MULTIPLE-SITE IGNITION OF A GAS MIXTURE AND ITS EFFECTS ON THE TRANSITION FROM BURNING TO DETONATION

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It was experimentally established that the effectiveness of exciting a transition from burning to detonation in explosive gas mixtures increases when the latter are ignited at multiple locations.

The effect of temporal and spatial components of the energy release mechanism of any real source initiating detonation manifests itself by the existence of critical t_* and r_* values in such a way, that at energy release times $t^0 > t_*$, or for energy release region size $r^0 > r_*$, the energy E required to directly initiate the detonation exceeds the critical initiation energy E_* which is characteristic for an ideal source. The ideal source is defined by an instantaneous ($t^0 = 0$) release of finite energy E_* at a point ($r^0 = 0$).

Investigations of the triggering of spherical detonation with an electric discharge [1] have shown that when $t^0 < t_*$, and the electrode geometry is maintained unchanged, $E = E_* = \text{const}$. The effect of the spatial component does not equal that of the temporal: Due to an energy redistribution in space when $0 < r^0 < r_*$, the E_* quantity varies in a U-shaped manner, such that for some optimum configuration of the energy release region, it reaches a minimum value $E_{*\min} \ll E_*$ [2]. Such behavior compels us to reexamine the classical concepts about the explosion hazard of combustible mixtures and to extend the investigation to include the effects of the spatial energy release components on the detonation excitation not only for strong initiation, but also for a relatively weak one due to the transition from burning to detonation (TBD).

In the present work, we performed experimental investigations of the spatial excitation of the explosive gas mixture burning and of its subsequent transition to detonation. The explosion chamber had a cylindrical shape (diameter and height both ~200 mm) and was provided with transparent windows along the lateral surface. In the first series of experiments the mixture was excited with a weak electric discharge across the electrodes (1-mm diameter) located axially at the end of the explosion chamber. The weakness of the discharge was revealed by the fact that within the operating pressure range, only the burning of the mixture without any TBD was observed, while a detonation was produced only at pressures which exceeded the operating pressure by approximately a factor of three, i.e., the discharge energy was about one order of magnitude smaller than E_*. Using this type of initiation, one excludes the initial stage of flame acceleration from the laminar in the quiescent medium to the turbulent one behind the shock wave (SW). A SW of this type is formed by the joining of the compression waves produced in the expansion of the initial mixture combustion products.

From the very beginning the electric discharge created a compression wave, whose velocity slightly exceeded the speed of sound and was notably below the magnitude at which TBD of the classical type appears, manifested by the emergence of a powerful site of an explosive type chemical reaction in the region between the SW and the flame front. It is the effect of this source that causes the transition from burning to detonation. The failure of the thermal igniter (without a SW) is linked to the uncontrollable scatter in the ignition instants in the mixture relative to the instant of heat-supply pulse, and its substitution by a weak electric discharge was dictated by the need to synchronize with the recording apparatus. The process was photographed using the SFR camera which was optically tied in to the IAB-458 shadowgraph apparatus.

The electric discharge provided only a localized ignition. In the multiple-source scheme, it is necessary to increase the number of electrodes and to achieve their synchro-

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nous operation. Additional technical difficulties arise when the configuration of the spatial positioning of the electrodes is changed. In order to eliminate the many difficulties of multielectrode initiation, the major part of experiments in the present investigation was performed according to the following scheme: A weak discharge electrode was placed at the top of a conical cavity which was expanding toward the explosion chamber (10° cone angle, 40-mm diameter of the exit opening). Disks (3-mm thick) with differently shaped openings and a spatial positioning with respect to each other were installed in the exit cone opening plane. By passing through such openings, the flame provided a three-dimensional distribution of ignition sites in the explosion chamber and a synchronicity of their "operation." Similar disks were used in the investigation of direct initiation of spherical detonation with the aid of a low-velocity hot gas jet [3, 4], in a three-dimensional detonation initiation [2, 5], and in the investigation of flame acceleration in pipes containing obstructions, etc.

The experiments were carried out with $C_2H_2 + 2.5O_2$ and $2H_2 + O_2$ mixtures. Commericial purity gases were used. The pressure of the mixture in the explosion chamber was controlled either with a standard vacuum gauge with 0.004 atm graduation, or with a U-shaped oil manometer. The operating range extended from a reduced pressure, at which only the burning of the mixture over the entire explosion chamber length was recorded, to the pressure when detonation occurs practically immediately behind the disk.

The verification of the failing of the electric discharge in the initiation at the cone vertex (similar to the above-described procedure for the ignition directly in the explosion chamber) showed that in this case, within the operating range of p_0, only turbulent burning regimes are observed, and that a detonation occurs at significantly higher pressures. One should note one peculiarity, which concerns the limiting pressure for initiating a detonation p^*, namely that using the cone, detonation is formed at a lower pressure. The reason for this is found in the additional mixture turbulization during the exit of the compression wave from the conical part into the explosion chamber, which corresponds to an intensification of the mixture burning and which accelerates the transition from burning to detonation. The experiments with $C_2H_2 + 2.5O_2$ demonstrated that

$$p^* \approx 8p_{**}, \tag{1}$$

where p_{**} is the pressure, at which a quasi-spherical detonation is initiated after the exit of the multiple-front detonation wave from a constant cross-section pipe, whose diameter equals that of the cone exit (40 mm in the present case). The transition of detonation from the pipe into the chamber space is characterized by the relation

$$d_{**}/a \simeq 8 \pm 2. \tag{2}$$

where d_{**} is the constant cross-sectional diameter of the pipe in which at the critical pressure p_{**} a transition into space is observed without any wave attenuation, and a is the characteristic dimension of the detonation wave cell at that pressure. Since $a \sim 1/p$, the detonation initiation during the flame exit increases the ratio (2) in accordance with (1):

$$d^*/a \approx 64 \pm 16. \tag{3}$$

Within the $p_{**} < p < p^*$ range, regimes of turbulent burning without TBD are recorded in the explosion chamber (in every case over the explosion chamber length). From the viewpoint of spatial form, the present case can be referred to as the quasi-plane uniform initiator with a finite dimension d.

The spatial redistribution of initiation sites was investigated on the basis of some-simple schemes:

a) the multiple-site scheme (igniters with a radius r uniformly arranged over the area of the cone exit opening with a diameter d, number of igniters n, $4nr^2 < d^2$);

b) six-site scheme (igniters with a radius r, situated uniformly around the circumference of a circle with radius $R < d/2$). As n is increased, such a discrete igniter transforms into a ring igniter.

c) linear scheme (a solitary rectilinear igniter was modeled either by several sources situated in parallel, or at an angle to each other).

A typical Schlieren trace of the transition from burning to detonation with a weak initiation is presented in Fig. 1. Figure 2 shows the variation of the transition from burning

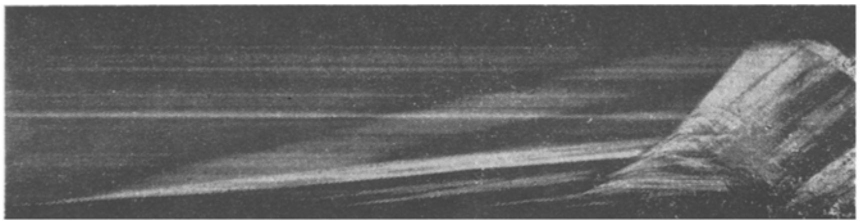

Fig. 1

to detonation coordinate x, measured from the exit disk plane, with the initial mixture pressure p_0: I identifies the direct initiation of detonation, II the TBD region, and III the burning regime; ℓ is the characteristic igniter dimension, which for a round igniter is the diameter, and the width for a linear one.

The multisite scheme was modeled by 19 holes whose diameter was 5 mm (one central, 6 openings on a R_1 = 10-mm circle, and 12 on a R_2 = 17.5-mm circle), and which were uniformly arranged on the cone exit cross-sectional plane. The experimental results with n = 19 are identified by the 1 symbol in Fig. 2.

Even though the overall flame area is reduced by the disks by approximately threefold, the detonation wave at p^* does not detach and, moreover, is formed directly behind the disk (in Fig. 2 the vertical dashed line corresponds to pressure p^*). In this case, the velocity of the compression wave exiting into space is ~$1.5c_0$, where c_0 is the speed of sound in the original mixture. It is evident that at such low compression wave amplitudes, the shock-wave autoignition processes play no important role.

The turbulization of the original mixture and the direct effect of the combustion products on it constitute the main reasons underlying the intensification of the process. It is necessary to point out three aspects relating to the generation of turbulence: 1) the creation of large-scale turbulence caused by the gas motion through the disk openings; 2) the influence, still during the stage of flame propagation in the cone, of compression waves reflected from the disk on the burning front, acting in addition to the self-turbulization of the flame, which leads to the appearance of small-scale turbulence; and 3) the three-dimensional interaction of compression waves among themselves and with the flame front even directly in the explosion chamber. The contribution and effect of each of the turbulence sources on its development depend on the initial mixture pressure.

In the multifront scheme, when p_0 is lowered below p^*, the collapse of the detonation process occurs not so suddenly (over the p_0 range), as is observed in the experiments without any exit disk. It is found that the detonation wave is formed because of the TBD, with the TBD coordinate increasing as the pressure is shifted away from p^* (see Fig. 2, points 1). The effectiveness of a three-dimensional distribution of igniters is confirmed also by the fact that it provides a TBD even at an initial pressure which is reduced to $p_{19}^* \approx 0.3p^*$. In this case, the third turbulence development aspect becomes decisive.

During the TBD there is no clearly defined structure with the characteristic three-dimensional dimensions, which is different from the multifrontal detonation, where the cell dimension a serves as the characteristic dimension of the detonation front structure. Selecting a, as the characteristic scale also for the TBD, it is necessary to note that the

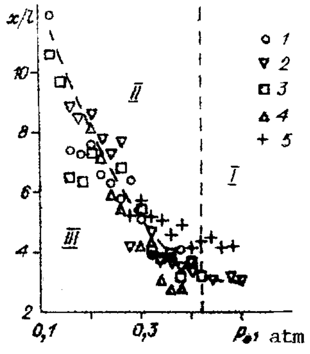

Fig. 2

value corresponding to the limiting pressure p_{19}^*, when a TBD can still be recorded, is found to be about half the diameter of a discrete opening, i.e., $a \simeq r$.

The six-site scheme was modeled by 5-mm diameter openings, which were evenly positioned on a circle with R = 17.5 mm. The total flame area is reduced by the disk by less than an order of magnitude, however, the effect of turbulence introduced by the disk is so great that it compensates for the losses linked to the reduction of the flame front area. Because of this, the TBD coordinates at $p = p^*$ for $n = 6$ and 19 are approximately the same. Just as in the case where $n = 19$, when p_0 is reduced, over a fairly wide pressure range TBD is recorded up to $p_6^* = 0.25p^*$, which is even less than for $n = 19$, even though from the viewpoint of the number of igniters, the difference between these cases is large. The reason for this may be the more defined large-scale turbulence for $n = 6$, which is related to the diameter of the circle, on which the openings are located. For $n = 19$ the turbulence of this scale appears at a smaller scale due to the R_2 value and the diameter of a discrete opening. For $n = 6$ and, particularly for a ring igniter, the dissipation time of the large-scale (linked to R) turbulence will be longer, therefore, its effect on the TBD is extended. The data for $n = 6$ are presented in Figs. 2, points 3. The linear igniters were modeled with the aid of slit disks. A 4 × 30-mm slit reduced the flame area approximately by an order of magnitude, however, as in the six-site scheme, the large-scale turbulence was absent in this case. As a result, the TBD region during a pressure reduction below p^* extends only to $p_{\ell 1}^* \simeq 0.6p^*$ (see Fig. 2, points 5). Two parallel 4 × 30-mm igniters with a displacement of 2h (h is the slot width) resulted in a widening of the TBD region ($p_{\ell 2}^* \simeq 0.4p^*$, Fig. 2, points 4). Finally, three linear igniters, arranged in a rectilinear triangle (inscribed in the cone exit opening) provided TBD up to $p_{\ell 3}^* \simeq 0.3p^*$, which is roughly equivalent to the multisite scheme with $n = 19$ (see Fig points 2).

The main conclusion from the investigation is that a three-dimensional igniter distribution significantly intensifies the transition from burning to detonation.

The photoscans make it possible to estimate the velocity of the compression waves and the visible flame velocity (along the explosion chamber axis). By subtracting the gas mass velocity behind the SW from the apparent flame velocity, we find the burning velocity relative to the particles. The obtained value markedly exceeds the laminar burning velocity under these conditions, which is characteristic of burning in highly turbulent flows.

In terms of chemical activity, the $2H_2 + O_2$ mixture is markedly inferior to $C_2H_2 + 2.5O_2$, therefore, the full scope of the investigation could not be carried out under laboratory conditions due to the need to use higher pressures of the explosive mixture (the explosive chamber allowed safe operation in the region $p_0 \leq 2.5$ atm). Nevertheless, the performed experiments confirmed the principal conclusion on the intensification of the transition from burning to detonation which is achievable with three-dimensional ignition of the mixture.

Thus, for $p_0 = 2.5$ atm, a detonation could not be produced with a weak source; however, using a multisite scheme described above led to the occurrence of a transition from burning to detonation at p_0 reduced from 2.5 atom down to $p_{19}^* \simeq 0.8$ atm. A similar picture, i.e., a TBD in the range between $p_0 = 2.5$ atm to a certain p^* is observed also for the other above-described schemes.

Along with the described experiments, the initial ignition stage of a multisite laminar flame, and its subsequent acceleration are of great interest. An optimization of the conditions for the transition from burning to detonation requires further investigations.

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