Parameter calculation of accident explosions at outdoor installations of power-intensive facilities

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Abstract. The current report provides an algorithm for parameter calculation of deflagration explosions which quite often accompany emergency situations at power-intensive outdoor installations. The paper compares the results of analytical calculations conducted according to the elaborated analytical model with the data acquired through experimental studies of explosive combustion processes in atmosphere. It analyses the results of calculations carried out according to techniques and algorithms described in other sources and compares them with those received within own analytical model. The paper demonstrates that apart from fireball dimensions and the visible flame propagation rate, the main parameters defining explosive loads should include the location of mixture ignition and the distribution pattern of the explosive material, i.e. concentration distribution within the explosive cloud. The results of math modeling of explosive combustion processes of explosive clouds with various concentration characteristics are also shown. It is demonstrated that different concentration distribution patterns inside the cloud provide various perceptions by accident witnesses which is related to spectrum singularities of time laws of explosive loads emerging from explosive combustion of heterogeneous gas-air clouds.

Keywords: accidental explosion, gas-air cloud, fireball, power-intensive installation, explosive loads

1. Method for parameter calculation of deflagration explosions

The algorithm of calculating dynamic characteristics of compressive waves emerging from deflagration explosions is based on the Fourier method. This method can roughly be considered as analytical, as it contains no simplifications or assumptions. The only assumption deals with the linear equations of motion used to describe the explosion generated wavy flows[1].

Considering the relatively insignificant flame propagation rates (in relation to the speed of sound), which are typical for the major part of deflagration explosions, acoustic (linear) approximation may be used for determining the dynamic parameters of compressive waves. For determining the dynamic parameters of compressive waves generated by external deflagration explosions, the well-known solution for the zero-order acoustic radiator (monopole) in free air should be used [2]. Monopole in acoustics is a sphere with radius a, which produces pulsatory oscillations with frequency \( \omega \) symmetrically regarding its center. The following boundary condition should be true on the surface of the sphere simulating the area occupied by combustion products at the end of explosive combustion [3]:

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Therefore, the acoustic pressure and oscillating speed equations at any given time $t$ and for any given point $r$ will be as follows:

$$
P = \rho \frac{dF}{dt} = \rho \cdot c^2 \cdot \frac{u_m \cdot ika}{c} \cdot \frac{e^{ika[r/a]}}{r/a},$$

$$
u = \frac{dF}{dr} = \frac{p}{\rho \cdot c} \cdot (1 + ikr),$$

where $k = \frac{2\pi}{\lambda}$ is the wave number ($k = \frac{2\pi}{cT}$, $T$ is the characteristic time; $u_m$ is the velocity amplitude on the monopole surface ($r=a$); $F$ is the velocity potential; $c$ is speed of sound; $r$ is the distance from the monopole (ignition point).

Assume the velocity of the gas-vapor mixture on the surface of the sphere is given in the form of:

$$
u(t) \bigg|_{r=a} = u_0 \cdot f(t),$$

which according to Fourier-analysis may be transformed into:

$$
u(t) = \sum u_m \cdot e^{im\nu t},$$

where

$$
u_m = \frac{2\pi}{T} \int_0^T u_m \cdot f(t) \cdot e^{im\nu t} dt.$$

So, knowing the fluid velocity variation law and the fireball dimensions $a=\text{R}_{FB}$ in form of (3) and by applying (2), (4), we can acquire equations for dynamic parameters of the compressive wave in any given point of space:

$$
P = \rho \cdot c^2 \sum_{m=1}^{\infty} \left( \frac{u_m}{c} \right) \cdot \frac{ika}{(1 + ikr) a} \cdot \frac{e^{ika[r/a]}}{r/a} = \sum_{m=1}^{\infty} P_m,$$

$$
U = \sum_{m=1}^{\infty} \frac{P_m}{\rho \cdot c} \cdot \frac{(1 + ikr)}{ikr}.$$

2. Calculation result
Let’s consider the results of experimental research tests conducted for a deflagration explosion in atmosphere [4]. The following explosion modeling pattern was used during the tests. A light container (with the linear dimension of 0.35m) was filled with rich propane-air mixture, which was dumped right before the explosion (see Figure 1). The container had turbulizers in a form of vertical bars inside.

![Figure 1. Figures of the gas and air mixing chamber](Image)
Figure 2 demonstrates photos of a deflagration explosion. The time step constituted about 40ms (24 frames per second), i.e. the overall time of the explosion process (its visual effect) was about 320 ms. The combustion explosion lasted for about 30-35ms. This is clearly demonstrated by the explosive pressure time law given in Figure 3, which provides experimental oscilloscope pattern of explosive pressure.

![Figure 2. Photos of explosive combustion of propane-air mixture](image1)

Figure 3 shows results of explosive pressure parameters calculation carried out according the afore-mentioned algorithm. Figure 3 comparing empirical and analytical explosive pressure-time relations provides that the elaborated algorithm describes dynamic parameters of the explosion rather accurately.

In order to prove the feasibility of the new algorithm, we have compared the results with those acquired through alternative calculation techniques. The calculations of explosive pressure from a deflagration explosion of 1000kg of propane are given below. The initial data was assumed the same as in example shown in [5] and solved with the help of Taylor’s theory of solid piston motion.

It is assumed that the explosion entails a fireball with the radius of $R_{FB} = 24.98m$ while the maximum flame velocity reaches $W_{MAX} = 97m/s$. Explosion parameters were determined at the distances of: 24.98  36.32  51.05  71.29  100.73  146.63  240.69  500.90m from the explosion site.

Maximum explosion pressure values at the indicated distances were acquired in [5]. We have conducted calculations based on similar initial data.

Calculations were provided for the following version of visual flame propagation rate settings assumed in [5]. There visual flame propagation rate - time relation $W(t)$ is given a certain value. In [5] it is assumed that if $0 < t < A_H \cdot t_{EXPLOSION}$ ($t_{EXPLOSION}$ is the overall time of explosive combustion), there takes place a linear increase in visible flame propagation rate from $W_{MIN}$ to $W_{MAX}$; if $A_H \cdot t_{EXPLOSION} < t < (A_H + A_P) \cdot t_{EXPLOSION}$, the visible flame propagation rate is $W_{MAX}$, while if...
\((A_H+A_P)\*t_{\text{EXPLOSION}}<t<\text{EXPLOSION}\), the visible flame propagation rate slows down from \(W_{\text{MAX}}\) to 0. In this case the following parameters are assumed: \(A_H=0.3;\ A_P=0.6;\ A_C=0.1\).

The calculation results are summarized in Table 1.

| R, m | Calculation results from [5] | Calculation results according to elaborated algorithm |
|------|-------------------------------|------------------------------------------------------|
|      | R, m | P_{MAX}, kPa | P_{MAX}, kPa | P_{MIN}, kPa | P_{MIN}, kPa | P_{MIN}, kPa | P_{MIN}, kPa |
|      |      | 24.98 | 36.32 | 51.05 | 71.29 | 100.73 | 146.63 | 240.69 | 500.90 | 24.98 | 36.32 | 51.05 | 71.29 | 100.73 | 146.63 | 240.69 | 500.90 | -12.55 | -8.63 | -6.14 | -4.40 | -3.11 | -2.14 | -1.30 | -0.63 |

Table 1 demonstrates that calculation results received within the test program are quite close to those acquired via the experimental algorithm set in [5].

Let’s get to the calculation results acquired through the elaborated algorithm. A series of computational experiments was conducted to reveal peculiarities of explosive load formation during accidental deflagration explosions of heterogeneous mixture. Below are the results of four calculations.

All calculation variants assumed that the explosion results in a fireball with the radius of \(R_{FB}=20.0\) m, the minimum flame velocity comprises \(W_{MIN}=30.0\) m/s, and the maximum flame propagation rate reaches \(W_{MAX}=100\) m/s. Explosion parameters were determined at the distance of 21 m from the explosion site, i.e. in the vicinity of the fireball’s boundary.

Let’s consider dynamic parameters of the load during an explosion of a homogeneous mixture. In this case, at the initial stage of the explosion the flame velocity is minimal and equals \(W_{MIN}\), i.e. it is assumed that there is no flame intensification or acceleration at this stage. Thus, for \(0<R<\frac{A_H}{1-A_C}R_{FB}\), it was assumed that the visible flame propagation rate equals \(W_{MIN}\). In case \(\frac{A_H}{1-A_C}R_{FB}<R<\frac{(A_H+A_P)R_{FB}}{A_P}\), the visible flame propagation rate rises evenly to \(W_{MAX}\), i.e. the flame accelerates (the cause of the acceleration in this case is not important) while for \(\frac{(A_H+A_P)R_{FB}}{A_P}<R<R_{FB}\) the visible flame propagation rate decreases from \(W_{MAX}\) to 0. The following parameter values were assumed in the calculations: \(A_H=0.10;\ A_P=0.8;\ A_C=0.10\) \((A_H+A_P+A_C=1)\). We will refer to this calculation variant as Variant VI.

Figure 4 provides calculation results for explosive pressure parameters in the point located 1 m away from the fireball’s boundary or 21 m away from the explosion site. The calculations demonstrated that the explosion’s integral parameters constitute: maximum pressure equals \(\Delta P_{MAX}=15.2\) kPa; minimum excessive pressure comprises \(\Delta P_{MIN}=-12.8\) kPa; compression phase impulse is \(1191\) Pa*s.

Figure 5 shows dynamic parameters of the fireball, as well as dynamics of the visible flame propagation rate and the velocity characteristics of the flow accompanying the explosion.

It can be observed (see Figure 5 Picture 2) that the flame velocity at the initial stage is constant, then there occurs acceleration and at the final stage the combustion process ends and the flame ‘stops’.

Figure 6 provides a narrowband spectrum of explosive pressure (with the bandwidth of 1.0Hz) which was demonstrated in Figure 4.
Figure 4. Expected excessive pressure-time relation at the distance of 21m from the explosion
Calculation Variant VI

Figure 5. Dynamic relations of fireball’s parameters, visible flame propagation rate and flow velocity at the fireball’s boundary
Calculation Variant VI
1 – flame front coordinate versus time characteristic;
2 – visible flame propagation rate versus flame front position characteristic;
3 – visible flame propagation rate versus time characteristic;
4 – flow velocity at the fireball’s boundary versus time characteristic

Figure 6. Expected excessive pressure spectrum. Bandwidth 1.0Hz. Calculation Variant VI
The expected value of total pressure level is $L=183.0$ dB while the level of sound pressure (starting from the second octave - 45Hz) equals $L_v=157.4$ dB.

Let’s consider another accident scenario when there is no flame acceleration at the initial stage of the explosion, its acceleration (intensification) appears in the vicinity of the fireball’s boundary. Then the following parameter values should be assumed in the calculations: $A_H=0.80; A_P=0.1; A_C=0.10$ $(A_H+A_P+A_C=1)$. We will refer to this calculation variant as Variant V.

The calculation results are demonstrated in Figure 7.

![Figure 7. Calculation results for Variant V](image)

1 - expected excessive pressure - time relation at the distance of 21m from the explosion site;
2 - dynamic relations of fireball’s parameters, visible flame propagation rate and flow velocity at the fireball’s boundary;
3 - expected excessive pressure spectrum. Bandwidth 1.0Hz

The calculations demonstrated that the explosion’s integral parameters constitute: maximum pressure equals $\Delta P_{\text{MAX}}=20.5$ kPa; minimum excessive pressure comprises $\Delta P_{\text{MIN}}=-4.4$ kPa; compression phase impulse is 710Pa*s. The expected value of total pressure level is $L=181.5$ dB while the level of sound pressure equals $L_v=166.2$ dB.

When comparing the integral parameters of the explosion for Variant V scenario with similar explosion parameters for a Variant VI accident, it can be observed that the explosive pressure increases (approximately by 5kPa or 33%), the pressure impulse decreases (approximately by 500Pa*s or 40%) while the acoustic and human-perceived pressure goes up (approximately by 9dB or roughly three times).

Thus, the following conclusions may be made. Explosive accident along Variant V will be defined by eye-witnesses as an explosion while Variant VI accident will be categorized as low-frequency rumble. Building constructions with a long natural period of oscillations will retain stability in case of an explosion under Variant V conditions, but constructions with short natural period of oscillations...
will get destroyed. Loads emerging from a Variant VI explosion will destroy structures with the load bearing capacity lower than explosive pressure, regardless of the natural oscillation frequency of the building.

Let’s consider scenarios of the accidents that are followed by an explosion of a heterogeneous mixture. It is assumed that at the initial stage of the explosion the flame velocity is minimal and equals \( W_{\text{MIN}} \), i.e. there is no flame intensification or acceleration at this stage. Thus, for \( 0 < R < A_H \times R_{FB} \), it was assumed that the visible flame propagation rate equals \( W_{\text{MIN}} \). If \( A_H \times R_{FB} < R < (A_H + A_P) \times R_{FB} \), the visible flame propagation rate periodically increases up to \( W_{\text{MAX}} \) and then decreases down to \( W_{\text{MIN}} \), i.e. there occur repetitive accelerations and decelerations of the flame. In case of \((A_H + A_P) \times R_{FB} = (1 - A_C) \times R_{FB} < R < R_{FB} \), the visible flame propagation rate drops from \( W_{\text{MAX}} \) to 0. The following parameter values were assumed in the calculations: \( A_H = 0.10; A_P = 0.8; A_C = 0.10 \). Depending on the number of velocity growth and drop periods, we will refer to these calculation variants as – Variant I (one period) and III (four periods). The number of periods defines spatial inhomogeneity of the mixture.

The calculation results for Variant I are demonstrated in Figure 8.

![Figure 8](image-url)

**Figure 8.** Calculation results for Variant III
1 - expected excessive pressure - time relation at the distance of 21m from the explosion site; 2 - dynamic relations of fireball’s parameters, visible flame propagation rate and flow velocity at the fireball’s boundary.
3 - expected excessive pressure spectrum. Bandwidth 1.0Hz

The calculation results for Variant I are demonstrated in Figure 9.
Figure 9. Calculation results for Variant I
1 - expected excessive pressure - time relation at the distance of 21m from the explosion site;
2 - dynamic relations of fireball’s parameters, visible flame propagation rate and flow velocity at the
fireball’s boundary.
3 - expected excessive pressure spectrum. Bandwidth 1.0Hz

3. Conclusion
There was developed and tested a calculation algorithm for dynamic loads followed by accidental
deflagration explosions.

The demonstrated calculation algorithm of defining parameters of a transient compression wave
emerging from a deflagration explosion can be used in modeling of accidental explosion consequences
at power-intensive facilities.

The elaborated calculation algorithm, which allows to set an arbitrary flame propagation pattern
during an explosion, may be useful when analyzing causes and consequences of real explosion
accidents.

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