AN INTEGRAL ENERGY-RELEASE IN DIVERGENT MULTIFRONT DETONATION

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Excitation of combustion or detonation in a combustible mixture usually has a threshold character (yes/no) for any initiator. In an idealized model of a strong explosion propagating over an inert medium the governing parameter determining the blast wave properties is the explosion energy. By analogy, the minimum energy of the initiator that ensures 100% excitation of combustion or detonation is usually called the critical energy for combustible mixtures as well. The critical ignition energy (at least, in the case of spark ignition) is traditionally considered as the basic parameter of the fire hazard of mixtures. The critical energy of detonation initiation E* by an ideal (in terms of spatial and temporal characteristics) initiator serves is a measure of the detonation hazard of mixtures: the smaller the value of E*, the more hazardous the mixture.
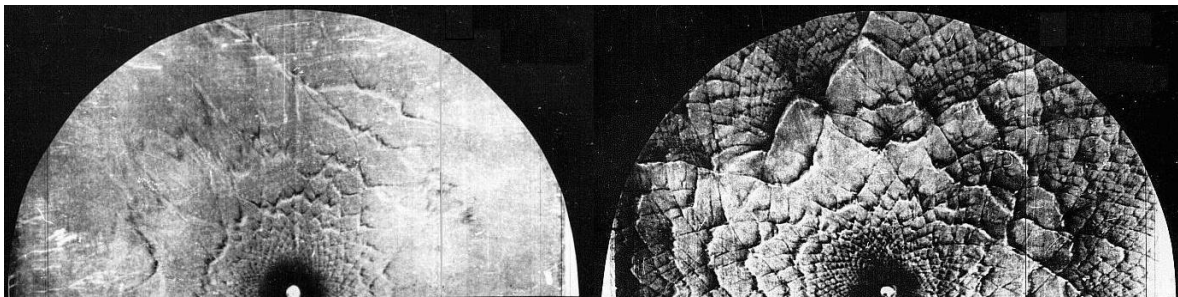

Fig.1. The typical smoked foils of the subcritical (E<E*, left) and the critical (E>E*, right) regimes of initiation of expanding multifront detonation (cylindrical case).

The idea of formulating the initiation condition on the basis of only single parameter (critical energy) is extremely attractive. However, because of the multifront structure of a real detonation wave (instead of its idealized one-dimensional model with a smooth front), the
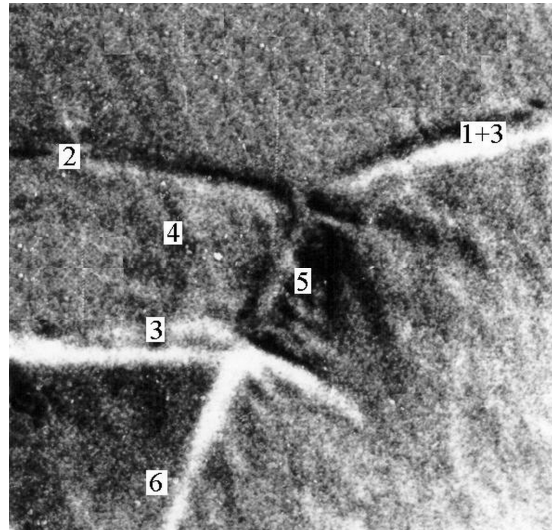

Fig.2. The typical schlieren image of the structure of real multifront detonation.

problem of initiation of combustion and detonation waves cannot be considered as being completely solved: the question about effective chemical energy-release for initiation and propagation of multifront detonation practically not investigated experimentally. Traditionally, the chemical energy release of a mixture Q is understood as the difference between the total enthalpy of formation of the initial components of the mixture (index i) and the total enthalpy of formation of chemical reaction products (index j):

$$Q = \sum \alpha_i \cdot H^{\circ}_{f_i} - \sum \alpha_j \cdot H^{\circ}_{f_j},$$

here α - numerical coefficients for the chemical substances involved in the reaction, H°_f - the enthalpy of formation of these substances at a standard temperature T = 298.15 K. It is this quantity that stands in the energy equation of the classical detonation theory with a plane front.

Despite the nearly 70-year history of detecting the instability of a classical one-dimensional detonation model with a smooth plane front and the discovery of the multifront gas detonation structure, the question of energy release in a multi-front detonation with significant spatial and temporal inhomogeneity of a detonation wave is actually unexplored. In this paper, we present some ideas and data concerning this unexplored area.

The next technique for determining the energy release Q of a combustible mixture is proposed, based on recalculation of the trajectory of an expanding wave from the position of a strong explosion model – the wave trajectory of the critical initiation of a multifront detonation in a combustible mixture is compared with the trajectory of an blast wave from the same initiator in an inert mixture whose gas-dynamic parameters are equivalent to the parameters of the combustible mixture. The energy release of the mixture is defined as the difference in the joint energy release of the initiator and the fuel mixture during the critical initiation and energy release of the initiator when the blast wave is excited in an inert mixture. The results of an experimental verification of such procedure on a stoichiometric acetylene-oxygen mixture are presented.

In this paper, the "useful" energy of an arbitrary source is determined on the basis of the intensity of the blast wave generated by this source at the stage of a strong explosion. The theory of a strong explosion [1, 2] in an inert medium yield the following relationship between the instantaneously released explosive energy E_v, initial density ρ_0, blast wave coordinate r, and time t:

$$r(t) = \left\lceil E_v / \left(\alpha_v \rho_0 \right) \right\rceil^{1/(v+2)} \cdot t^{2/(v+2)}.$$

In the coordinates $r^{(v+2)} - t^2$, which dependence should be a straight line. Based on its slope, it is possible to determine the energy E_v, which should be treated in our case as the "useful" energy of the source.

The theory of a strong explosion is used as a basis for the development of an experimental technique for determining the source energy that ensures initiation of the combustible mixture (initiation of blast wave in inert mixture and

recalculation of blast wave trajectory from point of view of blast theory) and the energy, which became the basic energy for propagation of detonation wave at critical initiation regime (initiation of reactive mixture and recalculation of trajectory of wave at common influence of initiator energy and increasing energy of explosive mixture). From these data the effective energy-release of mixture was determined.

When a cylindrical ($\nu = 2$) explosion is excited in an infinite space,

$$r(t) = \lceil E_2 /(\alpha_2 \rho_0) \rceil^{1/4} \cdot t^{2/4},$$

or

$$r^4 = \lceil E_2 /(\alpha_2 \rho_0) \rceil \cdot t^2,$$

whence

$$E_2 = \alpha_2 \rho_0 \lceil r_j^4 - r_i^4 \rceil / \Delta(t^2)_{ij} = E_2^*.$$

In [3-4], an experimental technique for determining the critical initiation energy of multifront detonation and the effective energy of the initiator used in this study is described in detail for example of an exploding wire ($\nu = 2$) and high-voltage electric discharge ($\nu = 3$).

Briefly recall the essence of the methodology. The procedure of the first stage consists in determining (for example, for the stoichiometric mixture C_2H_2-O_2) the threshold pressure of the mixture P*, above which this initiator with a $_{fixed}$ energy reserve reliably excites the DW (for example, with the same capacitance and voltage C, U of the pulse capacitor when used electric wire or electric discharge as an initiator).

According to the theory of a strong explosion for the fixed explosion energy E_0, the parameters of shock waves in different gases and their profiles will be the same (in the stage of a strong explosion) if the gas densities ρ_0 and the adiabat indices γ_0 are identical. Then, in order to determine the critical initiation energy of multi-front detonation for a given P* mixture, in the second stage it is necessary to determine the "useful" energy E_ν (in the shock wave from the same source) in a mixture of this fuel component with any diatomic inert gas (for example, $C_2H_2 + 2.5N_2$) at pressures that differ from P* by as many times as

many times the molecular masses of the initial mixture (at P*) and the chosen chemically inert analogue of it are different. This satisfies the condition that ρ_0 and γ_0 are identical for a fixed E_0. Thus, replacing O_2 by N_2 allows one to achieve the same value of γ_0 in a combustible mixture of stoichiometric composition and its inert analog, and to maintain the density ($\rho_{mix} \sim 106/3.5$, $\rho_{inert} \sim 96/3.5$), the experiment in an inert analog should be carried out at a pressure $P_0 = P^*\, 106/96$.

In the third stage, processing of the shlieren-scanning of the trajectory of the blast wave (BW) in an inert mixture is performed from the positions of the strong explosion model, which allows us to determine the critical energy (for example, for a spherical wave, along a rectilinear portion of the dependence on, and for a cylindrical wave on a straight line segment of the dependence on $\alpha_3 =$ 1.032 and $\alpha_2 = 1.197$ for the given mixture ($\gamma_0 = 1.3323$).

In the fourth stage, the shlieren trajectory of the critical initiation of the DW is treated in a similar way, when the chemical energy of the combustible mixture is added to the initiator and due to their collective action the wave is transformed into a self-sustaining DW, only at the expense of the energy release of the mixture.
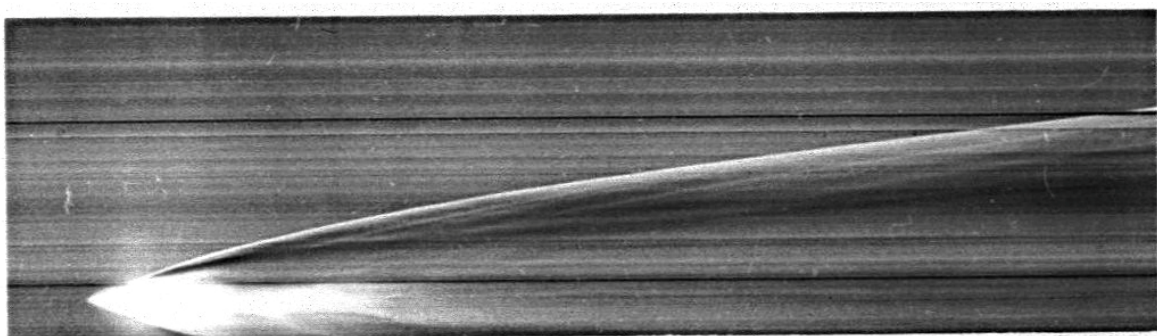

Fig.3. Typical shlieren trajectory of blast wave in inert media.

Figure 3 shows a typical schlieren-scan of the trajectory of an explosive excited in an inert medium. Qualitative behavior of BW - its gradual attenuation as far

as the distance from the source of initiation is the same as for a cylindrical diverging wave (initiation by an exploding wire in a channel between two parallel glasses) and for a spherical SW excited by an electric discharge between the electrodes. In addition, the behavior of the plasma bunch from the initiator can be clearly seen: it rapidly expands (playing the role of the piston) to its maximum volume (with the stabilization of the boundary), and then quickly cools down, ceasing to act on the blast wave (in any case - compression waves, rarefaction waves, of course, continue its movement after the expanding blast wave, weakening it).
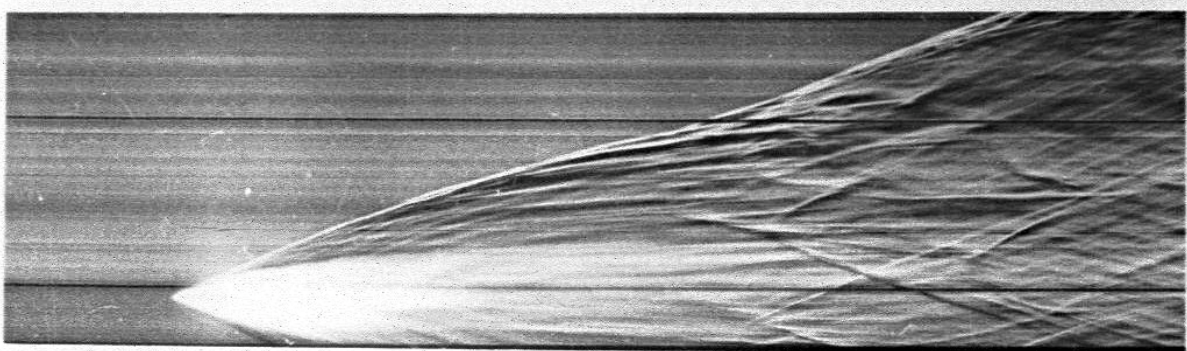

Fig.4. Typical shlieren trajectory of the critical initiation of multifront detonation.

Figure 4 shows a typical schlieren-scan of the trajectory of an explosive hydrocarbon during a critical initiation of a multi-front DW. It is clearly seen that, in contrast to the monotonic weakening of the blast wave in an inert medium, the nature of the behavior of the shock wave (SW) during the initiation of multi-front detonation is noticeably different. The attenuation of the shock wave is observed only near the initiator, when the contribution of the energy release of the mixture is still sufficiently small in comparison with the initiator energy. Then, as far as the distance from the initiator, the role of the chemical energy release of the mixture increases and becomes decisive. As a result, the decay of the hydrocarbon ceases and the wave, due to the chemical energy

release of the mixture, is transformed into a self-sustaining DW propagating at a constant velocity.

It should be noted that the plasma cloud in Fig.4 also differs from Fig.3, its luminescence is much longer. Most likely, the "delay" of the luminescence is due to the luminescence of the products of the chemical reaction of the mixture, which were exposed to the vapor of the wire metal. Figure 4 shows that the acceleration of the front of the headwave and the transition to detonation is observed even after the plasma cloud of the initiator has "completed" its effect on the expanding wave. Here it is clearly seen that almost simultaneously at many points local foci of chemical reaction arise that excite the waves diverging from these points (both after the SW and in the direction of the initial point of initiation).

The photo on Fig.4 clearly demonstrates that the chemical reaction behind the front of the initiating wave does not occur simultaneously, but at separate points distributed over space in an inhomogeneous manner. In other words, the actual energy release in the multifront FR significantly differs from the model based on the idea of a homogeneous ignition of a mixture on surfaces conjugated to the surface of the head shock wave. Of special interest is the region of spontaneous initiation of initiating centers in a damped blast wave. For example, in Fig.4, this is approximately 15 microseconds after the initiation pulse was applied to the exploding wire and when the radius of the blast wave reached approximately 40 mm. It is very important that by this time the release of the initiator energy has already been completed, and the gas dynamic flow of the blast wave was determined only by the "useful" energy released to its stationary value.

Figure 5 shows the trajectory of a blast wave processed in a strong explosion in an inert medium excited by an exploded wire (cylindrical SW) treated at a $CU^2/2$ energy stored in a capacitor (R1 = 10 J), which is processed with the help of a strong explosion model. It can be seen that on the graph there is an extended rectilinear section, the slope of which determines the effective energy of the

initiator with sufficient accuracy. The initial pressure of the inert mixture is selected in accordance with the conditions for the critical initiation of the $C_2H_2 + 2.5O_2$ mixture excited by this initiator with this energy reserve (see the above for the procedure for comparing the combustible and inert mixtures). We note that for the regime of critical initiation of a combustible mixture with an energy reserve of R2 = 40 J, the trajectory in the inert analog has a qualitative behavior of the dependence $r^4 = f(t^2)$, similar to that shown in Fig.5, only in numerical values.
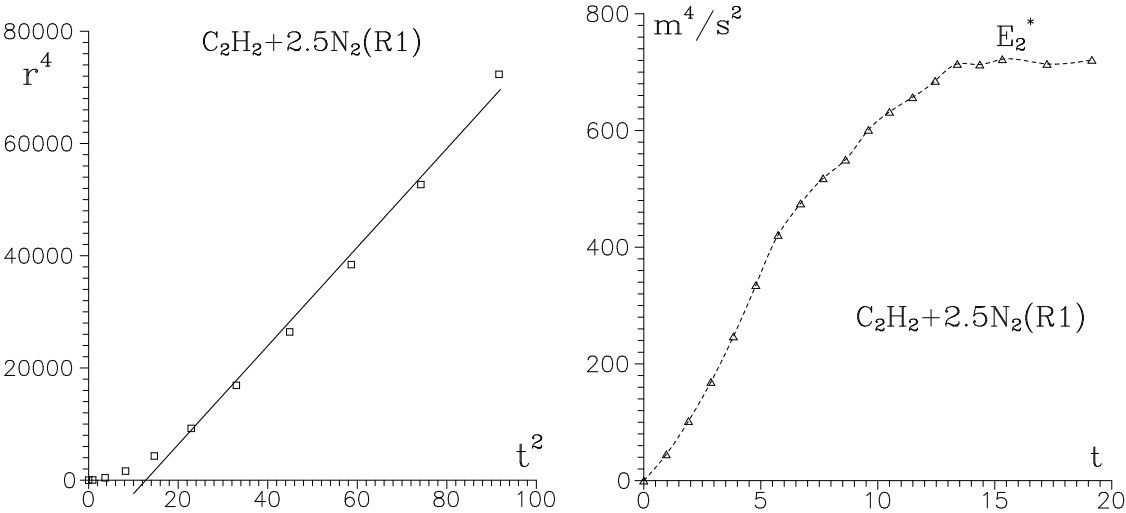

Fig.5. The trajectory of blast wave in inert medium from point of view of the "blast wave theory" for determination of "the usefull energy of initiator".

Fig.6. The trajectory of blast wave in inert medium from point of view of the "blast wave theory" for determination of degree of the energy-release of the initiator.

An approximation line whose slope determines the "useful" energy of the initiator (which is taken as the critical energy of the initiation of the combustible mixture) is given by the equation $Y = AX - B$, i.e. it does not pass through the coordinates origin, for a perfectly understandable reason, that the energy released by the initiator is non-existent; E = f (t). If the approximation line

8

continues to the x-axis, then the point of intersection with the axis $X_i = B/A$ and the time t_i recalculated along it will characterize the delay of equivalent instantaneous initiation with respect to the real instantaneous energy release. In other words, in the case of a non-instantaneous source, the time t_i characterizes the critical time of allocation of the "useful" energy. The energy released after the instant t_i until the formation of t_{form} in the self-sustaining mixture in the mixture will no longer affect the initiation process. So, for the example shown in Fig.5, the value of $t_i \approx 4$ μsec, i.e. the trajectory of the blast wave with a real instantaneous explosion of the wire almost completely coincides with the trajectory of an ideal instantaneous cylindrical explosion made with a delay $t_i \approx 4$ μsec.

Figure 7 shows the results of trajectory processing in an inert analog and wave trajectory during the critical initiation of cylindrical detonation in accordance with the model of a strong explosion. The trajectory in the inert mixture clearly demonstrates its linearity in the coordinates r^4-t^2, but the trajectory in the combustible mixture in the same coordinates clearly shows a steeper dependence, which indicates an increase in the energy of the system as the detonation wave moves away from the point of initiation. It is obvious that the source of this energy is the chemical energy Q, which is released when the initial fuel mixture is converted into reaction products.

Therefore, by subtracting the initiator energy (dashed line) from the total energy (solid line), one can obtain the energy release law $Q = f(t)$ (or $Q = g(r)$).

Figure 8 shows a graph of Q from r: solid line with symbols - experimental data, dotted line - approximation of experimental points by a quadratic polynomial, since with the distance from the point of initiation the amount of the burned mixture should be approximately proportional to the area covered by the wave. At a great distance resolution induction zones for different
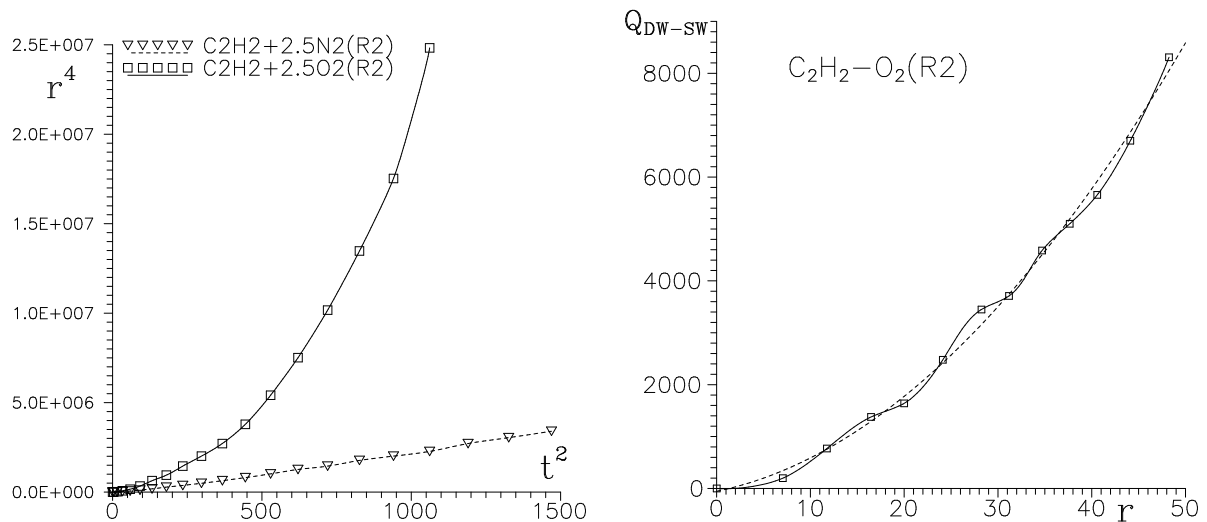
Fig.7. Typical trajectories of blast wave in inert medium and in combustible mixture at critical initiation at its recalculation from the point of view of the blast theory.

Fig.8. The non-monotonic chemical energy-release in multifront detonation wave on the wave radius.

elements of the detonation front becomes small compared with the radius of the wave. Figure 8 clearly shows that at the initial stage of initiating a detonation wave the experimental law of chemical energy release is more likely to be multi-step than to monotonous: starting from zero - increasing - reaching a maximum, new increase with an exit to the next maximum, another increase ...

Main results:

1. A method for determining the chemical energy release Q in a multi-front detonation is proposed, based on processing the trajectory of blast waves from the position of a strong explosion model.

2. The results on the energy release in a stoichiometric mixture of acetylene with oxygen are given when cylindrical and spherical multi-front detonation is initiated in it.

3. The experimental data on Q in the multi-detonation differ significantly from model representations for the classical one-dimensional theory.

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