Dynamic Effects at Internal Deflagration Explosions

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Abstract. The effects of quick pressure balance during deflagration explosions in the test chambers are considered. The experimental records of pressure time dependence obtained from various tests, as well as the results of the explosive combustion numeral modeling have been analyzed. The load levels of the explosion-affected structure and equipment elements due to the impulse and vibration actions formed during deflagration in the combustible gas have been assessed. It was demonstrated that the explosive actions formed during deflagration in the combustible gas in field could lead to dangerous loading of the critical equipment elements - sensors, instruments, electronic boards, etc., including the fire system elements of buildings and constructions, sea platforms, vessels and ships, as well as other sophisticated civil and military facilities. The experimental development programs for security systems of such facilities should include deflagration explosion testing with low prime cost and short periods of execution. Such testing cannot be replaced with the development on vibration and shock tables due to specific nature of loading during deflagration emergency explosions.

1. Introduction
Flame spreading in the combustible gases and mixtures with significantly subsonic speed makes it possible not to take into account the gas dynamic compressibility in the common engineering analysis and use the perfect gas equation as follows

\[ \text{grad} \left( \frac{\rho T}{\mu} \right) = 0, \]  

(1)

where \( \rho \) – density, \( T \) – temperature, \( \mu \) – average molal mass of gas and mixture. Therefore, any time the pressure appears to be constant space-wise.

The validity criteria of such approach are detailed in the works [1,2] and will not be discussed herein. It should be noted that for the conditions in the test explosion chambers discussed hereinafter, disregarding the dynamic (wave) effects has become a common practice in view of the relative small chamber volume and the used test methods which, as a rule, provide for full filling the chamber with the combustible gas and its preliminary mixing with the air.

From physical standpoint, the relation (1) for enclosed volumes means that the pressure during the deflagration explosion in all spatial points is able to balance due to multiple ranging of explosion acoustic waves. The exclusions are zones nearby open holes during testing of the safety and easy-detectable building structures where the process is significantly unstable as a result of leakage of the cold and then the heated gas and combustion products.

By further making common assumptions about similar initial temperature in all spatial points, adiabaticity of deflagration process, flame laminarity, constant heat capacity of combustible mixture...
and combustion products in the part of their temperature independence, no dissociation of combustion products, the chamber pressure can be related the burnt substance share. This relation is linear irrespective of the way of deflagration combustions spreading. In practice for the design estimate of the pressure time dependence $P(t)$, the spherical approximation of the testing chamber geometrical form is used to obtain relatively simple analytic expressions in case of central initiation of combustion. The experimental dependence of the mass specific speed of the substance burning-out should be additionally given as follows

$$m = bP^{n/2}e^{\beta T},$$  \hspace{1cm} (2)

where $m$ is measured in kg/(m$^2$s), $n$ – total order of chemical reaction of combustion, $b$ and $\beta$ – empirical coefficients. The modern experiments [3] show that the $m$ and $P$ dependence in the form (2) should be actually understood from stochastic point of view, however, with some $P$ values, a power function is performed irrespective of the properties of combustible substances.

The work [4] gives differential equation to determine excess pressure in the spherically symmetric case:

$$\frac{dP}{dt} = mM_k(P)/N_s(P),$$  \hspace{1cm} (3)

Where $M_k$ and $N_s$ are polynomials relative to $P$ with nonintegral degrees of terms which depend on adiabatic exponents of initial mixture and combustion products. Greater nonintegral degrees of terms are indicated by $k$ and $s$. In the standard [5], as well as its substituting standard [6] dated 01.05.2019, to determine the normal combustion rate of the substance, it is recommended to solve this transcendental equation in numerical way, to simplify the calculations by using the exponent approximation in the function (2) according to Franz-Kamenetsky, and in case of inability to use the PC, roughly to estimate the rate directly based on the $P(t)$ experimental history.

The monograph [7] demonstrates that, in fact, instead of numerical solution of equation (3), it can be simplified to the following form using the finite difference methods:

$$\tau = \int_1^P x^{-n/2}\left[1 - \frac{(x)^{1/2}}{\gamma} \left(1 - \frac{1}{\varepsilon-1}\right)\right]^{-2/3} e^{-\beta T_0 x(y-1)} dx,$$  \hspace{1cm} (4)

(where the case of equivalence of adiabatic exponents $\gamma$ of initial mixture and combustion products; $\tau = t4\pi a^2 P_0^{n/2}(\varepsilon-1)/M$, $\rho = P/P_0$, $a$ – chamber radius, $M$ – gas full mass, $P_0$ and $T_0$ – initial pressure and temperature, $\varepsilon$ – pressure ratio after the explosion relative to the initial one) and determine the integral value in the right part, not event replacing the exponent with the power function. The integral is calculated by approximation of the lower incomplete gamma function. The time and pressure curve will approximately correspond to the time cubic function, but have a flex point at a time when the flame “begins feeling” the availability of the chamber walls.

As it was set on the mathematical flame-spread model, the pressure is changed in time in a quasi-stable manner, its peak values are predictable and cannot induce resonant and cyclic phenomena in the exploded structure elements. Approximately the same results can be obtained by a simpler way if approximately estimate the normal combustion rate and ratio of expansion during combustion, similar to adiabatic exponent, using the process constants [8]. In this case, the increase of pressure occurs strictly according to the cube law $P(t) - P_0 \sim t^3$ without inflection points.

The objective of this work is, by analysing typical and representative experimental data about pressure activity during deflagration explosions in the laboratory conditions, to assess the load levels of structure and equipment elements in the full-scale emergency conditions, as well as to determine the most vulnerable kinds and classes of facilities for such loading. The tasks of the work include:
1) selection of experimental pressure histories from foreign and national sources for various test conditions;
2) assessment of spectral characteristics of typical functions $P(t)$, including levels and frequencies of unstable oscillatory components and shock spectra of quasi-stable (smooth) impulses;
3) analysis of regulatory documents on test loading of various civil and military facilities, their comparison with the data obtained for deflagration laboratory explosions and assessment of hazard level of real emergency explosion loads for certain classes of facilities - elements of equipment, security systems, etc.;
4) preparation of practical recommendations for experimental development of security systems of the facilities in case of emergency deflagration explosion.

2. Pressure history in explosion chambers

The analyzed continuous function $P(t)$ can be satisfying for the design engineer only until the possible loads at emergency deflagration explosions are determined for large and unbreakable structures - fencing, supporting, safety, etc., which have relatively low natural-vibration frequencies and heavy impact resistance. But in case of destruction during deflagration of glass small windows, lamps and lights, it turns out to be obscure how the excess pressure in 1 kPa, i.e. 1% of atmospheric pressure, can lead to the observed consequences. One more mysterious thing is the abnormal operation of electronic devices, for example, electronic clock, fire alarms, various sensors, certainly withstanding the supposed maximum explosion pressure during static testing.

As there is virtually no possibility to get the direct data about the loads in field, i.e. in the course of real emergency explosions in enclosed volumes, a single reliable method for giving answers for the above questions is supposed to be extensive experimental studies in explosion chambers. In spite of the lack of the legal framework for the test modes, such experiments make it possible to get both the $P(t)$ and $T(t)$ histories, and comparative data on the behavior during the internal explosive combustion of various samples of materials, units, assemblies, and items as a whole. By comparing a new item under test with that subjected to the extensive experimental development and having the excellent normal operation experience, certain conclusions about its reliability in case of emergency can be made. There is a perfect analogy with one of the areas in the foreign experimental studies of material flammability and combustibility - a comparative analysis [9].

The pressure records at deflagration explosion in field obtained from various sources demonstrate that the real processes can be unstable, have a form of broad-band random vibration when the main (carrier) frequency is overlaid by significantly distributed higher components of the frequency range. The share of high frequency amplitude can be determinative.

Figures 1 - 5 show the most characteristic ones from a range of the analyzed different pressure histories. Except for the wave process effects on the peak loads, the presence of sufficiently long series of high-frequency vibrations with relatively low amplitude capable of inducing the resonant responses subjected to the internal explosions of items and leading to their destructions due to low-cycle fatigue is evident. It should be also noted that the pressure gauges, in their turn, have both own frequencies, and final resolution that can lead to distortions and omissions of individual peaks. That is why the share of the pressure gauge errors cannot be referred to the factors on the safe side of the items under test.

It is indicative that it is sufficient to include the media compressibility into the mathematical model and the $P(t)$ design curves become capable of reproducing the vibration processes. The corresponding example is given in Fig. 5.

The drawback of all the experimental data given above is small volume of test chambers where they have been obtained and, correspondingly, there is no utter certainty in transferability of the test results to the emergency explosion field environment. This is due to that the above mentioned criterions of admissibility of quasi-stable approximation, i.e. factually the unstable pressure component significance test, depends on the enclosed volume and specific explosive zone size. The similar scaling problem occurs during testing in small explosive dust chambers [14]. To solve this problem,
the authors of some works mentioned above had artificially to increase one of the chamber sizes, i.e. to transfer to test pipes.

Figure 1. Pressure pulsations in the test chamber according to the work [10]

Figure 2. Unstable process in the adjacent explosion chamber based on the work [11]

Figure 3. Calibration tests in the chamber: the results of 10 physical tests according to the work [12]
Figure 4. Experimental (1) and design (2,3) data from the work [13]

Figure 5. Pressure dynamics in the chamber with a hole. Results of numerical modeling from the work [12]. (1- pressure, 2 – flame front area)

3. Discussions

The analysis of the given P(t) curves demonstrates that they are generally fractal, i.e. the relevant accidental processes are significantly broad-band. Every section of the curve is similar to itself and has signs of higher frequencies with reducing amplitudes - the sound wave harmonics. The ranges of the visually distinguished typical frequencies can be approximately determined. The duration of all the processes, except for the first two ones shown in Fig. 1, is about 0.5 s. The calculation of the quantity of peaks falling on the explosion time finds out that the frequency range makes from 120 to 400 Hz. The first curve of Fig. 1 shows the low-frequency process (~40 Hz), and the second one corresponding to the burning-to-detonation transition, vice versa, shows the high-frequency process of about 15 kHz. These data give a general picture about load frequency diversity during unstable deflagration. In particular, the frequencies specified are within the working frequency range of the external exposure for electric engineering products of civil (0.5...500 Hz) and military (1...2,000 Hz) purpose [15, 16], as well as ultra-small electronic products.

The duration of vibration loading cycles is also sufficient to induce fatigue breakdown of resonating elements, and the amplitudes of unstable surge reach 30% of the maximum explosion pressure. The characteristic values of the latter should be ranged as shown in the table.

The duration of internal deflagration explosion from the main quasi-stable component of the process should be additional estimated. For avoidance of doubt, the quasi-stable pressure peak is taken as a half-sine form of the maximum amplitude \( P_{\text{max}} \) and duration \( t \). The shock spectrum of such surge has a form shown in Fig. 6 and represents the envelope of maximum shifts \( u_{\text{max}} \) of conditional oscillators with own oscillation interval \( T \).

| Table 1. Maximum explosion pressure |
|-------------------------------------|
| Maximum pressure of internal deflagration explosion, kPa | Situation it corresponds to |
| 2 | Premises with normative prevention structures, ventilated premises |
| 7…10 | Residential premises with glass units installed |
| 15…20 | Maximum test pressures in standard explosion chambers. Destructions of fencing in residential and production premises |
| 70 | Complete destructions of residential and production premises |
| 100 | Critical or complete destructions of special civil and military facilities |
The shock spectrum shows that the maximum dynamic factor with such loading is about 1.77 and that the loads are distributed to the high frequency area where they reach the static ones by their efficiency caused by the pressure $P_{\text{max}}$. This means that all the explosion-affected elements of the structures and equipment with a frequency higher than the pressure surge conditional frequency $f=1/2\tau$ pick up. In the cases considered, the typical pressure surge duration makes $0.1\ldots0.2$ s and $f=2.5\ldots5$ Hz.

![Figure 6. Shock spectrum of half-sine pressure surge $\lambda=\tau/T$, $K_d=u_{\text{max}}/u_{\text{stat}}$](image)

It should be noted that when selecting the other pressure surge form, for example, suddenly applied rectangular or triangle (descending) surge simulating pre-detonating and detonating modes, more strict spectrum characteristics will be obtained: $K_{d\text{ max}}=2$ in the frequency area equal or higher than $f$.

For example, let’s estimate the shock acceleration of the fire alarm sensor (initiating device) in the internal deflagration explosion area DIP 141 ($m=0.2$ kg, dimensions $\Theta 0.94 \times 0.044$ m, $k=10^5$ N/m).

Let’s consider a case when the sensor is located in a way the base with the area $S$ (cover) is perpendicular to the arriving pressure wave. For the sensor own frequency $f_0=120$ Hz and surge duration $\tau=0.1$ s, we determine a dynamic factor by extrapolation to high $\lambda$ area according to Fig. 6; $K_d$ turns out to be approximately 1. Then the acceleration $u''_{\text{max}}=\omega_0^2u_{\text{max}}=\omega_0^2SP_{\text{max}}/k$. Value substitution gives $u''_{\text{max}}\approx 0.04P_{\text{max}}$ in m/s$^2$. For the lowest pressure level from the table, thus, we have $u''_{\text{max}}\approx 8$ g, and for the premises with modern glass units it is already 28…40 g that exceeds the loads provided in the standard [15] for civil construction facilities. It should be noted that this is about the impact failure of the sensor casing; the impact strength and tolerance of its electro optical content are to be analyzed individually.

4. Explosion load effect on the critical equipment elements and systems

The above given explosion surge frequency ranges are based on resonating frequencies both of fencing, carrying, housing and other basic and auxiliary structures, and the critical equipment elements, including sensors, instruments, devices, drivers, element-participating base (EPB) of security systems. If for the structures, the issue of loads during internal deflagration explosion is being actively developed, for the equipment elements and systems, the deflagration explosion is not currently a design case. The equipment testing for operation during and after the explosion are not conducted in general (the exclusions are engineering and development of reliability of constructions and modules of drilling rigs during which operation the gas explosions have become “a common event”). This can be formally explained by the standards regulating external mechanical effects on the equipment, devices and EPB. The standard [16] gives the values of the influencing factor for five classes of military facilities. For civil facilities, the comprehensive standard [15] has been developed basically to represent the norms of vibration and impact strength of engineering items divided into 47 unified structural design categories considering location on the structures and 34 severity levels.
The comparison of the obtained assessments for pressure dependence characteristics during internal deflagration with the data of these GOSTs makes it possible to find out the following reasons due to which the deflagration internal explosion effects are not included into the unified structure development techniques.

1. Unstable events during internal deflagration explosions are usually not considered due to virtually complete absence of theoretical and experimental data on this issue in the literature.

2. The shock impacts on the engineering items and EPB of security systems caused by quasi-stable rise of explosion pressure have the pulse duration significantly exceeding those provided by the standards. This means that the shock impact is low-frequency and non-hazardous, according to the standard developers. At the same time, as the above example of the initiating device shows, the impacts of the jump-in pressure can lead to destruction of the security system elements.

3. Possible frequency range of the explosion pressure impacts is fully overlapped by test ranges for harmonic and accidental vibration effect that, according to the standard authors, guarantees detecting all “weak points” of the test items. It is supposed that this approach also has material shortcomings. During the deflagration explosion, loading the devices, instruments and EPB of security systems is primarily ensured by direct pressure effect, and not only by vibration transmission through the fixing points of the element to the housing. Thus, there is the analogy to the structure acoustic loading. The pressure actuates the housings of sensors, devices, microcircuits and other elements by the distributed force that depends not only on the surge level, but on the overall dimensions of the loading items. As a result, the characteristics acoustic mini-systems are formed, the conventional vibration and impact protection means turn out to be inefficient, and the test methods with the use of vibration and impact benches to be unsuitable.

And even so, the main reason for ignoring the estimates and internal deflagration explosion tests is the assumption of low probability of the relevant emergency, and afterwards possible justification by referring to ‘such a thing had not occurred before’, and the wish to save money, etc.

In fact, the deflagration explosion tests of the security system are of extremely low prime-cost and can be conducted within the shortest period. As to the probability of emergency, to ensure correct situational assessment, it should be multiplied by the value of the probable damage.

The foregoing assumptions are relevant not only for buildings and constructions of civil and military purpose, but also for a number of complex civil and military equipment which explosive combustion is conditioned by flammable materials and potential sources of ignition and often by impossibility of erecting the preventive structures to reduce the pressure. Therefore, the publicly available materials on the Komsomolets atomic submarine accident expressly show that at a certain stage of the accident primarily caused by fire in one of compartments the low-intensity deflagration explosion occurred. The deflagration was accompanied by its characteristic popping effects when the flame front reached the adjacent compartments where the unburnt combustible gases had been displaced to that prevented the crew from quick closing some of inter-compartment partitions to localize burning. In such emergencies, the developers of state-of-the-art technology have no other perspectives except for wide use of explosion-proof electronic devices for automatic and manual control of the facility in emergency mode, creation of “safety barriers”, involvement of explosion and fire safety means, people damage control and rescue means.

One more significant large-scale accident due to failure during the gas explosion of critical security systems occurred in 2010 on the oil platform in the Gulf of Mexico. The produced gas from the deep-water well reached machine compartment via the ventilation pipelines. There occurred the primary explosion of the diesel engine, then the fire, and the deflagration specific line of explosions swinging the platform. The automation for fire-extinguishing, phlegmatization of gas mixture, pressure relief and emergency clogging of the opening in the unpressurized well has not actuated [18,19].

5. Conclusions
1. The kinds of pressure time dependences during internal deflagration explosions were considered. The shock spectra of the main relatively smooth (quasi-stable) component of the pressure variation
that forms 1-2 peaks of its increase were estimated. In addition to the main component, the pressure history included harmonic or impact-wave additional components which contribution depends on peculiarities of specific emergency explosion. The shock spectra of the main component and frequency of additional ones are within the frequencies over 2.5 Hz, i.e. within the range being hazardous for EPB of security systems. In particular, the failures, malfunctions and abnormality of operation modes of fire-extinguishing, survivability, fire alarm and evacuation systems can be conditioned by mechanical loads during deflagration modes.

2. The national regulatory documents provide for testing within the specified frequency ranges of engineering devices, instruments, equipment and EPB for various classes (in case of military purpose), structural design categories and location on the structures. These tests provide for availability or lack of resonating frequencies, vibration stability, vibration and impact strength during loading of different duration. However, these experiments are designed for verification and confirmation of product survivability under the normal operating loads. At the same time, the design case of emergency deflagration explosion that is needless for simple structures and operation conditions can be determinant for a number of complex diverse facilities, such as skyscrapers, oil and gas storage facilities, seal drill platforms, missile and space systems, submarines and so on. Irrespective of low probability of implementation of such design case, the damage in such situations will be catastrophic and unacceptable. For such facilities, the critical equipment components testing for internal emergency deflagration explosions is necessary to perform in explosion, and in extreme cases, in acoustics chambers, the standard vibration and impact bench tests are not suitable in this case.

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