Shock-wave and Jet Initiation of Gaseous Explosions

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Some methods of initiation of gaseous detonation under non-steady flow conditions behind colliding shock fronts have been explored. The auto-ignition conditions are achieved using shock wave focusing and interaction of supersonic jets inside cylindrical cavity. Comparative studies of selfignition process behind incident shock waves reflected from cylindrical concave and plane walls in stoichiometric hydrogen-oxygen mixture revealed that the boundary between the strong and mild ignition modes coincides for the both types of reflection. For different initiation modes, the detailed evolutions of flow structure were studied using a high-speed schlieren photographic observation.

To establish the mechanisms of transition from deflagration to detonation downstream of flow obstruction the runs were performed in a stoichiometric C_2H_2 /O_2 mixture with variable nitrogen dilution (*0 £ a £ 0.8)* and at initial pressures varying from *0.02* to *0.1 MPa.* It was found that critical shock strength corresponding to Mach number of *M @ 1* of unburned gas flow venting into the pipe generates the necessary conditions to trigger the onset of detonation downstream of the orifice plate. For subsonic outflow of unburned mixture, the flame front overtakes the leading shock wave and detonation does not develop in observation region.

Introduction

The qualitative aspects of the initiation of detonations in gaseous mixtures are fairly well understood and exposed in reviews [1,2]. The peculiarity of all modes of initiation is the generation of the critical states for the onset of detonation. These critical states correspond to those at the autoignition limit of the mixture and play the key role in initiation phenomena: namely, in self-initiation, blast initiation, and propagation of the wave itself.

In contrast to the familiar steady flow situation that exists in most shock tube experiments where the reaction proceeds behind the shock, the feedback effect of the exothermic processes is usually occurred during initiation by establishment of non-steady flow field between the shock and the reaction zone. Unlike the typical shock tube experiments, the acquisition of data obtained under non-steady flow conditions becomes necessary. Since especially pertinent in this respect is the establishment of non-steady flow fields behind the colliding shock fronts.

In present study, some gasdynamic methods of initiation of gaseous detonation under non-steady flow conditions were explored, such as:

- shock wave focusing due to reflection from concave surfaces;
- interaction of supersonic jets in combustible gas mixture;
- initiation by flame gas jets.

Selfignition of reactive mixtures induced by a shock wave focusing

The influence of a combined action of diffracted and reflected shock waves under focusing in reactive mixture on initiation processes are important for the better understanding of combustion in the real facilities. It is well known [3] when a plane shock wave collides with a concave surface, the reflected shock wave forms a focus or a caustic at which pressure and temperature can be enhanced. Depending on the shock strengths and mixture sensitivity, such collisions can create local hot spots capable of causing ignition or direct initiation of detonation in the combustible mixture [4-8].

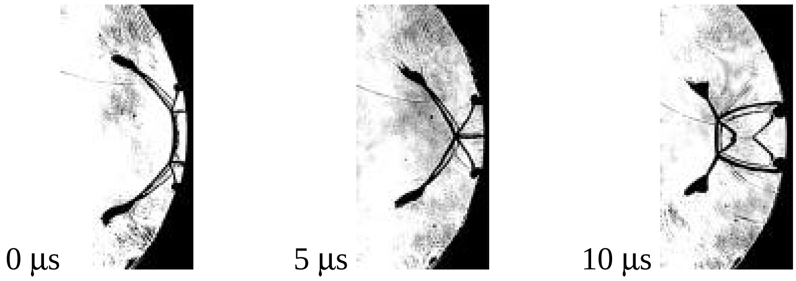

Figure 1. Triple shock collisions induced by a focused shock wave from concave cylindrical cavity in air. Incident shock Mach number $M = 2.0$, $P_0 = 30$ kPa.

The detail study of selfignition mechanism in the one-dimensional shock tube experiments is accomplished by the stochastic occurrences of ignition loci due to the flow instability and the reflected shock-boundary layer interactions. At the same time the shock reflection from concave surfaces can form hot spots with the temperature higher than in the main flow (Fig.1) and thereby ignite a mixture locally. Furthermore, the pressure amplification of focusing shock wave and the gasdynamic focus location are saturated for incident shock Mach numbers higher than 2. Basically, this is due to the saturation of critical transition angle from Mach to regular reflection [9]. Thus, the shock wave reflected from concave surface creates a local selfignition parameters which can be evaluated experimentally in a wide range of incident shock Mach numbers.

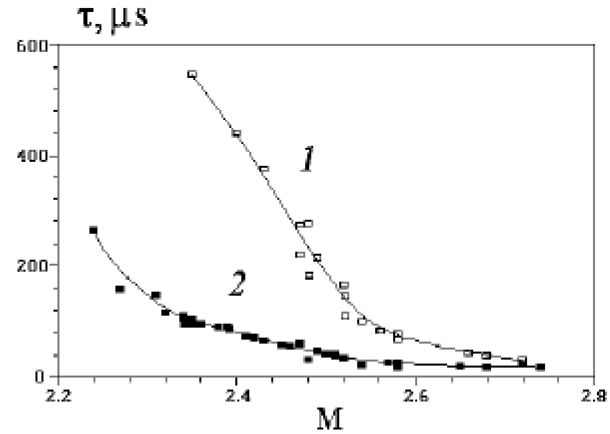

Figure 2. Ignition delay vs. incident shock Mach number in $2H_2 + O_2$ mixture: 1 – normal reflection; 2 – reflection from cylindrical cavity. Pressure 0.1 ± 0.01 MPa.

The experimental studies of selfignition behind shock waves reflected from cylindrical concave and flat surfaces in stoichiometric hydrogen-oxygen mixture indicated that, there is an evident correlation between the chemical induction time measurements and the various initiation mechanisms (mild, transient and strong) for the both types of reflection. Experiments were carried out in a single-diaphragm shock tube with a low-pressure channel $45´90\ mm^2$. For shock wave focusing, a hemicylindrical concave wall model with a diameter of *45 mm* and zero initial angle was installed at the end of test section. The ignition delay time was defined on the basis of OH radical emission, corresponding to transition ^2S-^2P in the bandwidth *(0.1)* with the edge of *342 nm*. To fix the instant at which the luminosity of the reacting gas mixture commences, the test volume was focused on a photomultiplier cathode. To eliminate light from easily excited impurities, a monochromatic interference filter with $l_{max} = 348$ *nm* and bandwidth of *16 nm* was used to pass only the desired portion of the emission spectrum of the mixture. Simultaneously to luminosity registration the pressure both on the bottom of the concave cavity and lateral wall of the channel was measured.

Figure 2 presents the ignition delay time versus incident shock wave Mach number for the same average conditions behind the reflected shock wave. As it follows from the plot the reflecting cylindrical cavity reduces this delay significantly. Nevertheless, it was surprisingly that boundary between the strong and mild ignition regimes coincides for the two types of reflection and corresponds to the point of inflection of the chemical induction curve for normal reflection.

Figure 3. Direct initiation of detonation induced by the shock wave focusing in stoichiometric hydrogen-oxygen mixture. Incident shock Mach number M = 2.65, Po = 2.76 kPa

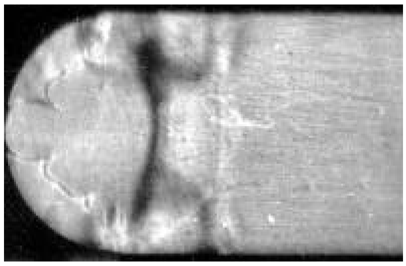

Figure 4. Transient regime of detonation initiation induced by the shock wave focusing in stoichiometric hydrogen- oxygen mixture. Incident shock Mach number M = 2.45, Po = 3.47 kPa

The critical incident shock Mach number required for strong initiation is found to be a higher than $M \geq 2.52$, that corresponds to characteristic gas temperatures behind reflected shock wave $T > 1010K$ at initial pressure $P_0 = 0.1 \pm 0.01$ MPa. For cylindrical cavity, the focusing of shock wave under these conditions produces the direct initiation of detonation (Fig.3) in gasdynamic focus [7,8]. For the incident shock Mach number range $M = 2.39 \div 2.51$ a transient regime is occurred. The secondary shock reflections initiate the two cylindrical detonations at the opposite sides of the channel near the cavity end (Fig.4). With the following decrease of incident shock Mach number below $M=2.39$ the detonation develops from the second gasdynamic focus due to mild ignition mechanism behind reflected shock wave.

Collision of Supersonic Jets

Jet interaction in the concave cavity forms a complex gasdynamic structure in the intersection region. A head shock wave is generated and radiates out, followed by a transient starting jet exiting from the opening itself. In the case of two jets, they can intersect each other as a result of head-on collision (Fig.5). At first, two fronts undergo, along the line of centers, a normal interaction producing a reflected shock. At the next instant, quadruple shock intersections are formed on both sides of the line of centers. When the intersection angle acquires a certain critical value, triple shock intersections set in. A turbulent vortex "bubble" heads the transient jet flow and most of the entrainment and mixing occurs in this region. When this complex gasdynamic structure collides with a circular concave wall, the reflection from the concave wall forms a focus at which the parameters can be enhanced [10]. It has been found that the focusing degree is higher when the jets inclined to the concave wall are used (Fig.6). Experiment has been carried out on the direct initiation of detonation by means of such jets.

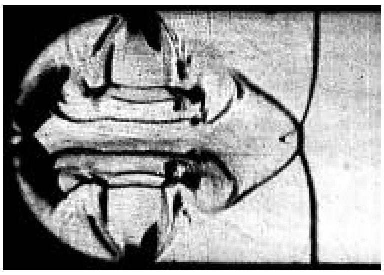

Figure 5. Normal collision of two supersonic jets in cylindrical cavity in air. Initials pressure 30 kPa.

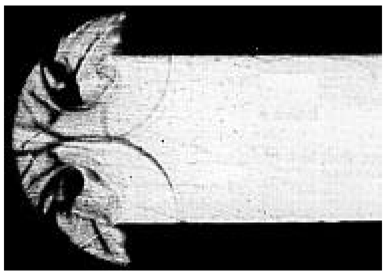

Figure 6. Interaction of two inclined supersonic jets in cylindrical cavity in air. Initial pressure 30 kPa

Initiation by Flame Jets

An experimental study to establish the mechanisms of transition from deflagration to detonation (DDT) downstream of flow obstruction has been performed and reported in a number of works [11-15]. Our experiments were conducted in a $10 \times 10\ mm^2$ square detonation tube. The observation zone with quartz sidewalls was placed at *10 mm* from the spark plug mounted at the channel end. The ignition energy was $E = 0.8\ mJ$. Orifice plates were used to stabilize the DDT distance and time in a wide range of changing initial conditions and compositions of the mixture. The runs were performed in a stoichiometric C_2H_2/O_2 mixture with variable nitrogen dilution ($0 \le \alpha \le 0.8$) and at initial pressures varying from *0.02* to *0.1 MPa.* Necessary requirements to trigger the onset of detonation have been investigated.

Figure 7 (curve *1)* presents the dependence of the transition distance *(L)* vs. a total nitrogen concentration in the channel without orifice plate. The transition distance is expressed in terms of the specific lengths *L/h,* where *h* is the channel height. As it follows from the figure, the nitrogen dilution of a stoichiometric acetylene-oxygen mixture affects strongly on the transition length when the total nitrogen concentration $x_{N_2} > 18.5\%$. For $x_{N_2} < 18.5\%$, detonation arises at a distance less than *17 mm* from the igniter. As the nitrogen concentration increases, the transition length grows rapidly. Figure 8a shows the typical schlieren streak- record of DDT process in a free channel. As it follows from Fig. 7(curve 2), a flame jets injection reduces the transition distance even for mixture with a higher nitrogen concentration.

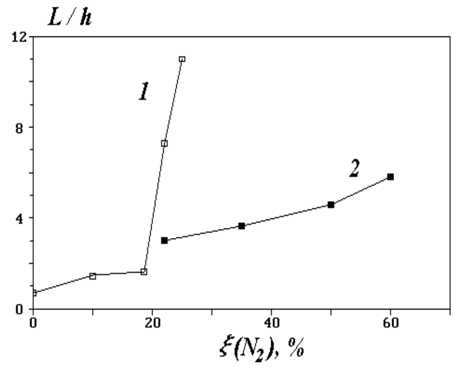

Figure 7. DDT distance vs. nitrogen concentration in the acetylene-oxygen-nitrogen mixture: 1 — free channel; 2 — channel with orifice plate. Po = 0.1 MPa, To = 300 K:

a)

b)

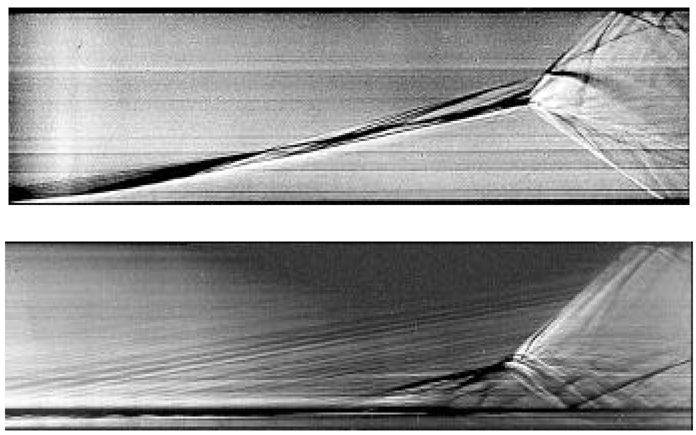

Figure 8. Schlieren streak records of the DDT process in the acetylene-oxygen-nitrogen mixture at initial pressure of 0.1 MPa: a - free channel, $x(N_2)$= 22%; b – DDT behind the orifice plate, $x(N_2)$= 60%.. Vertical scale is 10 mm

A schlieren streak record of the DDT process for the critical mixture composition corresponding $x_{N_2} = 60\%$ is displayed on the Figure 8b. It was found that a minimum leading shock and flame velocities of about $600\ ms^{-1}$ produced by hot jets injection were required for successful transmission to detonation for different mixture sensitivity. This critical shock strength corresponds to Mach number of $M \approx 1$ of unburned gas flow venting into the pipe and generates the necessary conditions to trigger the onset of detonation downstream of the orifice plate. For subsonic outflow of unburned mixture, the flame front overtakes the leading shock wave and detonation does not develop in observation region.

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