{\partial \rho U_y}{\partial t} + div\left(U_y \rho \overline{U}\right) + \dfrac{\partial p}{\partial y} = 0 \\ \dfrac{\partial \rho U_z}{\partial t} + div\left(U_z \rho \overline{U}\right) + \dfrac{\partial p}{\partial z} = 0 \\ \dfrac{\partial \rho B}{\partial t} + div\left(\mathrm{E} \rho \overline{U}\right) + div\left(p \overline{U}\right) = 0. \end{cases} \tag{7}$$

Encloses the system of equations of gas in the form of state:

$$p = \rho I\left(\gamma - 1\right) \tag{8}$$

where ρ – gas density, kg/m^3; $\overline{U}$ – velocity vector, m/s; E – specific total energy, J/kg; p – pressure, Pa; γ – adiabatic index of the medium; I – specific internal energy, J/kg; U_x, U_y, U_z – velocity components respectively along the axes *x, y, z*, m/s.

2.2 The initial and boundary conditions

It is assumed that all space is filled with a stoichiometric composition of methane-air mixtures, the initial pressure and temperature of the mixture has a normal value. Boundaries of the room impermeable, in explosions gas is ejected through the window. The gas composition is not changed in the process is the same combustion and air. Window is a weightless and collapsing at the initial moment of the explosion.

3 THE SOLVING THE SYSTEM OF EQUATIONS

3.1 The general principle of solving the system of equations

Numerical solution of the system is carried out by large particles, LPM, [10], developed by Belotserkovskii O.M. and Davydov Y.M. The basis of LPM is the idea of Harlow n particles in the cell, according to which the system of equations admits a "splitting" of physical processes. But in the LPM solid particles inside the cell are replaced by a single liquid particles fill the entire volume of the cell. Hence the name of the method. Method of large particles as well as other modern methods such as Godunov method [11], FLACS [6] et al, allow us to study the gas-dynamic flow without a priori information about the structure of the solution.

On the domain of integration is superimposed Euler (fixed) grid of rectangular cells with sides Δx, Δy and Δz. The calculation consists of repetitive time steps. In turn, each such step includes three steps:

1. “Euler” stage, when we neglect all effects associated with the movement of the fluid (mass flow through the cell boundaries is not); here on a fixed Eulerian grid defined intermediate values of the unknown parameters of the flow;
2. “Lagrangian” phase in which the movement is modeled mass flow across borders Euler cells and its redistribution takes place in space. It is assumed that the entire mass is transferred only through the normal to the boundary component of velocity;
3. “The final” stage - the final values are determined by the flow parameters based on the laws of conservation of mass, momentum and energy for each cell and the whole system.

The heat and mass transfer with the environment and the spread of flame have been incorporated in the structure of the system. Cooling processes on the chamber walls are estimated on the basis of physical experiments carried out according to pressure drop in the explosion in a closed chamber. To calculate the flow through the open border to border pressure cell is assumed equal to the average between the pressure from the chamber and atmospheric.

3.2 Accounting for the propagation of the flame front

To describe the process of flame propagation used approach fits well into an approximation model of the system, and according to which the introduction of an additional state variable cell - mass fraction of combustion products f cell [9]. This parameter for each cell can be expressed by the following ratio:

$$f = \frac{m_B}{m} \tag{9}$$

where m – the total weight of the mixture in the cell, kg; m_B – mass of combustion products in the cell, kg.

In this cell design can be divided into three groups (with an error of calculation – ε):

- cells with the original mixture, for which the condition – $f < \varepsilon$;
- "burnt" cells – $f > 1 - \varepsilon$;
- "burning" of the cell – $\varepsilon < f < 1 - \varepsilon$.

Full description of the model used and the difference schemes presented in [9].

3.3 The first step in the modeling process of flame propagation

Modeling of the combustion process is carried out in three steps. In the first step of combustion the gas is considered within the cells. For all the "conflagrant" of cells is determined by the share of gas that is burned during Δt, and calculated energy release ΔE:

$$\Delta f = \frac{\Delta t}{\Delta l} U_B \tag{10}$$

$$f_н = f + \Delta f \tag{11}$$

$$\Delta m = \Delta f \cdot m \tag{12}$$

$$\Delta E = \Delta m_B H \tag{13}$$

$$E_н = E + \frac{\Delta E}{m} = E + \Delta \mathrm{m} H \tag{14}$$

wehre U_B – is the normal velocity of flame propagation in motionless a mixture, m/s; Δl – edge length of the cell, m; E – specific total energy of the mixture in the cell, J/kg; ΔE – absolute energy release, J; H – calorific value of the mixture, J/kg; $f_н$ and $E_н$ – the proportion of the products of combustion and the total specific energy after step "burning" in the cell.

For spatial cells of a regular grid characteristic linear dimension is the length of the cube edge. There are several approaches to the definition of values as a function of the parameters of the mixture. In this paper, the authors accept a degree of dependence of the normal combustion rate on the relative change in temperature of the mixture [4]:

$$U_B = U_{BN} \left(\frac{T}{T_N} \right)^{\beta} \tag{15}$$

wehre U_{BN} – normal flame propagation velocity in the mixture at a fixed normal conditions, m/s; T и T_N – the current temperature of the mixture and the temperature of the mixture at normal conditions, K; β – indicator of power dependence.

The current temperature of the mixture can be determined from the equation of state of ideal gas:

$$T = \frac{p\mu}{\rho R} \tag{16}$$

where μ – molar mass of the mixture, kg/mol; R – universal gas constant, J/(K·mol).

The second step consists in modeling the propagation of combustion to adjacent cells. The first and second steps assume a stationary medium, which is typical for computing the Euler cycle stage of the method of large particles [10].

The third step is to account for the mass transfer of the burnt gas through the cell boundaries (the final stage of the method of large particles). Transfer modeled similarly to transfer the remaining parameters. However, due to the specific nature of the parameter f is the use of the same expression for determining tolerable values is inadequate. In this connection, the authors propose special calculation formula tolerable value f based on its physical interpretation.

General formulas for parameter transfer f:

$$f_{i+\frac{1}{2},j,k} = \begin{cases} 1, & \left(f_{i,j,k} > 1-\varepsilon\right) \vee \left(f_{i+1,j,k} > 1-\varepsilon\right) \\ 0, & \left(f_{i,j,k} < \varepsilon\right) \vee \left(f_{i+1,j,k} < \varepsilon\right) \\ \dfrac{f_{i,j,k} + f_{i+1,j,k}}{2} \end{cases} \quad (17)$$

Using formula (17) to determine the values of the parameter *f* ensures adequacy of the general formula for the transfer of this parameter. Expression (17) can also determine the conditions of combustion propagation to adjacent cells (the second step of the simulation of combustion). Condition "ignition" "initial" cells from the cell can be written as:

$$f_{i+\frac{1}{2},j,k} > \varepsilon \quad (18)$$

Enabling conditions for the propagation of the flame front in solving the system of equations seriously degrades the stability of the solution, so you have to take a step at a time, satisfying the Courant stability - Friedrichs - Lewy with a large (more than 10 fold) margin.

4 THE ADEQUACY OF THE MODEL

The adequacy of the numerical model is confirmed by comparing the results of physical and numerical experiments. Physical and computational models and similar premises presented a cylindrical chamber with a diameter of 200 mm and 1500 mm long with holes on the side of the surface: in the numerical model (Fig. 1) – 5 holes, and a physical model (Fig. 2) – 3 holes.

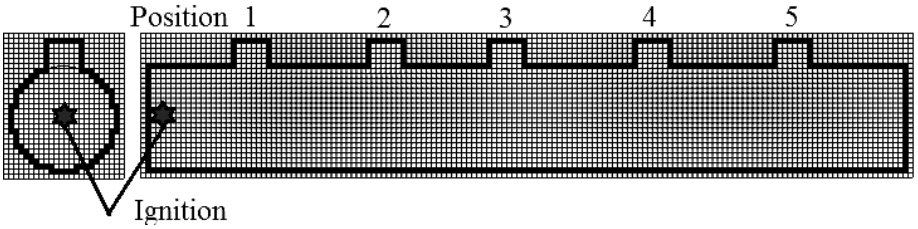

Figure 1. Estimated area

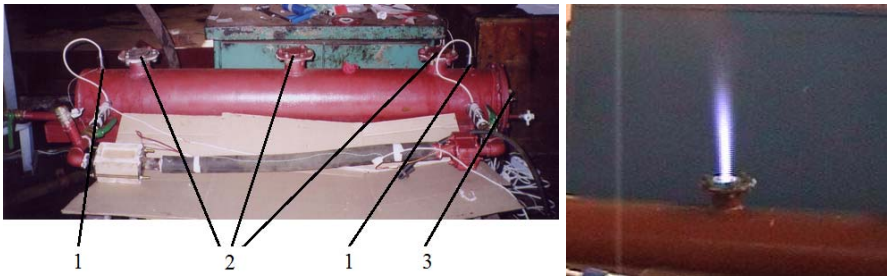

Figure 2. General view of “Sergeant” and experienced an explosion: 1 - pressure sensors, 2 - place of the explosion-relief valve, 3 - ignition device fitting position

Initial state holes - closed except one: the numerical model for one of the set {1, 2, 3, 4, 5} for the physical - from the set {1, 3, 5}. The hole diameter was varied from 20 to 70 mm. Chamber is filled with a stoichiometric mixture of propane-air gas. Ignition gas is always at the left end of [9]. In the numerical model edges of cells taken equal $\Delta x=\Delta y=\Delta z=0{,}01$ m, the total number is about 70,000, the time step $\Delta t = 5\cdot10^{-7}$ with.

To demonstrate reproducibility of the physical tests on the same chart 10 superimposed result conducted in the chamber with an opening 3 and an opening diameter of 40 mm (Fig. 3). For comparison with the results of numerical simulations (Fig. 3) selected these experiments, since the shape of the pressure curve in these experiments was quite difficult and had two peaks of pressure, and the process of the explosion was accompanied by acoustic oscillations (in other cases, the second peak is weak or even was not).

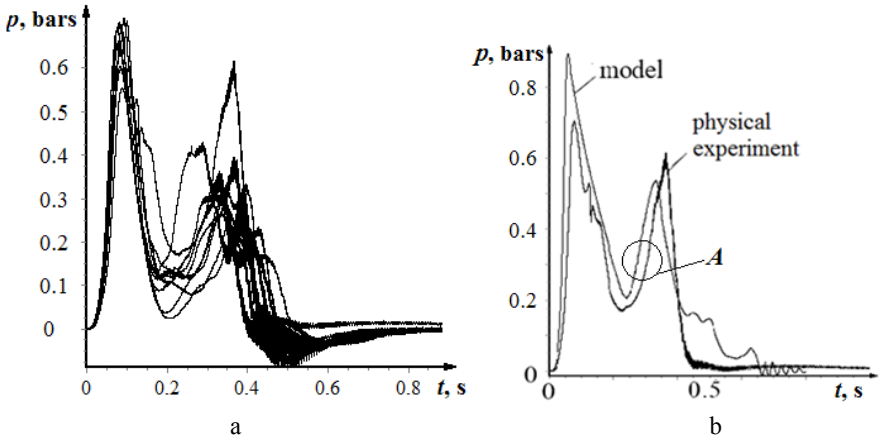

Figure 3. Ten physical experiments in position 3 with a diameter of 40 mm (a) and Comparison of the results of physical and numerical experiments (b)

Another confirmation of the adequacy of the numerical model is the presence of pressure fluctuations as in numerical simulations, and in physical experience, and these fluctuations had similar frequency and amplitude (Fig. 4). In experiments with other dimensions and position of windows such significant fluctuations do not. The difficulty of explaining their causes is that the system of equations describing the process of gas explosion, do not explicitly laid down in the mechanism of oscillations.

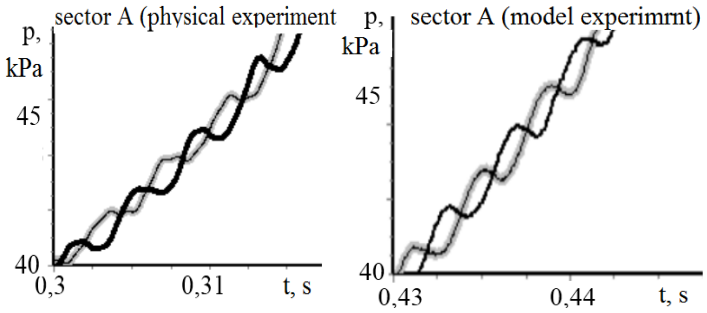

Figure 4. Pressure fluctuations in the explosion. Left – with the physical experience, on the on the right – the numerical model

5 EXPERIMENTAL RESULTS

Simulated explosion chamber having dimensions of 0.5 x 0.5 x 0.5 m and a window size of 0.3 x 0.2 m at the center of the wall. Ignition is always made at the rear wall on its center. The room was filled with a stoichiometric mixture of methane-air. The window is opened immediately after the start of the pressure rise in the chamber. Inside the chamber were set uniformly by volume 64 of the vertical column; cross-section of each of which was a square with a side length of 0.03 m. (Fig. 5). In the experiment, from one experiment to the pillars parted, forming a corridor, until completely merged with the side walls.

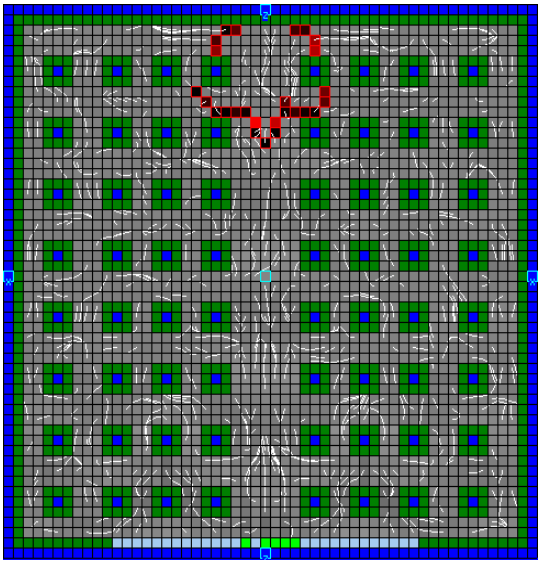

Figure 5. Horizontal cut of the chamber

Fig. 6 shows the calculated picture of the development of the flame front at the 3- versions of obstacles. Fig. 7 shows the evolution of pressure in these cases. Visible differences between the results.

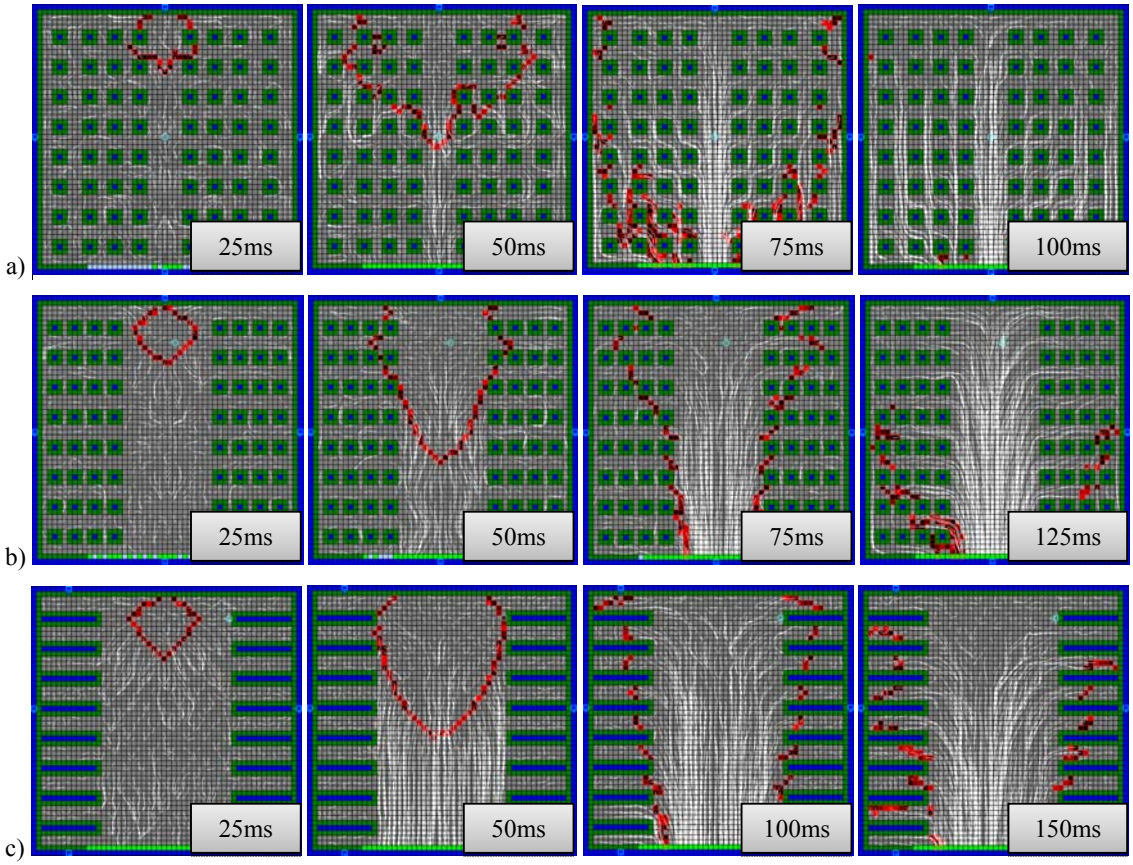

Figure 6. Dynamics of development of the explosion in chambers with a passage
a) 7 cm, b)18 cm, c) 26cm

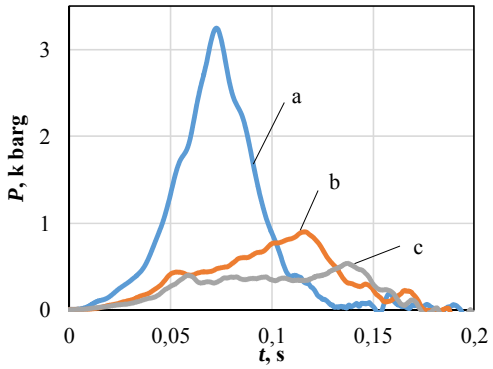

Figure 7. Explosion pressure in the chambers with a different passage
Passage width a) 7cm, b) 18cm, c) 26cm

For the synthesis of the results, we introduced of the notion of the maximum explosion pressure in the explosion, p_{max}, by which analyzed the impact of the provisions of the obstacles to the maximum explosion pressure. The obtained dependence is shown in Fig. 8. It can be seen that the chamber in case of a uniform arrangement of obstacles the explosion pressure is significantly higher than in the explosion of an empty chamber. However, even during the liberation of half of the chamber of obstacles the explosion pressure becomes even less than in the empty chamber.

From this we can conclude that the effect of obstacles in the maximum explosion pressure is ambiguous. If they are located on the way of the main flow of gases from the chamber to the window, the influence becomes serious and explosion pressure increases. And if the obstacles are located outside the main gas flow, the effect of their presence may be zero or even reversed. It is seen that the maximum reduction of pressure in this case is insignificant.

We pay attention to the kitchen, and noted that the traditional way of arranging the furniture along the walls is the most acceptable, not only in terms of ergonomics, but also reduce the risk of fracture in the kitchen gas explosion.

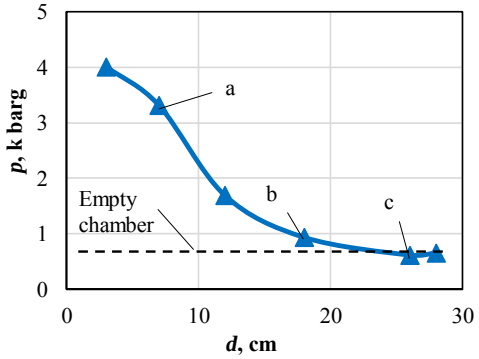

Figure 8. Maximum explosion pressure in the chambers with a different passage
Passage width a) 7cm, b) 18cm, c) 26cm

11 CONCLUSIONS

On the pressure of the gas explosion in the chamber can be influenced by the obstacles placed by volume. In addition to influencing the development of the explosion in the number and shape of obstacles, and is strongly influenced by location. The effect of the location of the obstacles to the development of the explosion in two ways: on the road at the location of the main flow of gas to the window, their presence increases the pressure of the explosion; if obstacles are located along the walls, they cannot influence the pressure. Moreover, in certain conditions, such an arrangement reduces the maximum explosion pressure, compared with the blast in an empty chamber, albeit slightly.

Known traditional furniture arrangement in the kitchen gasified along the walls helps reduce the risks of possible gas explosion.

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