Influence of the installation depth of the easily dumped structure on pressure in the room during a gas explosion

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Abstract. The paper investigates the possibility of regulating the efficiency of structures (EDS) to reduce the pressure inside the room during an internal explosion in it. It is noted that at the explosion stage preceding the beginning of the gas flow through the opening, the pressure increase can be minimized by reducing the installation depth of the EDS in the opening, reducing the mass of the EDS unit area and weakening the EDS attachment points to the building frame, that is, approaching the beginning of the opening process. After the beginning of the gas flow, the effectiveness of the EDS can be increased by increasing the perimeter of the opening, which is covered by an easily dumped structure. If the rate of explosive combustion is so high that the explosion develops faster than the release of gases is accelerated, it is necessary to increase the area of openings, preferably with an increase in their perimeter, both by changing the shape and by increasing their number.

1. Introduction
Emergency gas and dust explosions inside closed volumes have a long history. The scientific literature separately covers explosions in equipment and in premises. To protect against the consequences of an explosion, in both cases, easily dumped structures (EDS) are used, that is, structures that are destroyed or open part of the fence to relieve pressure. The peculiarity of an indoor explosion is that the limit States of load-bearing structures during explosions in buildings occur at relatively low explosion pressures $\leq 20 \text{ kPa}$. As a result, the EDS must operate so that the maximum explosion pressure in the room is significantly less than the maximum possible value of $\sim 800 \text{ kPa}$. Thus, it is necessary to impose increased requirements on EDS for buildings, since they are used to relieve pressure by orders of magnitude, and this discharge occurs against a background of low overpressure, when the discharge rate is low. The discharge rate is a direct monotonous function of the overpressure. Compliance with the increased requirements that must be imposed on EDS in buildings is ensured by increasing the area of openings covered by EDS and increasing the effectiveness of the EDS themselves. At the same time, modern regulatory documents [1-3] set requirements for the area of overlapping openings, but the requirements for the EDS themselves are not sufficiently considered [4-5]. As a result, there are often cases when the requirements for the area of the EDS are met, but they do not fulfill their purpose and do not protect the object. This is especially noticeable in explosions in residential buildings [6-8], where the requirements for the area of Windows in terms of illumination exceed the requirements for the area of openings in [1-3]. To determine the required area to protect buildings from a possible...
explosion, you need to know its load-bearing capabilities. To determine the bearing capacity of an
data object in an internal explosion, it is necessary to calculate the effect of the explosive load. Currently,
the task of the explosive load is not justified. When categorizing premises for their explosion hazard, a
conditional pressure $\Delta P = 5 \text{kPa}$ is taken [1] and it is assumed that if the explosion pressure can exceed
this value, then it is necessary to apply EDS to protect the object from explosion. The explosion
pressure in [1] is determined only based on the energy characteristics of the fuel mixture, that is, from
the heat of combustion and the degree of gas contamination. For the dynamics of the development of
an explosion, the most important characteristic is the burning rate [9-12]. The purpose of this work is
to determine the requirements for the properties of EDS and their fastening in order to increase their
efficiency, to determine the main time changes in the explosion pressure for the formation of the
calculated explosive load in an internal explosion.

2. Method of research
The area of openings covered by the EDS is determined either by calculation, or assigned $S_0 = 0.05V_0$
for rooms of category "A" и $S_0 = 0.03V_0$ or rooms of category "B" [3]. To determine the area of
openings by calculation, it is necessary to have information about the speed of the explosive
combustion of the mixture, the maximum possible area of flame during the explosion and the
maximum pressure at which still retained the bearing capacity of supporting structures [13-15]. When
determining the discharge area, the maximum rate of formation of an additional volume of gases
during an explosion and the rate of volume flow through the openings at the maximum permissible
excess pressure of the explosion are assumed to be equal.

$$
\frac{s_0}{V_0^2} = \frac{k_f U_r (\sigma - 1) \rho_0^2}{K_n1 \frac{1}{2} \sqrt{\Delta P_\alpha} K_n2} \tag{1}
$$

where $A_f = K_f V_0^2$ - the maximum area of the zone of combustion in the explosion, $K_f$ - the
shape factor, $V_0$ - the volume of the room, $S_0$ - area of door openings, $U_r$ - speed explosive combustion,
$\sigma$ - is the degree of expansion of the mixture during combustion, $\Delta P_\alpha$ - allowable pressure, ensuring the
bearing capacity of the structure, $K_n1$ - expense ratio, taking into account the narrowing of the gas jet
when passing through the doorway, $K_n2 = 1$, if the expires cold original mix, $K_n = \sqrt{\sigma}$, if expire the
hot products of combustion, $\rho_0$ - the density of the initial combustible mixture.

From expression (1) when substituting in it the typical values of the quantities included in it, it
turns out

$$
S_0 \approx (0.1 \div 0.2)V_0^2 \tag{2}
$$

For Fig.1 shows a schematic change in pressure during an internal explosion, taking into
account the opening of the EDS.
At point 0, an explosion is initiated, at point $t_0$ - EDS exits the opening, and the space for gas outflow opens. At the moment $t_1$ the pressure peak $\Delta P_1$ is formed as a result of the competition between the processes of gas outflow and explosive combustion. At this point, the area for the outflow $S_1 = X_1 \Pi$ ( $\Pi$ - the perimeter of the opening), the perimeter of the opening) is often part of the area of the fully open opening. If the EDS is effective, the flow rate increases faster than the rate of new volume generation, and the pressure drops, reaching $\Delta P_{min}$, in the case when $X_1 \Pi = S_0$. In the future, the area of the outflow does not change, and the area of the flame continues to grow. At the same time, the explosion pressure increases up to $\Delta P_2$. After that, the pressure begins to drop, as the flame touches the walls, and its area decreases sharply. From the moment $t = 0$ to the moment $t_{op}$, when the expiration begins, the pressure increases as in a sealed volume:

$$\frac{\Delta P(t)}{P_0} = \frac{4\pi \gamma U_1^2(\sigma - 1)\sigma^2}{3V_0}t^3$$

where $P_0$ - the initial pressure in the volume, $\gamma$ - the Poisson's ratio.

To determine the pressure in the volume, $\Delta P_v$ (the opening pressure) in (3) is substituted $t = t_v$, nd the opening pressure $\Delta P_{op}$ will be defined as:

$$\Delta P_{op} = \Delta P_v \left(\frac{t_{op}}{t_v}\right)^3 = \Delta P_v (1 + \theta_0)^3$$

where $\theta_0 = \frac{t_{op}-t_v}{t_v}$

During the movement of the EDS in the opening, the process of increasing pressure in the volume and the regularities of the movement of the EDS are determined by the criterion "B" [14-17]
where \( \rho_n = \frac{M}{S_0} \) – the mass per unit area of EDS, \( X_0 \) the offset EDS from the time \( t_v \) until \( t_{op} \), \( t \) even before sources gases.

The value \( \theta_0 \), which characterizes the time of displacement by the distance \( X_0 \) is determined from the condition:

\[
\frac{4}{B} = \left[ \frac{1 + Q_0}{5} - (1 + \theta_0) + \frac{4}{5} \right]^{-1}
\]

Having determined \( \theta_0 \), we can calculate from (4) the pressure \( \Delta P_{op} \), corresponding to the end of the explosion mode in a sealed volume. After shifting the EDS by a distance of \( X_0 \) the "idle run" of the EDS acquires a speed equal to:

\[
\frac{\partial \bar{X}}{\partial t} = X_0 = \frac{B}{4} [(1 + \theta_0)^4 - 1]
\]

the ratio (7) gives a dimensionless speed value, the dimensional value is obtained by multiplying by \( \frac{X_0}{t_v} \).

After the beginning of the gas flow through the opening, the system of equations describing the movement of the EDS and the change in the explosion pressure looks like this:

\[
\frac{\partial \bar{\rho}}{\partial \bar{t}} = 3(1 + \bar{t}_1)^2 - \frac{K_u 2^{1/2} \bar{y}^{2/3}}{\left( \frac{4}{3} \pi (\sigma - 1) \sigma^2 \right)^{1/3}} \times \left( \frac{P_0}{\Delta P_v} \right)^{1/6} \times \frac{S_0 \bar{X}}{V_0^{2/3}} \times \frac{\bar{X}}{U_r} \sqrt{1 + \bar{\rho}}
\]

Entry conditions:

\[
\bar{P}_{(0)} = 0; \bar{X}_{(0)} = 0 : \frac{\partial \bar{X}_1}{\partial \bar{t}}(0) = \frac{B \bar{X}}{4} [(1 + \theta_0)^5 - (1 + \theta_0)]
\]

\[
\bar{P}_1 = \frac{\Delta P(t) - \Delta P_{op}}{\Delta P_{op}} \bar{t}_1 = \frac{t - t_{op}}{t_v}; \bar{X}_1 = \frac{x_1}{s_0}; \bar{X}_0 = \frac{x_0}{s_0};
\]

The new offset \( X_1 \) and time \( t_1 \) in (8) and (9) count from "0".

3. Results of analysis and calculations

From the beginning of the explosion to the beginning of the opening, that is, until the beginning of the movement of the EDS (\( t_v \)) the pressure increases in a sealed volume. This pressure is usually set by selecting the connections that hold the EDS. The opening time is determined from (3). then, given the values \( V_0, \rho_n, U_r, \) and \( \sigma \), the parameter \( \langle B \rangle \rangle \) (5), the value \( (1 + \theta_0) \) from (6) and the opening pressure \( \Delta P_{op} \), (4) are determined.
Table 1.

| \( B \) | 0.5 | 1   | 2   | 4   | 6.35 | 8   | 10  | 12  | 12.7 | 16   | 24.8 | 30  | 50  |
|------|-----|-----|-----|-----|------|-----|-----|-----|------|------|------|-----|-----|
| \( \Delta P_{op} / \Delta P_v \) | 10  | 7   | 5   | 3.65| 3    | 2.8 | 2.6 | 2.4 | 2.38 | 2.25 | 1.95 | 2.0 | 1.66 |

Table 1 shows that at low values of the "B" parameter, the explosion pressure increases several times and may exceed the permissible level. There are two ways to reduce the opening pressure by changing the EDS device: 1st - to reduce the opening pressure; 2nd – to reduce the product \( \rho n \times X_0 \). A decrease in pressure \( \Delta P_v \) will lead to a drop of the parameter «B», and consequently, to increase the ratio \( \Delta P_{op} / \Delta P_v \), but this relationship does not compensate for the decrease in \( \Delta P_v \), and as a result \( \Delta P_{op} \) decreases. 

Let \( B=4 \) and \( \Delta P_v=2 \) kPa, a \( \Delta P_{op} = \Delta P_v \times (10)^3 = 2 \times 1.54^3 = 7.3 \) kPa. It is required to reduce \( \Delta P_{op} \leq 5 \) kPa. If we provide the opening pressure \( \Delta P_v = 1 \) kPa, we have \((1 + \theta_0)^3 = 5\), which corresponds to «B»=2. Since reducing \( \Delta P_v \) by 2 times reduces «B» by \( 2^{5/3} = 3.175 \) times, and to bring the parameter "B" to the required value \( B=2 \) it is enough to reduce the product of \( \rho n \times X_{op} \) by 1.6 times. The above calculations are valid for a constant volume and burning rate. After the beginning of the expiration, the dynamics of pressure changes in the volume during the explosion and the displacement of the EDS were determined by the numerical solution of the system (8)-(9). The solution started with a new time reference \( \bar{t}=0 \) and a new offset reference \( X_1=0 \). The initial speed of the EDS was equal to the final speed after passing the EDS inside the opening. The solution was carried out until \( \bar{X}_1=1 \). At this time, the area of the outflow through the side surface \( S = X_1 \Pi \) was compared with the area of the opening \( S_0 \), and further displacement of the EDS did not lead to an increase in the outflow area, so the variable \( \bar{X}_1 \) was fixed at the level \( \bar{X}_1=1 \). From the analysis of the system (8)-(9), it follows that there are new parameters other than "B" that determine the development of the process. It's \( S_0 \left/ \sqrt[3]{V_0} \right. \) - dimensionless maximum expiration, \( \bar{X}_0 = \frac{X_0 \Pi}{S_0} \), dimensionless depth of EDS in the aperture, which determines the initial speed at the EDS stage pressure relief, \((\frac{\bar{P}_0}{\Delta P_v})^{1/6} \) – weakly dependent on the opening pressure. It can be combined with a dimensionless area of the outflow and with a dimensionless burning rate \( U_r \left/ \left( \gamma \frac{P_0}{\rho_0} \right)^{1/2} \right. \). The burning rate is usually unknown in advance in case of emergency explosions, but in experiments it can be varied, and, thus, the possible variants of the development of a real explosion can be predicted. Table 2 shows the results of the numerical solution of system (8) - (9) with varying different initial values. [18,19]
Table 2. The explosion parameters by varying the initial values.

|   | 1 | 2            | 3            | 4            | 5            | 6            | 7            | 8            | 9            | 10           | 11           | 12           |
|---|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
|   | Specified Calculated | Initial data | $2\rho_n$ | $2x_0$ | $\Delta 2\Delta p_v$ | $2U_r$ | $\Pi$ | $2V_0$ | $x_0 = 0.05$ | $V = 1000$ | $S_0 = 15$ | $\Pi = 15.5$ |
| 2 | B | 4            | 2            | 2            | 12.7        | 1            | 4            | 6.35        | 12           | 24.8         | 2            | 0.55         |
| 3 | $t_v$ sec | 0.1095       | 0.1095       | 0.1095       | 0.138       | 0.55         | 0.10         | 0.139       | 0.1095       | 0.274        | 0.55         | 0.082        |
| 4 | $t_{op}$ sec | 0.167        | 0.188        | 0.188        | 0.184       | 0.105        | 0.167        | 0.2         | 0.154        | 0.342        | 0.094        | 0.174        |
| 5 | $\frac{\Delta t_1}{\Delta t_0} = \frac{\Delta t_1}{t_{op}}$ | 0.13         | 0.16         | 0.09         | 0.1         | -            | 0.06         | 0.14        | 0.25         | 0.15         | 0.36         | -            |
| 6 | $1 + \theta_0$ | 1.54         | 1.71         | 1.71         | 1.335       | 1.91         | 1.54         | 1.44        | 1.34         | 1.25         | 1.71         | 2.12         |
| 7 | $\Delta P_{op}(x/\Pi a)$ | 3.65         | 5            | 5            | 4.76        | 6.97         | 3.65         | 3.05        | 2.42         | 1.956        | 5            | 9.5          |
| 8 | $\Delta P_l(x/\Pi a)$ | 4.39         | 6.245        | 5.6          | 5.5         | -            | 4            | 3.75        | 3.52         | 2.48         | 8            | -            |
| 9 | $\Delta P_0(x/\Pi a)$ | 5.26         | 7.83         | 6.14         | 6.4         | -            | 4.34         | 4.54        | 4.72         | 2.97         | 12.3         | -            |
| 10 | $\frac{\partial x_1}{\partial t_1}$ | 0.39         | 0.39         | 0.78         | 0.39        | 0.39        | 0.78         | 0.31        | 0.123        | 0.156        | 0.39         | 0.39         |
| 11 | $\frac{\partial x_1}{\partial t_1}$ | 2.74         | 2.52         | 5.03         | 3.6         | 2.29        | 5.55         | 2.42        | 1.15         | 1.75         | 2.52         | 2.1          |

Table 2 is based on the following principle: in the 1st column, the defined values are indicated, and in the 1st row, the specified values are specified. The set values are based on the initial data: $V_0 = 64$ m$^3$, $P_0 = 101.3$ kPa, $\Delta P_v = 1$ kPa, $\rho_0 = 1.2$ kg/m$^3$, $U_i = 0.707$ m/s, $\rho_n = 20$ kg/m$^3$. EDS dimensions (1,6×1,5) m, $X_0 = 0.151$ m, $S_0 = 2.4$ m$^2$, $\sigma = 6.5$, $\gamma = 1.4$, $K_n = 0.77$. It is for these initial data that the explosion parameters in the 2nd column are defined. In columns (3-8), the explosion parameters are defined for the specified doubled values of the initial values, and the other specified conditions correspond to the initial data. For example, in column 3, the mass of the EDS, and therefore the pH, is doubled. The remaining initial values correspond to column 2. Columns (9-12) indicate specific changes to the source data, while the rest correspond to column 2.

In the 2nd line, the parameter "B" is presented, in the 3rd line, the opening time is 10 seconds, the destruction of the links holding the EDS. In the 4th line, the time $t_{op}$ sec, the beginning of the gas flow through the opening, in the 5th line, the dimensionless time from the beginning of the flow to the first peak, referred to the time $t_{op}$, that is $\Delta t_1 = \frac{t_1 - t_{op}}{t_{op}}$. In the 6th line, the parameter $(1 + \theta_0)$ is defined by (6), that is, it is a derivative of the parameter "B". In (7-8) lines, the pressure values at the opening of the opening and the pressure of the first peak $\Delta P_1$ are presented. In the 9th line, the value of the possible explosion pressure is given at the time corresponding to the first peak in case of failure of the EDS. In the 10th line, a dimensionless value $\bar{X}_0 = \frac{x_{Pi}}{S_0}$, is given, which, along with the parameter "B", determines the speed of the EDS at the moment of its exit from the opening. This value determines the speed of opening the space for the outflow of gases (line 11), and therefore the efficiency of the EDS.

As noted earlier, reducing the parameter "B" leads to an increase in the ratio $\frac{\Delta P_{op}}{\Delta P_v}$, that is, the greater the pressure increases during the movement of the EDS opening. It follows that for the same initial opening pressures, $\Delta P_{op}$ will always be the greater the lower the parameter "B". This is illustrated in table 1.
Analysis of the pressure increase from the beginning of the process to the formation of the first peak shows that an important role in reducing the pressure at the first peak is played by an increase in the perimeter of the opening "P" (column 7). Increasing the "B" parameter also reduces the pressure at the first peak. However, this effect only applies to the absolute value of \( \Delta P_1 \) (Row 8, columns 2-4). As for the relative growth \( \Delta P_1 / \Delta P_{op} \), this ratio increases with the growth of "B" (columns 2, 3). This ratio increases with the growth of "B" (in columns 2, 3). A special role in the formation of a pressure blast playing the burning rate. It happens that an increase in the combustion rate of \( U_r \) does not lead to the formation of the first pressure peak under the condition \( \bar{X} < 1 \). This means that an increase in the combustion area leads to the fact that the flame area reaches the maximum possible \( A_f \) value before the opening is fully opened (columns 6, 12) [20,21]. This phenomenon can be compensated for by increasing the parameter "B" by reducing the installation depth of the EDS and / or the EDS mass (columns 9, 10). Another option for increasing the efficiency of the EDS in this case to compensate for the high burning rate is to increase the complex

\[
\left( \frac{P_0}{\Delta P_0} \right)^{1/6} \left( \frac{p_0}{p_0} \right)^{1/2} \frac{S_0}{U_r V_0} \]

Reducing the opening pressure \( \Delta P_v \) is ineffective, due to the fact that it is initially selected as the minimum. In addition, the 1/6 degree excludes the possibility of making a big difference. Thus, there remains the option of increasing the area \( S_0 \) beyond the defined according to (1) for the 2nd pressure peak. When the area \( S_0 \) increases, it becomes possible to increase the perimeter of openings, both by changing the shape and by increasing their number.

4. Conclusion
To ensure the minimum pressure at the 1m peak, it is necessary to:

- set the minimum possible opening pressure for a given wind area \( \Delta P, \text{EDS} \)
- achieve the maximum possible parameter "B" by reducing the mass of the EDS \( \rho_{12} \) and/or the installation depth of \( X_0 \).

In the future, it is necessary to achieve the minimum value of the explosion pressure at the 1m peak. First of all, this is achieved by increasing the perimeter of the opening without or with an increase in the area of the openings. When increasing the area of openings to meet the condition \( \Delta P_1 < \Delta P_d \), the safety condition at the 2nd peak is performed automatically if condition (1) was met.

During calculations, it was assumed that the flame front up to the 1st peak has a spherical shape. Deviation from this position can be corrected by comparison with the experiment. The Institute of integrated safety in construction of MSUCE is expected to conduct experiments on explosive chambers of various scales. These works are also important for clarifying the actual dynamic load on building structures during an internal explosion.

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