Impact of the idle run of a rotating easily dumped structure on pressure in the room

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Abstract. The work addresses the alternative use of window sashes as an easily dumped structure (EDS) with window casement rotation to ensure gas release from the room and pressure venting. The paper focuses on the use of the option with one outside rotating casement as EDS while the other part of the window sash can be opened inside or be immobile. The work records equations for the movement of a swivelling safety structure and changes in pressure in a dimensionless form with identified dimensionless complexes, which equivalence ensures the likeness of aperture opening. The study is limited to the idle run period. It was demonstrated that with small room volumes, the idle run must be taken into account and its impact on a pressure growth must be reduced. The work shows ways to reduce the idle run time.

1. Introduction
Household gas explosions in living premises cause human casualties, material loss and cause social tension. [1-3] In relation to more extensive development of the gas infrastructure of the residential sector, the frequency of explosions may increase. One of efficient ways to fight the consequences of these explosions is to relieve pressure using easily dumped structure (EDS) in enclosures. Existing regulations and legal documents do not help with efficient protection of living premises using EDS in case of an internal explosion. The requirements and recommendations outlined in these documents are contradictory and are not justified. For example, [4] requires that EDS opening pressure must not exceed 0.7 kPa. Pursuant to [5], the opening pressure must be 1.4-fold the peak wind load which may cause a conflict. The formal list of requirements to the protection of industrial buildings with EDS may result in the serious underestimation of consequences due to more severe conditions of an internal explosion in small-volume living premises. [6,7]. There two aspects resulting in an unfavorable outcome:

1) An explosion in a room with a small volume takes less time to occur and delayed-action EDSs do not have time to perform their protection function.
2) Before opening space for pressure relief, EDSs in living premises run idle while an explosion pressure may reach hazardous limits [8-11].

Window sashes are used as EDS in living premises [12]. Such sashes should be opened at the sites of their attachment to the walls of the building where reliable opening conditions are hard to provide. Loose sash attachment can cause accidental opening by wind and unintentional closing in the result of human actions.
2. Characteristics of opening EDS with a rotating casement

We consider EDS rotating against the vertical axis. Opening pressure ($\Delta P_V$) of this EDS is determined by the equality of moments from the effect of an explosion pressure on the portion of a rotating part area, which contacts the gas medium with volume $S_0$ and by the reaction moment at the attachment. (Fig. 1a)

$$\Delta P_V \cdot S_0 \cdot l_0 = F_R \cdot l_1$$  \hspace{1cm} (1)

$l_0$ is distance from the geometrical center of the area ($S_0$) to the axis of rotation $F_R$ is the strength of attachment point destruction, $l_1$ is distance from the attachment point to the axis of rotation. After destruction of the attachment point, EDS starts rotating. Depending on the jointing of the rotating EDS with an immobile part of the window sash, various pressure relieve options are possible at the initial stage of explosion development. In case of splice, the rotating part contacts the immobile part through sealing while there is no direct contact. In this case, there is no idle run and the space for gas outflow opens immediately once movement is started [13-16].

![Figure 1a. EDS rotating against the vertical axis.](image)

When there is no splice, the outflow starts immediately after the idle turn to an angle of $\phi_0$ (Fig. 1b). The work describes the second conservative jointing option for spherical deflagration burning at a constant speed of $U_r$.

![Figure 1b. The idle turn to an angle of $\phi_0$.](image)

The sash (EDS) starts moving from the standstill position in the period between the starting point of an explosion $t = 0$ and the point of opening $t_v$, i.e. destruction of the attachment points of a rotating sash with overpressure $\Delta P_V$. Then, until it turns ($t_{\phi_0}$) to an angle of $\phi_0$ (idle run), pressure in the room...
grows as in geometric scope. After \( t_{op} \), space gas outflow opens. This space is made up of a vertical square section with an area of:

\[
S_v = 2h \cdot \left( R - \frac{\delta}{\sin \varphi} \right) \cdot \sin \frac{\varphi}{2}
\]

and two horizontal triangular sections each with an area of (Fig. 1b).

\[
S_h = \left( R - \frac{\delta}{\sin \varphi} \right)^2 \cdot \sin \frac{\varphi}{2}
\]

The full outflow area is the sum of the areas of the square vertical and two triangular sections until the maximum opening angle is reached. This angle is determined by the equality of the said sum of areas and the free area of a fully open aperture \( S_{op} \) (Fig. 2).

![Figure 2. A fully open aperture.](image)

Equations (2) and (3) are recorded in assumption \( \sin \varphi \approx \tan \varphi \). By equating (4) and the sum of (2)+2×(3), we get the equation for the maximum opening angle \( \varphi_{lim} \), so that for \( \varphi \geq \varphi_{lim} \) the outflow area remains constant and is equal to \( S_{op} \). The value of the maximum opening angle is determined by the equation:

\[
S_{op} = (h - 2\Delta)(R - \Delta - \delta)
\]

\[
S_{op} = 2 \left( R - \frac{\delta}{\sin \varphi} \right) \left( h + R - \frac{\delta}{\sin \varphi} \right) \cdot \sin \frac{\varphi}{2}
\]

If we assume that \( \sin \varphi \approx 2 \sin \frac{\varphi}{2} \) \( (\varphi \leq 30^\circ) \) and ignore members \( \frac{\delta^2}{R \times h}, \frac{\Delta^2}{R \times h}, \frac{\Delta \times \delta}{R \times h} \), we get:

\[
\sin \varphi_{lim} = \frac{1 + \frac{\delta}{R} - \Delta \left( \frac{2}{R} \frac{1}{h} \right)}{1 + \frac{h}{R}}
\]

The above option of gas outflow from the opening with rotating EDS corresponds to the case when the EDS external side is in the same plane with the external side of the building wall, \( a = 0 \) (Fig. 3). On the practical side, cases are important when a window is deep in the recess (Fig. 3) and an opening
sash is separated from the top and lower platform of the aperture at a distance of \( \delta \) taking into account a protruding part of \( \Delta \).

**Figure 3.** The EDS external side is in the same plane with the external side of the building wall

In case \( a > b \), \( \sin \varphi \leq \frac{a}{R} \):

\[
S_v = \min \left\{ h \cdot \left( R - \frac{\delta}{\sin \varphi} \right) \cdot \sin \varphi \right\} \\
S_H = \min \left\{ \left( R - \frac{\delta}{\sin \varphi} \right)^2 \cdot \sin \varphi \right\} \\
\tag{7}
\]

For case \( \sin \varphi > \frac{a}{R} \):

\[
S_v = \min \left\{ h \cdot \left( R - \frac{\delta}{\sin \varphi} \right) \cdot \sin \varphi \right\} \\
S_H = \left( \frac{a}{\sin \varphi} - \frac{\delta}{\sin \varphi} \right) \cdot \delta_1 + \left( R - a - \cos \varphi \right)^2 \cdot \sin \varphi \tag{8}
\]

Provided \( b > a \), ratios (7) and (8) are correct.

The total outflow area is \( S = S_v + 2S_H \) and it must still satisfy the condition \( S_\Sigma \geq \varphi_{\text{lim}} = S_{\text{op}} \).

EDSs with a rotating sash were considered previously in [17] from the position of their structure and without regard for pressure changes and the idle run phenomenon. In [7], pressure changes were considered for the simplest case of \( \delta = \varphi \) without the idle run which applies to living premises as it offers too optimistic outlooks.

Pressure changes in case of an internal explosion, taking into account the opening of rotating EDS at idle run. EDS opening and the start of its movement at a time point of \( t_v \) results from the destruction of EDS attachment points to the walls of the building at a pressure of \( \Delta P_v \), [18,19].

\[
\Delta P_v = \frac{P_0}{V_0} \cdot \frac{4}{3} \cdot \pi \cdot \gamma \cdot (\sigma - 1) \cdot \sigma^2 \cdot U_r^3 \cdot t_v^3 \tag{11}
\]

\( U_r \) is burning speed based on source mixture particles, \( \sigma \) is degree of gas expansion during combustion.

EDS rotational movement until it reaches the turning angle of \( \varphi_0 = \frac{\delta}{R} \) is idle, i.e. it does not result in the opening of space for gas outflow. This movement is described by the following ratio:

\[
\frac{m \cdot R^2}{3} \cdot \frac{d^2 \varphi}{dt^2} = \Delta P \cdot S_1 \cdot \frac{R}{2} \tag{12}
\]

This equation in a non-dimensional form reads as follows:
Here $\bar{\varphi} = \frac{\varphi}{\rho_0}$ is counted from $\varphi = \varphi_0$, $\theta = \frac{t_v - t}{t_v}$:

$$B = \frac{\Delta P_{v}^{5/3} \varphi^{2/3}}{\rho_0 \delta^{7/3}} - \text{non-dimensional parameter}, \quad \rho_0 = \frac{m}{s} \text{ - weight of an area unit of EDS.}$$

Equation solution (13) over section $\bar{\varphi} = 0 \div 1$ and $0 \leq \theta \leq \theta_0$:

$$\bar{\varphi} = \frac{3}{8} \cdot B \cdot \left[ \frac{(1 + \theta)^5}{5} \cdot \theta - \frac{1}{5} \right]$$

After reaching the value $\bar{\varphi} = 1$ at a time point of $\theta = \theta_0$, the space for gas outflow opens. Time $\theta_0 = \frac{t_{op} - t_v}{t_v}$ meets the condition $\bar{\varphi} = 1$, is determined by the ratio:

$$\frac{8}{3} \cdot B = \left[ \frac{(1 + \theta_0)^5}{5} \cdot \theta_0 - \frac{1}{5} \right]$$

The angle speed of EDS rotation at the moment that meets the conditions $\varphi = \varphi_{op}$, $t = t_{op}$ is determined by the equation:

$$\frac{d\bar{\varphi}}{d\theta} |_{\theta = \theta_{op}} = \frac{3}{8} \cdot B \cdot \left[ (1 + \theta_0)^4 - 1 \right]$$

3. Results of analysis and calculations

Table 1 summarizes the results of the calculation of when EDS starts to rotate, time of opening of the gas outflow $t_{op}$, pressure at that moment $\Delta P_{op}$ and angle speed of EDS rotation $\frac{d\bar{\varphi}}{d\theta} |_{\theta = \theta_{op}}$.

The calculations were performed with the variation of $\Delta P_v$ and $V_0$. The following characteristics were taken for rotating EDS: $\rho_s = 24 \text{ kg/m}^2$, $\delta = 7.5 \text{ cm}$, $R = 1.5 \text{ m}$. Mixture burning at a speed of $U_r = 3.1 \cdot 0.35 = 1.035 \text{ m/sec}$ [20] expansion degree $\sigma = 6.5$ had spherical symmetry. Poisson factor $\gamma = 1.4$.

| $t_{op}$ | $\Delta P_v = 1 \text{ kPa}$ | $\Delta P_v = 2 \text{ kPa}$ | $\Delta P_v = 3.54 \text{ kPa}$ |
|-----|-----------------|-----------------|-----------------|
| $V_0$ | $t_{op}$, sec   | $t_{op}$, sec   | $t_{op}$, sec   |
| 27   | 0.031           | 0.041           | 0.031           |
| 64   | 0.041           | 0.041           | 0.031           |
| 125  | 0.041           | 0.041           | 0.031           |
| $B$  | 33.18           | 51.06           | 66.82           |
| 8    | 110.57          | 110.57          | 110.57          |
| 114  | 224.03          | 224.03          | 224.03          |
| $\theta_0$ | 0.505       | 0.31           | 0.31           |
| 8    | 0.29           | 0.29           | 0.29           |
| 7    | 0.09           | 0.09           | 0.09           |
| $\Delta P_{op}$ | 44.35         | 44.35           | 44.35           |
| 22.7 | 110.57          | 110.57          | 110.57          |
| 22.7 | 33.18           | 33.18           | 33.18           |
| 22.7 | 110.57          | 110.57          | 110.57          |
| 8.8  | 55.7            | 55.7            | 55.7            |
| 4    | 11.79           | 11.79           | 11.79           |
| 4    | 55.7            | 55.7            | 55.7            |
| 4    | 11.79           | 11.79           | 11.79           |
| $\frac{d\bar{\varphi}}{d\theta_{op}}$ | 44.1          | 44.1           | 44.1           |
| 66   | 77.4            | 77.4            | 77.4            |
| 88.4 | 11.79           | 11.79           | 11.79           |
| 3    | 11.79           | 11.79           | 11.79           |
| 4    | 11.79           | 11.79           | 11.79           |

The analysis of Table 1 shows: a pressure growth with the idle run $\frac{\Delta P_{op}}{\Delta P_v} = (1 + \theta_0)^3$ decreases with the growth of $B$ parameter. This means that the value changes resulting in the growth of $B$ parameter and a reduction in the final pressure at the end of the idle run is $\Delta P_{op}$. The opening pressure $\Delta P_v$ is an exception. When it increases, the $B$ parameter increases, the ratio $\frac{\Delta P_{op}}{\Delta P_v}$ decreases, while $\Delta P_{op}$ value...
increases. It means that $(1+\theta_o)^3$ decreases with $B$ growth since $\Delta P_v$ increases slower than it $\Delta P_v$ grows. Thus, the pressure after the idle run in large-volume premises is less than in small-volume premises, all other conditions being the same. Increasing burning speed, weight of a EDS unit area and EDS thickness ($\delta$) causes a pressure increase $\Delta P_{op}$.

The growth of $B$ parameter causes an increase in the expression speed at the end of the idle run $\frac{dp}{d\theta}|_{\theta=\theta_{op}}$, which will have a favorable impact on pressure relief in the future. Equation (15) for absolute angle speed of rotation looks as follows:

$$\frac{d\varphi}{dt}|_{t=t_{op}} = \frac{3}{8} \cdot B^{1/2} \cdot q_0^{1/2} \cdot \Delta P_v^{1/2} \cdot h^{1/2} \cdot m^{1/2} \cdot [ (1 + \theta_{op})^4 - 1 ]$$

4. Discussion of research results

The analysis of the results summarized in Table 1 shows that with typical source values for window sashes and physical characteristics of a combustible gas mixture, there are situations when rotating EDS are too slow to relieve the explosion pressure and even do not start this action.

As a result of an increased explosion pressure, the bearing capacity of the building may get lost at this stage. And a pressure growth during an internal explosion with EDS at the idle run does not depend on EDS area but depends on the weight of an EDS unit area. Further pressure relief after the start of gas outflow will be determined by the aperture perimeter, EDS thickness and depth of setting of EDS. The turning angle reaches its maximum value of $\varphi_{lim}$, when the total outflow area is equal to a full open area of the aperture. The research shows that in order to reduce the impact of the idle run on the growth of the explosion pressure, it is necessary to reduce the opening pressure, weight of an EDS area unit and thickness of the EDS part that contacts the immobile part of the window structure. In order to ensure the effectiveness of further pressure relief after the idle run, the $a$ size, window setting depth from the external side, should be reduced and the $b$ size, which can be a wide immobile part of the window or open inside, should be increased. For better pressure relief through the triangular horizontal parts, it makes sense to increase the $\delta$ size that separates the bottom and top parts of the aperture from relevant EDS boundaries.

5. Conclusion

This paper is the first to address the role of the idle run of rotating EDS in pressure changes during the internal explosion. It was established that with small room volumes, the idle run must be taken into account and its impact on a pressure growth must be reduced. The work shows ways to reduce the idle run time. Main ratios are recorded as non-dimensional values. This offers an opportunity to conduct large-scale experimental simulation. [21]

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