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ON THE DEPENDENCE OF INTERNAL EXPLOSION PARAMETERS ON THE INSTALLATION OF SAFETY STRUCTURES IN THE APERTURES OF THE PROTECTING WALLS OF INDUSTRIAL AND RESIDENTIAL BUILDINGS

The issue of protection of residential buildings against gas mixture explosion in which glazing windows are considered as safety structures (SS), which are mounted in the depth of a window aperture, is considered. It is shown that when the fastenings, fixing the window frames to the wall of the building, are destroyed, the SS starts moving inside the aperture, the area for the gases discharge does not open, and the explosion occurs in the conditions of a sealed volume. It has been established that for small spaces (30–150 m^3) the rise time of pressure in an internal explosion is comparable to the movement time of the SS inside the aperture. The magnitude of the pressure increase during the movement of the SS inside the aperture has been determined. A dimensionless parameter has been selected that determines the pressure increase from the moment the SS begins to move until the aperture opens for gas outflow. It has been shown that twofold or tenfold pressure increase can cause destruction before its discharge. An expression for determining the speed of the SS at the moment of opening the aperture has been obtained, and this speed mainly determines the rate of pressure discharge due to the gases outflow. It has been established that the pressure increase during the movement of the SS inside the aperture exceeds the pressure increase pressure after the opening. It was revealed that when testing and designing SS, it is necessary to take into account the depth of SS embedment depth in the aperture, especially for residential premises, the volume of which does not usually exceed 120 m^3.

Keywords: internal explosion; pressure discharge; opening pressure; explosive burning speed; embedment depth; safety structures.

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Introduction

Domestic gas explosions in residential buildings have become a real national problem. Frequent reports from the scene, information on the number of victims and the causes of the incident are disturbing, which gives place to analysis of the causes and consequences of gas explosions in residential premises. In order to insure protection against the effect of overpressure in case of an internal crash explosion at industrial facilities, safety structures (SS) are required when these facilities are classified as explosive [1]. At the same time, the area of apertures that should be covered [2, 3] is regulated, as well as the requirements for SS, namely, their area in the case of collapsing glasses, as well as to the mass of an area unit in the case if SS is located in the coating.

The destruction of the glass depends on the shape and the thickness of the glazing sheets [3], as well as on the multiplicity of the glazing [4]. For SS located in the coating, it is required that their mass per unit area does not exceed 70 kg/m^2. Such requirements are not imposed for SS located in enclosing structures, since their optimality is not confirmed by research. It is obvious that these requirements should depend on the load-bearing ability of the facility to be protected and the characteristics of the explosion, primarily on the pressure rise rate during an explosion inside the volume.

Residential buildings and kitchen premises are not characterized as explosive, and special measures for their protection against explosion are not provided. However, the frequent explosions of domestic gas in residential buildings force us to pay attention to this problem, in particular to raise the question of using SS in kitchens.

In residential buildings, window sashes serve as natural protective structures, which are sealed inside apertures. Glass blocks in window sashes retain integrity with increasing pressure up to values that correspond to the opening of SS. Therefore, the emphasis is on the separation of the window sash from the enclosing walls and its movement in the aperture with the subsequent opening of the space for the gases outflow from the volume. When the safety structures move inside the aperture, the volume in which the explosion occurs remains closed, so the pressure in it increases at a high rate. During the movement of the SS inside the aperture, the pressure in the volume can increase noticeably before its discharge begins after the SS is removed from the aperture.

The opening of inertial SS in the application for building protection has not been studied well enough. Most of the works are devoted to the protection of explosive equipment and structures that are more resistant to explosive loads [5–8].

The purpose of this work is to study the effect of the depth of SS embedment in the aperture on the nature of the explosion. In order to achieve this goal, it is necessary to solve two problems: to determine the pressure change during the movement of the SS in the aperture, as well as to find out how the pressure increase and acceleration of the SS during the movement in the aperture affect the pressure discharge after opening the space for the gases outflow. For a more fruitful consideration of the issue, it is necessary to recall the main points that occur during an internal explosion. As we go forward, it is assumed quasistatic nature of the explosion [5, 9].

Research methods

Explosive burning is deflagrational and begins in an airtight volume. The change in pressure is described by the expression [10, 11]:

$$\frac{P_{(t)} - P_0}{P_{\max} - P_0} = \frac{m_{(t)}}{m_0}, \qquad (1)$$

where $P_{(t)}$ — the current pressure in the room, kPa;

P_0 — external pressure, most often atmospheric, kPa;

$P_{\max}$ — maximum explosion pressure in a completely sealed volume, kPa;

$m_{(t)}$ — mass of the mixture burned to the timepoint t, kg;

m_0 — the mass of the combustible mixture at the initial moment of the explosion in a completely thick with fumes volume, kg.

Parameter $P_{\max}$ depends on the properties of the original combustible mixture in a completely thick with fumes volume. If we accept that the calculated allowable pressure $\Delta P_{allowable}$ is about 7 kPa, $P_{\max}$ = 800 kPa, then from (1) it follows:

$$\frac{\Delta P_{allowable}}{\Delta P_{\max}} = \frac{m_{(t)}}{m_0} = 10^{-2}.$$

This estimate shows that even when gas is 1 %, the explosion pressure will already reach the calculated allowable value. The calculated values of allowable pressure are determined by the calculation of the carrying capacity of the first group of limit states [12–16].

It follows from the expression (1) after differentiation:

$$\frac{\mathrm{d}\Delta P_{(t)}}{\mathrm{d}t} = \Delta P_{\max} \frac{4\pi U_{b1}^3 \sigma^2 t^2}{V_0}, \qquad (2)$$

where $\Delta P_{(t)} = P_{(t)} - P_0$;

U_b — burning rate, the constant up to the moment of depressurization of the volume;

σ — expansion ratio during burning, that is, the ratio of the initial mixture density to the combustion residue density;

t — time before opening the SS, sec;

V_0 — free volume of the room, m^3.

Expression (2) was obtained under the assumption that the proportion of the burned substance is small, therefore the density of the initial mixture is constant and equal to the initial density ρ_0; the focus of the explosion has a spherical shape. It follows from the expression (2):

$$\frac{\Delta P_{(t)}}{P_0} = \Delta P_{\max} \frac{4\pi \frac{(\sigma - 1)\sigma^3}{\sigma} U_{b1}^3 t^3}{3V_0} = \gamma \frac{\sigma - 1}{\sigma} \frac{V_{(t)}}{V_0}, \qquad (3)$$

where $\gamma = C_p / C_V$ for combustion residue;

C_p — specific isobaric heat capacity, J/(kg·K);

C_V — specific isochoric heat capacity, J/(kg·K).

With γ = 1.27 and $\bar{P}_{\max} = P_{\max}/P_0 = 8$ expansion ratio σ = 6.5. From (3) it can be seen that the pressure at the initial stage of the explosion grows in proportion to $U_{b1}^3 \sigma^3 t^3$ before reaching pressure ΔP_{open}, at which the window sashes are opened for the gases outflow at the timepoint t_{open} (Fig. 1). The content and meaning of Fig. 1 are disclosed when discussing experimental oscillograms $\Delta P_{(t)}$ in works [17–20].

Starting from the moment t_{break} to the moment t_{open} the SS moves inside the aperture, without opening

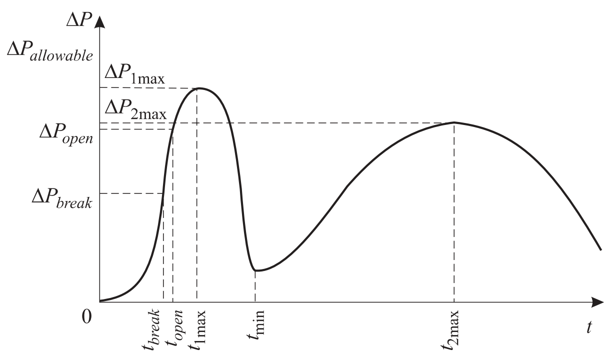

Fig. 1. The nature of the pressure change during an explosion in a volume with opening apertures: ΔP_{break} — opening pressure of the SS, corresponding to the time of destruction of the fixation of the SS to the building frame

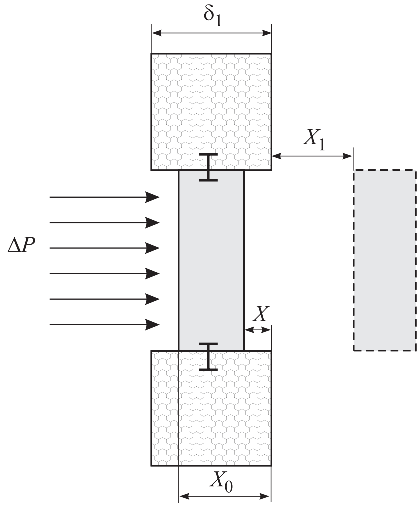

Fig. 2. SS movement inside the aperture

the space for the gases outflow (Fig. 2). This means that the volume in the time interval $0 - t_{open}$ remains sealed, although in the period from t_{break} to t_{open} the SS are in motion. The increase in free volume during the movement of the SS is neglected. After the beginning of the opening of the space for the gases outflow, the pressure in the volume increases to P_{1max} for a time $\Delta t_1 = t_{1max} - t_{open}$.

The area of open space for the gases outflow at the moment t_{1max} will make:

$$S_{1max} = X_{1max} Pr,$$

where Pr — perimeter of the aperture, m.

This area is usually smaller than the area of a fully open aperture S_o. As the SS continues to move, the discharge area increases faster than the burning area increases, and the pressure in the volume drops to ΔP_{min}. Around the time t_{min} there is a change in the composition of the outflowing mixture. Instead of the cold initial mixture, hot combustion residue start flowing at a rate of $\sigma^{1/2}$ of the amount. As a result of the opening of the aperture and the beginning of the hot gases outflow, a rarefaction wave occurs inside the volume, which leads, as a rule, to the development of flame instability and to its possible turbulence. When this happens, the burning rate increases. After the full opening of the aperture, the area of outflow gases will be constant, and the expansion of the seat of fire will continue with a simultaneous increase in the area of burning; the pressure in the volume will increase until the front approaches the walls and the corners of the room. At this moment, the maximum burning area and maximum pressure are realized ΔP_{2max}.

Results of analysis and calculations

So, after the destruction of the SS fixtures to the walls, they begin to move in the aperture. The equation of motion of the SS is:

$$M\frac{d^2X}{dt^2} = ab\Delta P_{(t)}, \qquad (4)$$

where $X = 0$, $dX/dt = 0$ with $t = 0$;

$\Delta P(0) = \Delta P_{open}$;

M — the mass of the safety structure;

ab — SS area;

$\Delta P_{(t)}$ — excess pressure effecting the SS since t_{break} until the moment t_{open}, when the SS will go section X_0, and the space for the gas outflow will begin to open.

Solution of equation (4) on the section $0 - X_0$ or in the range of t_{break} to t_{open} is given by:

$$\bar{X} = \frac{B}{4}\left[\frac{(1+\theta)^5}{5} - \theta - \frac{1}{5}\right], \qquad (5)$$

where $B = \dfrac{ab t_{break}^2 \Delta P_{break}}{mX_0}$;

$$t_{break} = \frac{1}{U_{b1}\sigma}\left[\frac{3\Delta P_{break} V_0 \sigma}{P_0 4\pi\gamma(\sigma - 1)}\right]^{1/3};$$

$$\bar{X} = \frac{X}{X_0};\ \theta = \frac{t - t_{break}}{t_{break}}. \qquad (5)$$

After reaching the value $\bar{X} = 1$ the space starts to open space for the gases outflow. The dimensionless time to reach the opening moment $\theta_o = \dfrac{t_{open} - t_{break}}{t_{break}}$ determined by the condition $\bar{X} = 1$ from (5):

$$\frac{4}{B} = \left[\frac{(1+\theta_o)^5}{5} - (1+\theta_o) + \frac{4}{5}\right]. \qquad (6)$$

The rate of the SS at the beginning of the opening of the aperture at $\bar{X} = 1$, $t = t_{open}$, $\theta = \theta_o$ is given by

$$\left.\frac{d\bar{X}}{d\theta}\right|_{\substack{\bar{X}=1\\ \theta=\theta_o}} = \frac{B}{4}[(1+\theta_o)^4 - 1]. \qquad (7)$$

Table 1 shows the results of the calculation of the time of breaking t_{break} and opening time beginning t_{open} depending on the volume of the room and ΔP_{break} or ΔP_{open}. Calculations are given for $U_{b1} = 3.1U_n = 3.1 \cdot 0.35 = 1.085$ m/s and $\sigma = 6.5$, $\gamma = 1.27$.

In table 1, the difference between the time values for the rooms with the same volume (i. e. in the same column) gives the time of movement of the SS inside the aperture since the destruction of the SS fixtures t_{break}, until the opening of the aperture t_{open}. It follows from the table data analysis 1 that with a slight time difference t_{break} and t_{open} the pressure in the volume changes several times and may exceed the allowable pressure before the opening of the aperture. Thus, the SS is subject to a strict requirement, namely: they have to go their way in the aperture before it opens for the time $\theta_o = (\Delta t_{open} - \Delta t_{break})/\Delta t_{break} << 1$.

Table 1. Breaking time t_{break} and opening time beginning t_{open} calculation results depending on the volume of the room and pressure

Pressure, kPa	Time, sec, with the room volume of m^3						
	30	40	50	60	100	120	150
$\Delta P_{break} = 2$	0.0725	0.080	0.086	0.091	0.108	0.1150	0.124
$\Delta P_{open} = 5$	0.0984	0.109	0.117	0.123	0.147	0.1560	0.167
$\Delta P_{open} = 7$	0.1100	0.121	0.130	0.138	0.164	0.1740	0.188
$\Delta P_{open} = 10$	0.1240	0.137	0.147	0.156	0.185	0.1970	0.210
$\Delta P_{open} = 15$	0.1420	0.156	0.168	0.178	0.210	0.2255	0.243

Note. For ΔP_{break} is specified breaking time, for ΔP_{open} — opening time beginning of SS.

After the beginning of the opening of the aperture for the gases outflow, the equation of motion of the SS can be represented as

$$m\frac{d^2X_1}{dt_1^2} = ab\frac{\Delta P_{open} + \Delta P_{1\max}}{2}, \qquad (8)$$

where X_1 — SS displacement after aperture opening t_{open};

t_1 — SS movement time after the opening of the aperture t_{open}.

The starting point of movement and begin time starts at 0, the initial value of rate — $\left.\frac{dX_1}{dt_1}\right|_{t_1=0} = \left.\frac{dX}{dt}\right|_{t=t_{open}}$, that is, at the time of opening the aperture, the SS has sufficient rate, and the further opening of the aperture is determined by its value.

In equation (8) the maximum pressure in the volume after opening the aperture $\Delta P_{1\max}$ should not be more than the allowable, i. e. $\Delta P_{1\max} \le \Delta P_{allowable}$.

In solving (8), it was considered that the average pressure effects the SS $(\Delta P_{open} + \Delta P_{1\max})/2$. Given that when leaving the aperture, the SS starts with the initial rate determined from (7), it can be assumed that the pressure $\Delta P_{1\max}$ is slightly different from ΔP_{open}.

Then the solution of equation (8) is

$$X_1 = \frac{ab}{m}\frac{\Delta P_{open}}{2}t_1^2 + B_1 t_1; \qquad (9)$$

$$B_1 = \frac{BX_0}{4t_{break}}[(1+\theta_o)^4 - 1]$$

or

$$\bar{B}_1 = \frac{B}{4}[(1+\theta_o)^4 - 1], \qquad (10)$$

where $\bar{B}_1$ — the dimensionless rate of the safety structures at the time of their removal from the aperture.

The opening time of the aperture is determined from (6) for different values M. Magnitude M varies over a wide range and determines the time from the beginning of the breaking to the opening of the aperture. The smaller the value of M is, the longer time the safety structure moves before the opening of the aperture and the higher the pressure in the volume at the time of its opening.

When determining the force effecting the SS from the side of the explosion, it is necessary to take into account the pressure distribution over the SS surface. The pressure decreases from the center of the SS to the periphery. Taking into account this circumstance in a stationary flow around a circular SS causes twofold reduction in the driving force. This circumstance affects the movement of the SS after opening the aperture and has little effect on the nature of the pressure change [5]. In the considered case, the motion of the SS begins inside the aperture, and there is no flow of gas around it. The main pressure increase also occurs when the SS moves inside the aperture. After the opening of the aperture, the movement of the SS is determined by its initial rate, and the acceleration can be neglected.

There are shown in Table 2 time dependencies $t_{open} = t_{break}(1+\theta_o)$, of the ratio $\Delta P_{open}/\Delta P_{break} = (1+\theta_o)^3$ and the value $\bar{B}_1$ from parameter B.

In analyzing solution (9) and (10), $\Delta P_{allowable} \approx \Delta P_{1\max}$, which is true for lightweight SS. In this case we receive:

$$\bar{X}_1 = B\theta_1\left[\frac{(1+\theta_o)}{2}\theta_1 + (1+\theta_o)^4 - 1\right]; \qquad (11)$$

$$\bar{X}_1 = \frac{X_1(t)}{X_0};\ \theta_1 = \frac{t_1}{t_{break}}.$$

Table 2. Time dependence $t_{open} = t_{break}(1+\theta_o)$, of the ration $\Delta P_{open}/\Delta P_{break} = (1+\theta_o)^3$ and the value $\bar{B}_1$ from parameter B

Parameter	Parameter value depending on B								
	0.5	1.0	2.0	4.0	6.0	10	16	30	50
$t_{open} = t_{break}(1+\theta_o)$	2.16	1.91	1.71	1.54	1.41	1.37	1.31	1.26	1.18
$\Delta P_{open}/\Delta P_{break} = (1+\theta_o)^3$	10.08	7	5	3.65	2.8	2.6	2.25	2.0	1.66
$\bar{B}_1$	2.6	3.1	3.75	4.65	5.86	7.6	8.25	9.7	12

When opening the aperture, the gases begin to outflow from the volume, and the pressure in the volume is described by the expression

$$\frac{d\Delta\overline{P}_1'}{d\theta_1} = \frac{3\left(1+\dfrac{\theta_1}{1+\theta_o}\right)^2}{1+\theta_o} - 0.266\nu_1 \frac{\Pi\Delta P_{break}^{3/2}\,\theta_1}{\sigma^2(\sigma-1)U_b^3} \times \times \frac{\dfrac{1+\theta_o}{2}\theta_1 + (1+\theta_o)^4 - 1}{\rho_0^{1/2}\rho_{area}(1+\theta_o)^{3/2}}\sqrt{1+\Delta\overline{P}_1'}, \quad (12)$$

where $\Delta\overline{P}_1' = (P_{(t)} - P_{open})/\Delta P_{open}$;

ν_1 — discharge coefficient; $\nu_1 \approx 0.8$;

ρ_0 — initial mixture density, kg/m^3;

ρ_{area} — SS area unit mass, kg/m^2; $\rho_{area} = M/(ab)$.

As noted earlier, after passing a section of the path X_0 SS gains the rate $\overline{B}_1\,(X_0/t_{break})$, which is tens of meters per second, and the further opening of the aperture is determined by its value. At the same time $\Delta\overline{P}_1' << 1$ and $\theta_1 << 1$, therefore, in the equation (12) these values can be neglected in comparison with the unity. Then the equation (12) becomes:

$$\frac{d\Delta\overline{P}_1'(\theta_1)}{d\theta_1} = A - F\theta_1; \quad (13)$$

$$A = \frac{3}{1+\theta_o};$$

$$F = 0.266\nu_1 \frac{\Pi\Delta P_{break}^{3/2}}{\sigma^2(\sigma-1)U_b^3}\frac{(1+\theta_o)^4-1}{\rho_0^{1/2}\rho_{area}(1+\theta_o)^{3/2}}, \quad (14)$$

where $0.266 = 3\cdot 2^{1/2}/(4\pi\gamma)$.

The perimeter of the aperture is determined after establishing the required area of apertures [4, 17, 18].

Then the solution of equation (13) is

$$\Delta\overline{P}_1' = A\theta_1 - \frac{F\theta_1^2}{2}. \quad (15)$$

It can be seen from the solution of equation (15) that the pressure after the opening of the aperture increases, and when $\theta_{1\max} = A/F$ its maximum is realized. At the same time the maximum pressure rise $\Delta\overline{P}_{1\max}' = A^2/(2F)$.

Total pressure in the volume up to the moment $\Delta t_{1\max} = t_{break}(1+\theta_o) + t_{break}\theta_{1\max}$ (see Fig. 1) is defined as

$$\Delta P_{1\max} = \Delta P_{break}(1+\theta_o)^3\left(1+\frac{A}{2F}\right). \quad (16)$$

By the time the maximum pressure is reached $\Delta P_{1\max}$ the aperture is not fully open. This means that the distance covered by the SS after opening the aperture for the time $\Delta t_{1\max} = t_{break}\,\theta_{1\max}$, is less than the distance X_2, corresponding to a fully open aperture ($X_2 = S_o/Pr$).

Table 3 presents the results of calculations of characteristic magnitudes for the initial stage of explosion development, taking into account the motion of the SS in the aperture and the gases outflow.

The data was used on the perimeter of the aperture through which the pressure is discharged in compiling Table 3. The shape and size of the aperture was chosen while performing the design according to the known required area of apertures S_o, which is determined from the condition of maintaining the load-bearing capacity of building structures. As already noted, the allowable explosion pressure is established by calculating the building elements on the load-bearing capacity of the first group of limit states. For a specific allowable pressure $\Delta P_{allowable}$ the required area of the apertures opened by that moment is calculated S_o. Allowable pressure should not be less than the pressure $\Delta P_{2\max}$ (see Fig. 1), which is implemented at the moment of maximum area of the flame during the explosion. This maximum area is determined by calculation, for example, by the method of large particles [21], or experimentally on small scale models [22–24]. To estimate the maximum area of the flame during explosions in rectangular rooms, the dependence was used $S_{2\max} = 4.5V_0^{2/3}$.

Thus, obtained area by 10 % exceeds the surface area of the sphere, the volume of which is equal to the volume of the room V_0.

Burning rate U_{b2}, corresponding to the moment of realization of the second pressure maximum, was determined from the assumption of low initial turbulence in the volume $U'/U_n < 1$, when the burning rate is determined by the flame instability [24–27]. Flame instability is always manifested when changing the composition of the outflow gases [19, 20]. By the time of realization of the maximum area of burning, the outflow of hot combustion residue is always observed. When compiling Table 3 was taken $U_{b2} = 5U_n = 5\cdot 0.35 = 1.75$ m/sec [26, 28–33]. The very area of apertures was determined from the condition of reaching the second pressure peak $\Delta P_{2\max}$.

The condition for the realization of the second maximum is the equality of the volumetric flow rate of:

- outflow gases $\dot{V}_-$:

$$\dot{V}_- = S_o\nu_2\sqrt{\frac{2\Delta P_{allowable}\,\sigma}{\rho_0}}; \quad (17)$$

- gas production during burning $\dot{V}_+$:

$$\dot{V}_+ = U_{b2}(\sigma-1)K_f V^{2/3}, \quad (18)$$

where K_f — coefficient of a form.

The coefficient of a form is assumed to be 4.5. As a result, for the room with the volumes of $V_0 = 30$; 50 and 100 m^3 outflow areas S_o make up 1.5; 2.1 and 3.34 m^2, and the perimeters of the apertures Pr — 5.0; 5.9 and 7.5 m. In determining S_o allowable pressure was assumed $\Delta P_{allowable} = 9$ kPa.

Table 3. The results of calculations of characteristic values for the initial stage of the development of the explosion development. taking into account the motion of the SS in the aperture and gas outflow

Parameter	$B = 1$			$B = 2$			$B = 4$			$B = 8$			$B = 16$			$B = 30$			$B \to \infty$					
	Room volume V_0, m^3																							
	30	50	100	30	50	100	30	50	100	30	50	100	30	50	100	30	50	100	30		50		100	
	Aperture area S_o, m^2 / Aperture perimeter Pr, m																							
	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{2.1}{5.9}$	$\frac{3.34}{7.5}$	$\frac{1.5}{5}$	$\frac{3 \cdot 0.5}{11.8}$	$\frac{2.1}{5.9}$	$\frac{3 \cdot 0.7}{14.1}$	$\frac{3.34}{7.5}$	$\frac{3 \cdot 1.113}{19.1}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
ρ_{area}, kg/m^2	33.1	37.2	49.2	26.25	29.5	33.7	25	30	30; 10; 20	20	25	27	13.125	18.44	27	10			20		25		27	
X_0, m	0.32	0.4	0.48	0.2	0.25	0.32	0.105	0.123	0.18; 0.54; 0.27	0.066	0.074	0.1	0.05			0.0345	0.048	0.072	0					
$1 + \theta_o$	1.91			1.71			1.54			1.41			1.31			1.26			1					
A	1.57			1.75			1.95			2.13			2.29			2.38			3					
$F(F_1)$	45.1	47.4	45.5	41.3	43.36	48.25	31	25.9	39.2; 116.7; 58.2	28.22	26.6	31.6	31.76	26.7	23.16	34.5	40.7	41.3	14.11	33.36	13.3	31.8	15.8	40.23
θ_{1max}	0.0348	0.033	0.0345	0.0423	0.04	0.0364	0.063	0.075	0.05; 0.0167; 0.0338	0.0755	0.08	0.067	0.072	0.086	0.099	0.069	0.0585	0.046	0.46	0.29	0.475	0.307	0.436	0.273
$\Delta\overline{P}_{1\,max}$	0.0273	0.026	0.027	0.0372	0.0355	0.032	0.0613	0.073	0.0465; 0.0163; 0.032	0.08	0.085	0.072	0.0826	0.098	0.11	0.082	0.0696	0.055	0.92	0.598	0.95	0.614	0.872	0.546
ΔP_{1max}, kPa	14.38	14.36	14.38	10.372	10.355	10.32	7.75	7.83	7.654; 7.42; 7.53	6.05	6.076	6.0	4.87	4.94	5	4.32	4.28	4.22	3.84	3.2	3.9	3.23	3.75	3.09
X_2, m	0.3	0.356	0.445	0.3	0.356	0.445	0.3	0.356	0.445	0.3	0.356	0.445	0.3	0.356	0.445	0.3	0.356	0.445	0.3	0.188	0.356	0.149	0.445	0.175
X_{1max}, m	0.137	0.16	0.2	0.128	0.151	0.137	0.122	0.171	0.166; 0.166; 0.163	0.118	0.14	0.159	0.106	0.128	0.147	0.077	0.09	0.107	0.08	0.0305	0.123	0.036	0.159	0.041
K_f	0.46	0.445	0.45	0.427	0.424	0.31	0.41	0.48	0.373; 0.374; 0.373	0.393	0.392	0.357	0.353	0.36	0.31	0.26	0.253	0.24	0.27	0.24	0.35	0.24	0.36	0.234
ΔP_{open}, kPa	14.0			10.0			7.3			5.6			4.5			4			2					

The burning rate at the first maximum until the outflow of the hot combustion residue was determined from the condition that in this case the burning occurs in a sealed volume.

Explosive burning rate U_b depends on many parameters: primarily from the laminar flame rate of the combustible mixture U_n; secondly — from the level of turbulence in the initial mixture before the combustion zone. The turbulence level mainly depends on the interaction of the gas flow caused by the expansion during burning process with obstacles. During an explosion at petrochemical and chemical plants, barriers play an important role in accelerating burning process. They are in free space there, and the stream flows around them. Another thing is with the kitchen space. The barriers are located here directly at the walls, and the stream, moving perpendicular to the walls, does not completely flow around the barriers. However, when approaching the walls and barriers, the flame is deformed, and its shape deviates from the spherical one. At the same time, its surface area increases, but when it comes into contact with the walls and barriers, the second pressure peak is realized $\Delta P_{2\max}$. With weak turbulence in the initial mixture, the burning rate is determined by auto-turbulence, which in its turn is caused by flame instability [25, 30–33].

According to [25] the burning rate provided $U_n / U' > 1$ and flame instability is determined by the expression

$$U_b = U_n \psi(\sigma) \ln \frac{U_b L_{\max}}{a\sigma}, \quad (19)$$

where $\psi(\sigma) = \frac{\sigma}{\sigma+1}\left(\sqrt{\sigma+1-\frac{1}{\sigma}}-1\right) = 1.48$ with $\sigma = 6.5$;

$L_{\max}$ — maximum perturbation at the flame front;

a — thermal diffusivity.

In case of emergency explosions, especially at the initial stage, the explosive mixture is heterogeneous, and the burning rate at this moment depends on random leak conditions. Instability and auto-turbulence develop by the time when the Peclet number, determined by the initial fire radius $\text{Pe} = U_n R/a > 10^5$ (where R — initial fire radius) [31]. When burning air mixtures, including natural gas, the size of the initial fire radius corresponds to 4–5 m, while the volume of the initial fire is 400 m^3, which greatly exceeds the volume of kitchen space. Therefore, when burning in the conditions of kitchen premises, auto-turbulence does not occur until the moment of the volume depressurization. In [31] the maximum burning rate corresponding to the start of auto-turbulence is estimated as

$$U_b / U_n = 3.1. \quad (20)$$

The burning rate is evaluated in this way U_{b1} at the first peak of pressure. After hot combustion residue begin to outflow, a rarefaction wave propagates into the volume, which causes spontaneous flame instability with a finite amplitude of disturbances. This, in turn, may cause earlier burning turbulence. Due to this, the burning rate U_{b2} is given with a higher value.

Discussion of research results

Analysis of the data presented in Table 3 shows that with $B = 1$ and $B = 2$ the pressure of the explosion before the opening of the aperture increased, respectively, to 14 and 10 kPa, which is higher than the allowable value $\Delta P_{allowable} = 9$ kPa. This means that the facility does not meet the requirements for load bearing capacity. It is possible to reduce the explosion pressure by increasing the parameter B by reducing the product $\rho_{area} X_0$. It is useful to consider the possibility of reducing the pressure of the explosion by the time of aperture opening. ΔP_{open}, reducing breaking pressure ΔP_{break}. Breaking pressure reduction ΔP_{break} from 2 to 1 kPa reduces parameter B in $2^{5/3}$ times. So, if with $\Delta P_{break} = 2$ kPa $V = 2$, then with $\Delta P_{break} = 1$ kPa we get $B = 0.63$.

Despite the decrease in the parameter B by reducing the breaking pressure, the final pressure of the explosion in a sealed volume ΔP_{open} decreases by reducing ΔP_{break}. With $B = 0.63$, it follows from the expression (6), that $(1 + \theta_o) = 2.07$, so $\Delta P_{open} = 8.87$ kPa, which is less than $\Delta P_{open} = 10$ kPa with $B = 2$ and $\Delta P_{break} = 2$ kPa.

The increase in pressure after the start of gases outflow from the volume is insignificant and is usually no more than 10 %. This situation is a direct consequence of the SS acceleration in the initial section of the motion on the way X_0.

The increase B parameter causes a decrease in the final pressure of the explosion only in the case of a decrease in the product $\rho_{area} X_0$. Reduction in magnitude ρ_{area} is limited: value $\rho_{area} = 10$ kg/m^2 with $B = 30$ is already close to the limit. The reduction of X_0 to 0 can be probably achieved by fastening the SS to the outer wall of the enclosures or profiling by the corresponding expansion of the apenture. When the parameter B tends to infinity, equation (13) takes the form:

$$\frac{d\Delta \overline{P}'}{d\theta} = A(1+\theta)^2 - F_1 \theta^2 (1 + \Delta\overline{P}')^{1/2}. \quad (21)$$

With $X \to 0$ magnitude θ_o tends to 0, that is why

$$\Delta \overline{P}_{(t)} = \frac{\Delta P_{(t)} - \Delta P_{break}}{\Delta P_{break}}; \quad \theta = \frac{t - t_{break}}{t_{break}};$$

$$F_1 = \frac{0{,}133 \nu Pr \Delta P_{break}^{3/2}}{\sigma^2 (\sigma - 1) U_{b1}^3 \rho_0^{1/2} \rho_{area}}.$$

Analysis of equation (21) with the assumption of smallness of θ and $\Delta\overline{P}''_{1\max}$ is possible only if the value of the parameter F_1 exceeds ~30. When taken for estimates $\sigma = 6.5$, $U_{b1} = 1.035$ m/sec, $\Delta P_{break} = 2000$ Pa we get $Pr/\rho_{area} \approx 1$ m^3/kg. This situation can be implemented in the case of small values $\rho_{area} \approx 10$ kg/m^2 and the use of several SS with a smaller area, but provided that their total area is equal to the required one. In this case, the total perimeter increases in $K^{1/2}$ times. Increacing the perimeter can also be achieved by changing the shape of the aperture as a result of increasing the difference in the sizes of its sides.

Since the required area of the open apertures $S_o \sim \sim V_0^{2/3}$, and $Pr \sim V_0^{1/3}$, it becomes clear that for large volumes the condition $Pr/\rho_{area} \sim 1$ m^3/kg can be achieved easier. In Table 3 in columns 20–25 with $B \to \infty$ the data on the opening of the apertures covered with SS are shown, which are not included in the aperture but are attached to the outer side of the wall ($X_0 = 0$). Columns 20, 22, and 24 contain the results obtained for a single aperture, and columns 21,23, and 25 show the results obtained for the same total outflow area, but implemented in three apertures. As a result, the pressure discharge rate through three apertures is higher than through one aperture. Time for reaching the maximum pressure $\theta_{\max} = \sqrt{A/F_1}$, and the maximum pressure itself — $\Delta\overline{P}_{1\max} = 2/3 \cdot A\sqrt{A/F_1}$. For the explosion area of a spherical shape, which at the initial moment of the explosion is quite real, $A = 3$. Comparison of data from Table 3 for the case $B \to \infty$ with other cases shows that the final absolute pressure at the first maximum ($\Delta P_{1\max}$) is always less for the occasion $B \to \infty$. It should be noted that the approximation adopted in obtaining the results for $B \to \infty$, especially for columns 20, 22 and 24, is performed badly and value $\Delta\overline{P}_{1\max}$ is sufficiently large. For the approximation, it was necessary to reduce ρ_{area} and U_{b1}. The case $B \to \infty$ was compared with case $B = 8$. In fact, when is applied $B \to \infty$ maximum explosion pressure is not determined by this parameter. It is necessary to remind that estimates $\Delta\overline{P}_{1\max}$ for $B \to \infty$ is somewhat overestimated in comparison with the results of the numerical solution (21). Therefore, the conclusions that if $B \to \infty$, when $X_0 = 0$, the maximum explosion pressure is always less than for the final values B, remains in force. Since, as has been shown, SS embedment inside the opening leads to a noticeable and sometimes significant increase in the explosion pressure during the opening process of the aperture, it is necessary to analyze the effect of various parameters on the pressure increase. The highest rate of pressure growth in an internal explosion is observed before the opening of the apertures, while the maximum pressure rise is controlled by B. The smaller parameter B is, the higher the pressure in the volume before opening the aperture. You can use four parameters to control B parameter: SS mass unit area ρ_{area}, the depth of SS embedment in the aperture X_0, breaking pressure ΔP_{break} (destruction of SS fixation with the enclosure), perimeter of apertures through which gases outflow. When reducing the product $\rho_{area} X_0$ the parameter B increases and the opening pressure of the aperture is reduced. With increasing breaking pressure ΔP_{break} B parameter, and dimensionless opening pressure reduces $\Delta\overline{P}_{open} = \Delta P_{open} / \Delta P_{break}$ as well, but absolute pressure $\Delta P_{open} = \Delta P_{break}(1 + \theta_o)^3$ increases. Therefore, if the breaking pressure decreases ΔP_{break}, then the explosion pressure decreases, despite the increase in the parameter B. As while opening the area for the gases outflow the maximum pressure $\Delta P_{1\max}$ is achieved with not fully open aperture ($X_{1\max} < X_0$), the value of the perimeter of the aperture becomes rather significant. The increase in the perimeter leads to an increase in parameters F and F_1, and as a result, to a more rapid opening of the outflow areas and to a decrease in pressure at the first maximum $\Delta P_{1\max}$. It is possible to increase the perimeter of the apertures by increasing the number of apertures covered with SS, as well as by the difference in the length of the sides of the aperture. The first method is more effective. It should be noted that the product has the most significant influence on the pressure at the first peak and on the opening pressure $U_{b1}^2 \sigma^2 (\sigma - 1)$, but it is impossible to control this value in advance due to the randomness of the process of gas pollution and combustion. The results of [25, 30–33] were adopted to estimate this value in the work which are rather pessimistic.

In this work, the most typical and possible values of the B parameter are considered, for which the motion of SS can be divided into two periods. The motion inside the aperture before it opens and the motion after removal from the aperture after opening it. When moving inside the aperture, the SS accelerates and by the time it leaves the aperture it has sufficient rate. B_1, so displacement X_1, ensuring the gases outflow is determined by this rate: $X_1 \approx B_1 \Delta t_1$. At higher values B, including with $B \to \infty$ with $X_0 \to 0$, SS displacement after opening the aperture is determined by the SS acceleration, and $X_1 \approx \dfrac{\Delta P_{break} + \Delta P_{\max}}{4\rho_{area}} t_1^2$. This explains the difference in expressions for determining maximum values $\theta_{1\max}$ and $\Delta\overline{P}_{1\max}$.

Conclusion

In conclusion, it should be noted that, before publishing this work, the issue of SS embedment in apertures was not given due attention. This state of affairs needs to be reviewed and when designing ways of SS fixture, it is necessary to take into account the depth of SS embedment inside the aperture. It should be noted that the goal, which was to find out the effect of the depth of the SS inside the aperture on the nature of the explosion, has been achieved. The influence of various factors, such as the breaking pressure, the SS mass, the burning rate, the initial volume of an explosive object, on the change in pressure during motion of the SS in the opening, has been revealed. The task has been completed relating to the magnitude and rate of pressure change during the motion of the SS inside the aperture. The task has been completed relating to the effect of depth of the SS embedment inside the aperture on the pressure discharge rate after gases outflow. The pressure discharge occurs faster due to the SS initial rate at the time of the gases outflow. When testing SS apertures on model installations, they also often do not take into account the possibility of embedding the fixture, assuming that the SS mass and the SS fixture properties completely solve the issue of SS efficiency. The results obtained in the work clearly show that it is necessary to take into account the depth of the SS embedment. SS tests on model installations take place at high values of the parameter *B*, as the explosive burning rate at the initial moment of explosion during testing corresponds to the flame propagation laminar rate. In this regard, the test results often give overly optimistic results.

REFERENCES

1. Set of rules 12.13130.2009. *Determination of categories of rooms, buildings and external installations on explosion and fire hazard*. Moscow, All-Russian Research Institute for Fire Protection of Emercom of Russia Publ., 2009. 28 p. (in Russian).
2. Set of rules 4.13130.2013. *Systems of fire protection. Restriction of fire spread at object of defense. Requirements to special layout and structural decisions*. Moscow, All-Russian Research Institute for Fire Protection of Emercom of Russia Publ., 2013. 184 p. (in Russian).
3. Set of rules 56.13330.2011. *Production buildings*. Moscow, Ministry of Regional Development of Russia Publ., 2011. 18 p. (in Russian).
4. Pilyugin L. P. *Obespecheniye vzryvoustoychivosti zdaniy s pomoshchyu predokhranitelnykh konstruktsiy* [Maintenance explosion proof buildings with relief designs]. Moscow, Pozhnauka Publ., 2000. 224 p. (in Russian).
5. Molkov V. V., Eber R. M., Grigorash A. V., Tamanini F., Dobashi R. Vented gaseous deflagrations: modelling of translating inertial vent covers. *Journal of Loss Prevention in the Process Industries*, 2003, vol. 16, no. 5, pp. 395–402. DOI: 10.1016/s0950-4230(03)00066-4.
6. Molkov V. V., Grigorash A. V., Eber R. M., Makarov D. V. Vented gaseous deflagrations: modelling of hinged inertial vent covers. *Journal of Hazardous Materials*, 2004, vol. 116, issue 1-2, pp. 1–10. DOI: 10.1016/j.jhazmat.2004.08.027.
7. Molkov V. V., Grigorash A. V., Eber R. M., Tamanini F., Dobashi R. Vented gaseous deflagrations with inertial vent covers: State-of-the-art and progress. *Process Safety Progress*, 2004, vol. 23, no. 1, pp. 29–36. DOI: 10.1002/prs.10002.
8. Molkov V. V., Grigorash A. V., Eber R. M. Vented gaseous deflagrations: Modelling of spring-loaded inertial vent covers. *Fire Safety Journal*, 2005, vol. 40, issue 4, pp. 307–319. DOI: 10.1016/j.firesaf.2005.01.004.
9. Gorev V. A., Salymova E. Yu. About the possibility of vibration combustion at internal explosions. *Pozharovzryvobezopasnost / Fire and Explosion Safety*, 2017, vol. 26, no. 5, pp. 13–20 (in Russian). DOI: 10.18322/PVB.2017.26.05.13-20.
10. Gorev V. A. Actions of explosive loads of the protecting designs taking into account vibration combustion. *IOP Conference Series: Materials Science and Engineering*, 2018, vol. 365, issue 4, art. no. 042047. DOI: 10.1088/1757-899X/365/4/042047.
11. Joes V. *Explosions and burning gases*. Moscow, Foreign Languages Publishing House, 1952. 687 p.
12. Markstein G. H. (ed.). *Nonsteady flame propagation*. Oxford, Pergamon Press, 1964. DOI: 10.1016/c2013-0-07744-4 (Russ. ed.: Markstein G. (ed.). Nestatsionarnoye rasprostraneniye plameni. Moscow, Mir Publ., 1968. 438 p.).
13. Pilyugin L. P. *Konstruktsii sooruzheniy vzryvoopasnykh proizvodstv (teoreticheskiye osnovy proyektirovaniya* [Designs of constructions of explosive productions (theoretical bases of design)]. Moscow, Stroyizdat Publ., 1988. 316 p. (in Russian).
14. Pilyugin L. P. *Prognozirovaniye posledstviy vnutrennikh avariynykh vzryvov* [Forecasting of consequences of internal emergency explosions]. Moscow, Pozhnauka Publ., 2010. 380 p. (in Russian).
15. Gorev V. A., Plotnikov A. I. Stability at external emergency explosions. In: *Gorodskoy stroitelnyy kompleks i bezopasnost zhizneobespecheniya grazhdan. Sbornik trudov nauchno-prakticheskoy konferentsii* [Urban building complex and safety of life support of citizens. Proceedings of scientific and practical conference]. Moscow, ASV Publ., 2005, pp. 32–45 (in Russian).

16. Luzhin O. V., Popov N. N., Rastorguyev B. S. Calculation of designs of constructions on action of blast waves. In: Korenev B.G., Rabinovich I.M. (ed.). *Dinamicheskiy raschet sooruzheniy na spetsialnyye vozdeystviya* [Dynamic calculation of constructions on special influences]. Moscow, Stroyizdat Publ., 1981, pp. 5–28 (in Russian).
17. Salymova E. Yu. *Dynamics of development of dangerous factors in buildings with enclosing structures made of sandwich panels in fires and explosions*. Cand. tech. sci. diss. Moscow, 2014. 110 p. (in Russian).
18. Gorev V. A., Salymova E. Yu. Usage of sandwich-panels as effective easily jettisonable constructions by inside combustions in industrial buildings. *Pozharovzryvobezopasnost / Fire and Explosion Safety*, 2010, vol. 19, no. 2, pp. 41–44 (in Russian).
19. Gorev V. A., Belyaev V. V., Fedotov V. N. Condition of the beginning of vibrational gas combustion in an unsealed vessel of rectangular shape. *Combustion, Explosion, and Shock Waves*, 1989, vol. 25, no. 1, pp. 31–34. DOI: 10.1007/BF00758231.
20. Gorev V. A., Fedotov V. N. About a role of acoustic vibrations at explosive combustion of gases in the depressurized vessel. In: *Struktura gazovykh plamen. Materialy Mezhdunarodnogo seminara po strukture gazovykh plamen* [Structure gas flames. Proceedings of International Seminar on Structure Gas Flames]. Novosibirsk, July 1986, pp. 202–208 (in Russian).
21. Polandov Yu. Kh., Babankov V. A. Effect of location source of fire in the room on the development of gas explosion. *Pozharovzryvobezopasnost / Fire and Explosion Safety*, 2014, vol. 23, no. 3, pp. 68–74 (in Russian).
22. Ellis O. C. *Flame movement in gaseous explosive mixtures*. Part 7. Fuel in Science and Practice, 1928, vol. 7, p. 502-509.
23. Popov V. A. The initial site of distribution of a flame in the closed pipes. *Izvestiya Akademii nauk SSSR. Otdeleniye tekhnicheskikh nauk / Proceedings of the USSR Academy of Sciences. Department of Technical Sciences*, 1956, no. 3, pp. 116-125 (in Russian).
24. Ellis O. C. *Flame movement in gaseous explosive mixtures*. Part 2. Fuel in Science and Practice, 1928, vol. 7, pp. 245–251.
25. Kuznetsov V. R., Sabelnikov V. A. *Turbulentnost i goreniye* [Turbulence and combustion]. Moscow, Nauka Publ., 1986. 288 p. (in Russian).
26. Gorev V. A. Assessment of speed of burning of uniform gas mix at the defining influence of instability of a flame. *Pozharovzryvobezopasnost / Fire and Explosion Safety*, 2008, vol. 17, no. 1, pp. 12–16 (in Russian).
27. Shchelkin K. I., Troshin Ya. K. *Gazodinamika goreniya* [Gas dynamics burning]. Moscow, Academy of Sciences of USSR, 1963. 255 p. (in Russian).
28. Bradley D. How fast can we burn? In: *Symposium (International) on Combustion*, 1992, vol. 24, issue 1, pp. 247–262. DOI: 10.1016/s0082-0784(06)80034-2.
29. Abdel-Gayed R. G., Bradly D. Dependence of turbulent burning velocity on turbulent Reynolds number and ratio of flaminar burning velocity to R.M.S. turbulent velocity. In: *Symposium (International) on Combustion*, 1977, vol. 16, issue 1, pp. 1725–1735. DOI: 10.1016/s0082-0784(77)80450-5.
30. Kakutkina N. A., Korzhavin A. A., Zamashchikov V. V., Pleslov A. A., Babkin V. S. Scale modelling of internal gas explosions. In: Molkov V. V. (ed.). *Proceedings of Ist International Seminar on Fire-and-Explosion Hazard of Substances and Venting Deflagrations*. Moscow, All-Russian Research Institute for Fire Protection, 1995, pp. 225–230.
31. Bradly D. Evolution of flame propagation in large diameter explosions. In: Molkov V.V. (ed.). *Proceedings of 2nd International Seminar on Fire-and-Explosion Hazard of Substances and Venting Deflagrations*. Moscow, All-Russian Research Institute for Fire Protection, 1997, pp. 51–59.
32. Pocheau A. Front propagation in a turbulent medium. *Europhysics Letters (EPL)*, 1992, vol. 20, issue 5, pp. 401–406. DOI: 10.1209/0295-5075/20/5/004.
33. Peters N. The turbulent burning velocity for large-scale and small-scale turbulence. *Journal of Fluid Mechanics*, 1999, vol. 384, pp. 107–132. DOI: 10.1017/s0022112098004212.

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