Initiation of explosive mixtures having multi-sized structures

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Abstract. Theory of strong blast was used as the experimental method of determining the energy of source which provides the initiation of combustible mixture. For mono-fuel mixtures the following parameters were experimentally determined at testing: the critical initiation energy of a cylindrical detonation wave in mixtures 2H₂+O₂ and C₂H₂+2.5O₂ (exploding wire); the critical initiation energy of a spherical detonation in a mixture of C₂H₂+2.5O₂ (electrical discharge). Similarly, for the double-fuel mixtures of acetylene – nitrous oxide – oxygen (having bifurcation cellular structures) the critical initiation energy of spherical wave was determined also. It was found that for the stoichiometric mixture on both fuel components the critical energy of mixture with the bifurcation structure was undervalued by several times in comparison with the value of the critical energy for the mono-fuel mixture, in which the cell size at a given pressure is determined by the large scale of bifurcation cells. This result shows the decrease of the critical energy with an increase of the number of "hot spots", which are the numerous areas of collision of the transverse waves of large and small scales in a mixture with bifurcation properties.

1. Introduction
The effect of excitation of combustion and detonation processes in the fuel-oxidizer mixture usually demonstrates a "threshold" character ("yes" - "no") for each initiator (Figure 1). In an idealized model of strong blast in an inert medium (for example, [1-2]) the energy of the explosion is defined as the parameter that identify the function of the velocity of the blast wave on distance (or time). By analogy,

Figure 1. Threshold character of initiation: left – no initiation, right – successful initiation of detonation in monofuel mixture C₂H₂+2.5O₂.
the minimum energy of an initiator, providing 100-percent excitation of burning or detonation regimes, is commonly known as the critical energy for combustible mixture. The critical ignition energy \( E_{\text{ign}} \) at the spark ignition has traditionally been treated as the primary parameter of the flammability of mixture. The critical energy of detonation initiation \( E^* \) by the ideal source (in terms of spatial and temporal characteristics of the initiator) is a measure of the detonability of mixtures: the smaller \( E^* \), the more dangerous is the mixture.

The formulation of the initiation condition on the basis of a single parameter - the critical energy - is very attractive. However, the multi-front structure of a real detonation wave (instead of its idealized one-dimensional model with a smooth front) does not allow to consider the problem of initiation of waves of combustion and detonation as completely solved: up to now the following questions are poorly studied: the influence of the spatial and temporal characteristics of the initiator on the excitement of the combustible mixture; the formation of self-supporting wave (detonation or combustion), including the case of an initiation of charges of intermediate symmetry [3].

Indeed, each mixture at fixed conditions (pressure, temperature, composition) has some characteristic spatial \( r^* \) and temporal \( t^* \) scales (for example, the sizes of the induction zone or the reaction zone and the corresponding induction or reaction periods). At the same time, under these conditions, the explosive mixture absorbs the energy \( E_v \) from the initiator for the finite period of time \( t_0 \) in some limited area of space \( V_0 = f(r) \) (\( E_v \) is part of the energy \( E_0 \), initially stored in the initiator):

\[
E_v = \int_0^{t_0} \int_0^{V_0} \varepsilon(t,V) \cdot dt \cdot dV = \eta E_0
\]

\( \varepsilon(r,t) \) is a function, which describes the spatial-temporal law of the input energy, \( \nu \) is the index of symmetry (\( \nu = 1, 2, 3 \) for planar, cylindrical and spherical case, respectively). It is evident that for different initiators (electric or laser spark, exploding wire, explosive charge, thermal igniter, flow of hot and active particles, etc.) the function \( \varepsilon(r,t) \) has its own specific type, and, in general, \( E_v \) is a complex function of the characteristic scales of the initiator and the mixture (more precisely – of their ratio). Influence of temporal and spatial factors of the energy transfer from the initiator to combustible mixture and the features of excitation and development of a chemical reaction in the mixture are crucial in initiating tasks, and above all – in the correct experimental determination of the critical energy and its optimization.

Note that recently the new type of gas detonation structure was experimentally observed: the fixed structures of various sizes (large and small) [4-5] were detected simultaneously on the smoked imprint. In connection with the discovery of two-sized (bifurcation) cellular structures the following question becomes fundamental: which the scale of the cells is responsible for the initiation of a mixture. This work is the world's first study devoted to the critical initiation of mixtures with multiscale structures.

It should be noted that the problem of determining the critical initiation energy of the multi-front detonation is fundamental in gas dynamics of reacting systems. A lack of reliable data on the initiation significantly hinders the creation of a perspective detonation engine for the aviation and aerospace industries, which are engaged in intensive development of the world's leading countries.

2. **Energetic equivalence of different initiators**

A wide range of combustible mixtures – from close to stoichiometric of fuel-oxygen mix (FOM), and fuel-air mix (FAM) – up to enriched or depleted mixtures, makes it impossible to apply any single type of initiator (a range of critical energy is about 15 orders of magnitude). The real initiators have individual spatial-temporal characteristics of its energy input in the explosive mixture. As a
consequence the problem of comparison of different sources and identification of "useful" energy using a universal method equally suitable for various initiators and various mixtures becomes important.

Figure 2. Trajectory of the blast wave in the inert mixture C2H2+2.5N2.

Figure 3. Trajectory of spherical blast wave in the inert mixture from the point of view of the strong blast theory \((y^3 - x^3)\) with a large linear part. The similar dependence with the linear part is characteristic also for the cylindrical blast wave (in coordinates \(y^4 - x^2\)).

In this paper, the "useful" energy of an arbitrary source was determined using the intensity of the blast wave produced by a source at the stage of the "strong explosion", see Figure 2. The theory of strong explosion [1-2] in an inert atmosphere gives the ratio between the energy of the explosion (at instant release) \(E_v\), initial density \(\rho_0\), coordinate blast wave \(r\) and time \(t\) in the following form:

\[
r(t) = \left[ E_v \cdot \left( \alpha, \rho_0 \right) \right]^{\frac{1}{(v+2)}} \cdot t^{\frac{2}{(v+2)}}.
\]

In coordinates \(r^{v+2} - t^2\) function (2) is represented by a straight line, see Figure 3. The energy \(E_v\) is determined by the slope of the linear part, which in this case can be attributed to the meaning of "useful" energy of source.

3. Experimental details and results
This technique has been successfully tested for the case of the cylindrical initiating of detonation wave (DW) using exploding wires [6]. The energy \(E^*_2\) in mixture C2H2+2.5O2 and 2H2+O2 was experimentally determined as a test.

This article presents the results of the hemispherical initiation of wave by pointed electrical discharge also. The mixture of C2H2+2.5O2 was used as the base for mono-fuel system and the mixture C2H2+(2.5–k/2)O2+k·N2O was choose as 2–fuel system with bifurcation properties. Initiation of the mixture was carried out using a high-voltage generator (at the capacitor \(C = 1\) µF charged to a voltage of \(U = 4.5\) kV (mode of R1 with the stored energy of 10 joules) or \(U = 9\) kV
(R2 mode with 40 J of stored energy). The typical schlieren streak image of critical regime of initiation of detonation is demonstrated on Figure 4.

The energy $E^*_3$ at using of electrical discharge in mixture C2H2+2.5O2 was experimentally determined as a test. Figure 2 shows the photographic scan of the blast wave trajectory in an inert mixture C2H2+2.5N2 as an analog of the combustible mixture (replacement of O2 to N2, see [6]). Figure 3 shows the dependence $r^5 = f(t^2)$, obtained by the recalculation of the trajectory of the blast wave from the point of view of the theory of the strong explosion (hereinafter the blast wave coordinate $r$ and time $t$ is replaced by $x$ and $y$ coordinates of the trajectory image of the blast wave on a film).

It is clearly seen that there is a large linear region, and its linearity over a large area of the trajectory allows one to determine the critical energy with a reasonable accuracy. The critical mode of initiation in R1 regime (10 J) was observed at the initial pressure $P_{r1}^* = 0.1$ atm, while in R2 regime (40 J) it was observed at $P_{r2}^* = 0.04$ atm. By the linear parts of graphs of $r^5 = f(t^2)$ the critical energy was defined: $E^*_1 = 6.8$ J (68% of the stored energy) at $P_0 = 0.1$ atm and $E^*_2 = 23.2$ J ($\eta = 58\%$) at $P_0 = 0.04$ atm.

Figure 4. Trajectory of the wave at critical regime of initiation of detonation in the mixture C2H2+O2+3N2O with the bifurcation structure on the detonation front.

Figure 5. The experimental results about initiation of the cylindrical detonation in mono-fuel mixtures 2H2+O2 and C2H2+2.5O2.

Figure 6. The experimental results about initiation of spherical detonation in the mono-fuel mixture C2H2+2.5O2 and in 2-fuel mixture C2H2+O2+3N2O with bifurcation structures of the detonation front.
Figure 5 presents data on the critical energy initiation of cylindrical DW together with data from the [7-9]: symbols - experimental data, lines – calculated results (the details of initiation models can be found in [10]). It should be noted a significant difference between the experimental data obtained at various initiators, both among themselves and in their slopes (dependence $E_2^* = f(P_0)$).

Figure 6 is a summary graph of an experimentally determined critical initiation energy of the spherical detonation for classical mixture C2H2+2.5O2 supplemented by the data of initiation energy $E_3^*$ for the same mixture as in [9] when using electric (E-spark) and laser (L-spark) discharge as the initiator. One can see an appreciable spread of data in [9], not only in the values (several times smaller at the laser initiation), but also in the nature of tilting approximating lines for each type of the initiator. Authors of [9] do not discuss the reason for such differences, the true nature of this is not clear and requires detailed studies. Experimental points presented in this paper for mixture C2H2+2.5O2 are located closer to the calculated line data in comparison with Canadian researchers.

Approximate line, the slope of which determines the critical energy of initiation, is defined by the equation $Y = AX - B$, i.e. it does not pass through the origin of coordinates, due to a non-instantaneousness of allocated initiated energy (see Eq. (1)). Let $X_i = B / A$ be the point of intersection of the continuation of the approximate line with the $x$-axis. Then the corresponding time $t_i$ characterizes the delay of equivalent instantaneous initiation with respect to the real non-instantaneous energy release. In other words, in the case of non-instantaneous source (i.e., $E^* = f(t)$) the time $t_i$ characterizes the critical time allocation of the "useful" energy. The energy released after the time $t_i$ until the time of formation of a self-sustaining DW in the mix $t_{form}$ does not affects the initiation process.

Similarly, for the dual-fuel mixtures of acetylene – nitrous oxide – oxygen, having the bifurcation properties of cellular structures, $E_3^*$ was determined also. For example, in mixture of C2H2 + O2 + 3N2O the critical mode of initiation of the mixture with the bifurcation properties using R1 (10 J) mode was observed at the initial pressure $P_{1i}^* = 0.4$ atm, and in R2 (40 J) regime at $P_{12}^* = 0.16$ atm. The processing path of the blast wave trajectory in an inert mixture from the standpoint of the model of a strong explosion on a straight-line portion of the graph of the dependence $r^5$ on $t^2$ allows one to determine the corresponding critical energy for the initiation of the spherical DW: $P_0 = 0.4$ bar $E_3^* = 1.7$ J ($\eta = 17\%$), while at $P_0 = 0.16$ atm $E_3^* = 11.4$ J ($\eta = 28\%$).

In Figure 6 the symbols on the vertical dotted lines mark the data on initiation of a mixture of C2H2 + O2 + 3N2O with bifurcation properties. Inclined dotted line is the calculated data for the mixture of C2H2 + 3N2 + 2.5O2 as its non-bifurcation analogue. It is evident that the experimental values for a mixture of C2H2 + O2 + 3N2O are located significantly below the estimated line for the mixture of C2H2 + 2.5O2 + 3N2 (about 3 times), although the sizes of the cells were unexpectedly close.

4. Conclusion
It was found that for stoichiometric mixture (on both fuel) the critical energy for mixture with bifurcation structure is understated by several times in comparison with the value for mono-fuel mixture, in which the cell size at a given pressure is determined by the large scale bifurcation cells. This result shows a decline of $E_3^*$ with an increase in the number of "hot spots", which are the
numerous areas of collisions of large and small-scale transverse waves in a mixture with bifurcation properties.

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References
[1] Sedov L I 1993 Similarity and dimensional methods in mechanics. (CRC press)
[2] Korobeinikov V P 1991 Problems of point blast theory. (Springer Science & Business Media)
[3] Vasil’ev A A 2015 The cellular structure of the multi-detonation and initiation (review) Comb. Expl. & Shock Waves 51 1 9–30
[4] Presles H N, Desbordes D, Guirard M and Guerraud C 1996 Gaseous nitromethane and nitromethane-oxygen mixture, a new detonation structure Shock Waves 6 111–14
[5] Vasil’ev A A 2014 Monopropellant as a source of bifurcation properties of multi-systems Comb. Expl. & Shock Waves 50 2 14–23
[6] Vasil’ev A A 1983 Study of critical initiation of gas detonation Comb. Expl. & Shock Waves 19 1 121-31
[7] Lee J H 1977 Initiation of gaseous detonation Ann. Rev. Phys. Chem. 28 75–104
[8] Lee J H and Ramamurthi K 1976 On the concept of the critical size of a detonation kernel Comb. Flame 27 331–40
[9] Lee J H and Matsui H 1977 A comparison of the critical energies for direct initiation of spherical detonations in acetylene-oxygen mixtures Combust. Flame 28 61–66
[10] Vasil’ev A A 2012 Dynamic parameters of detonation Shock Waves Science and Technology Reference Library, Volume 6: Detonation Dynamics ed F Zhang (Berlin-Heidelberg: Springer-Verlag) pp 213-79