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Detonation and deflagration initiation at the focusing of shock waves in combustible gaseous mixture

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Abstract. Detonation and deflagration initiation under focusing conditions in a lean hydrogen-air mixture was experimentally investigated. The experiments were carried out in a shock tube equipped with the laser schlieren system and pressure transducers. Two-dimensional wedges (53° and 90°), semi-cylinder and parabola, were used as the focusing elements. The peculiarities of mild and strong ignition inside the reflector cavity were visualized. A hydrogen-nitrogen mixture was taken for comparison between reactive and inert mixture. It was found that mild ignition inside the reflector cavity can lead to detonation initiation outside the cavity. Schlieren pictures of the process were obtained and the dependence of the distance of detonation initiation on Mach number of the incident shock wave was established.

Key words: Focusing, Shock wave, Ignition, Detonation

1 Introduction

The phenomenon of self-ignition is of fundamental importance in major transport and power systems, such as liquid propellant rocket engines and diesel engines. The characteristics of self-ignition process are responsible for the structure and stability of a burning zone in combustion chambers. Self-ignition of combustible homogeneous systems has been widely studied with the aid of the shock tube technique. The commonly accepted procedure includes the investigation of combustion and detonation phenomena behind the shock wave reflected from a plane end-wall of a low-pressure section of a tube.

It was shown in (Borisov et al. 1988) that the application of the curved end-wall instead of the planar wall gives rise to a significant decrease of the intensity of the shock wave that causes self-ignition. The changes of flow structure near the curved surface were defined as "focusing of shock waves" (Grönig, 1989). A general result of gas flow focusing is the formation of local zones with elevated pressure and temperature. The generation of such hot zones promotes self-ignition and, sometimes, spontaneous detonation onset. The study of self-ignition by standard methods in the case of flow focusing does not allow us to understand the basic features of resulting chemical-gasdynamical interaction. The traditional ways of self-ignition delay measurements in combustible mixtures (with the aid of pressure-time diagrams) give no possibility of interpreting unambiguously the explosion phenomenon in the vicinity of curved surfaces. Therefore, conclusions about the dynamics of the explosive phenomena in converging-diverging gas flow can be drawn with the help of pressure-time diagrams together with the flow visualization method.

We categorize the different regimes of the self-ignition at focusing conditions in the following terms: mild and strong, in the same way as it was made in (Gelfand et al. 1995, and Oppenheim, 1985). The possibility of the realization of mild (deflagration) and strong (detonation) modes of ignition in the highly sensitive oxyhydrogen mixture depends on the Mach number of the incident shock wave (Chan et al. 1989). The existence of two modes of ignition was shown for stoichiometric hydrocarbon-air mixtures in (Borisov et al. 1988). Experiments on focusing in hydrogen-air mixture (Gelfand et al. 1995) revealed another ignition mode that is characterized by the high-pressure spikes behind the reflected shock wave. The values of the Mach numbers corresponding to this ignition mode fall in the range between the Mach numbers responsible for mild and strong ignition.

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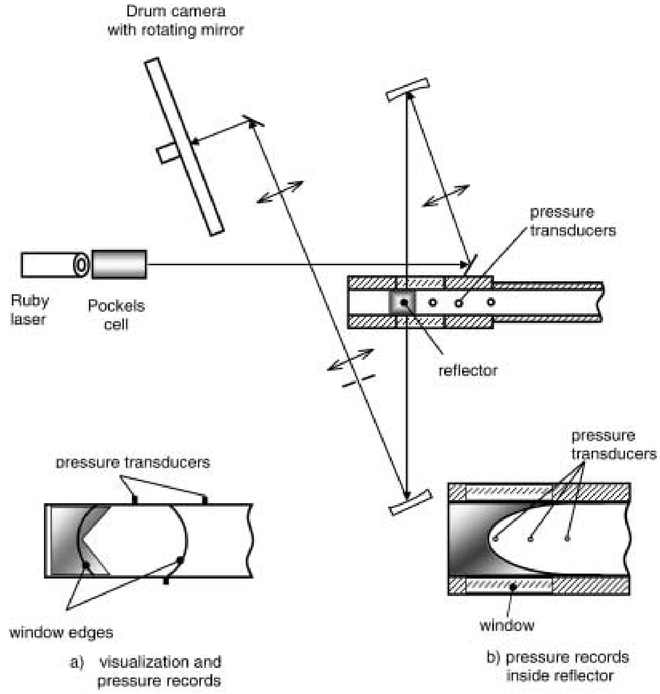

Fig. 1. Schematic of experimental setup

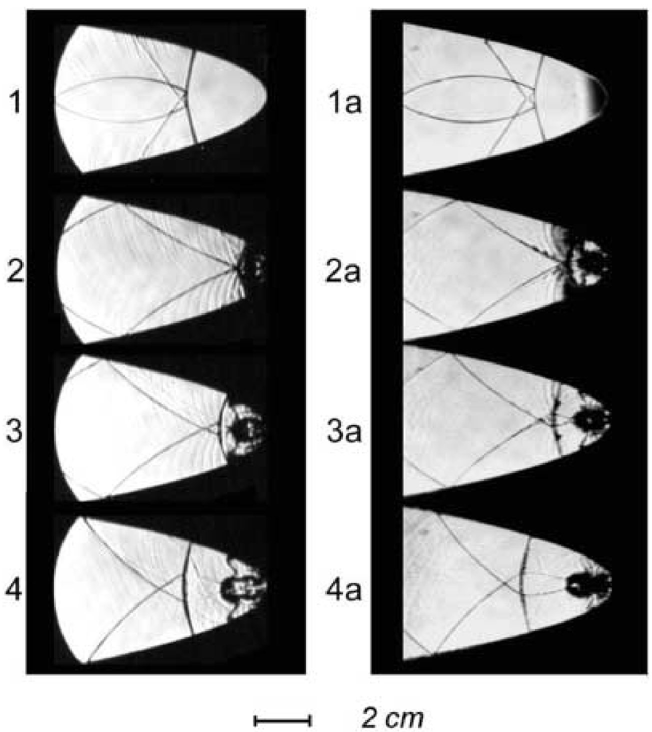

Fig. 2. Parabolic reflector. Mach number $M = 2.31$. Reactive mixture (frames 1–4); inert mixture (frames 1a–4a). Time between frames: 1–2: 40 μs, 2–3: 10 μs, 3–4: 20 μs

The present work is devoted to the investigation of the self-ignition processes due to focusing shock waves with various intensities at different reflectors.

2 Experimental

The experimental setup is shown in Fig. 1. The shock tube of 54 mm × 54 mm in cross section (low-pressure section of 6.25 m in length and high-pressure section of 3.15 m in length) was used. Before the test, the low-pressure section was filled with the mixture under study up to the initial pressure of 26.3–40 kPa. The mixture of 15% H2 + 85% air was used in the tests. A hydrogen-nitrogen mixture with the same content of hydrogen was taken for comparison between reactive and inert mixtures behavior at the focusing conditions. The laser schlieren high-speed photography was used simultaneously with pressure recording by transducers located on the top and bottom walls of the tube. Pressure transducers were Kistler 603B. The high-intensity ruby laser combined with the Pockels cell produced light pulses with the duration of about 12 ns, providing an excellent stop-motion capability. The rotating mirror camera produced frames, and the minimal time between them was 6 μs. The symmetrical wedge reflectors with apex angles of 53° and 90°, the semi-cylindrical reflector with radius $R = 27,$mm and the parabolic reflector $y = 0.11x^2$ (where y is the distance along the tube axis; x varies from 0 to 27 mm) were used to focus the shock waves. The Mach number of the incident shock wave was calculated by processing the instants of the shock wave arrival to the pressure transducers and was accurate to about 2% .

3 Results

3.1 Mild ignition

Figure 2 shows the results of focusing a shock wave with Mach number of $M = 2.31$ at the parabolic reflector in the reactive (frames 1-4) and inert (frames 1a–4a) mixtures. It should be noted that, in these experiments, the time between the frames was different, and therefore the two sets of frames are similar but not identical. The comparison of the frames 2 and 2a gives us the self-ignition in the region around the focus for the reactive mixture and the separate existence of the reflected shock wave and vortex-shape structure for the inert mixture. Frames 3, 4 and 3a, 4a demonstrate the development of these structures in time. This presents the case of mild ignition at the focusing on the reflector with the focus placed close to the apex. The depth of the parabolic reflector (81 mm) makes it possible to record the pressure profiles inside the reflector at different distances from the apex. The pressure profiles presented in Fig. 3 give additional information about the mild mode of self-ignition. The presented records indicate the slow pressure rise behind the reflected shock wave front in the combustible mixture and the absence of this

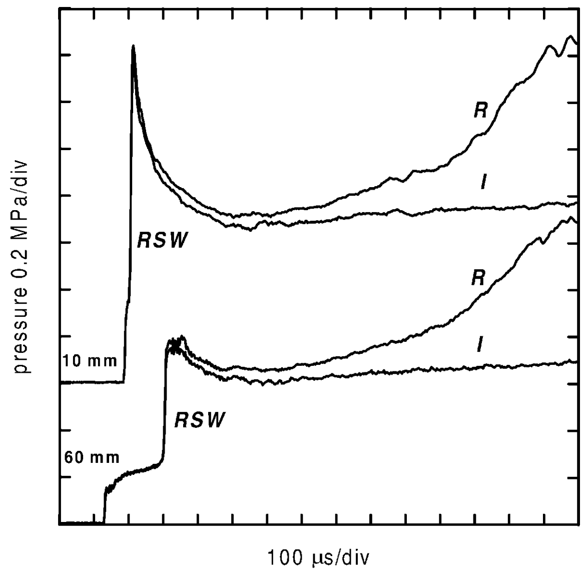

Fig. 3. Pressure records at different distances from the apex inside the parabolic reflector in the reactive (R) and inert (I) mixture. Initial pressure 0.033 MPa and Mach number of the incident shock wave $M = 2.21$. RSW: reflected shock wave

phenomenon in the inert case. At the same time there is no visible difference between the maximum values of the pressure of the reflected shock waves for reactive and inert mixture.

A similar situation takes place when using a semi-cylindrical reflector, which has the focus located at a longer distance from the apex than the parabolic reflector does. For this case, as it is seen in Fig. 4 frame 3, that self-ignition takes place in a point that is located very close to the gasdynamics focus. Further combustion is developing in the central part of the reflector. The specific feature of the self-ignition for these reflectors is the development of the flame front in the central parts of the tube and the reflector cavity. Later, after several hundred microseconds the flame front can reach the top and bottom wall of the tube, Fig. 4, frame 8.

Let us consider the test with the wedge reflector 53°. In this case, as it was shown in (Milton, 1989), Mach stems can collide more than once prior to the arrival at the reflector apex. The flow field after the first interaction is shown in the frame 1 Fig. 5. After that the self-ignition takes place (between frames 2 and 3). It should be noted that in the frame 3 there is no difference between the front of the reflected shock and the flame front. The difference between reactive and inert mixtures exists, still being not very large on this stage (compare frames 3 and 3a). Only in the frames 4 we can see the separation of the shock and combustion front. Besides, the difference between the reactive and inert mixture becomes more significant (see frame 4a). Further the process develops significantly in the central part of the tube, as in the above cases.

The focusing at the wedge 90° causes a change of the flame brush. As it is seen in Fig. 6, this case is characterized by self-ignition of the combustible mixture in the vicinity of the reflector apex. Then the reflected shock

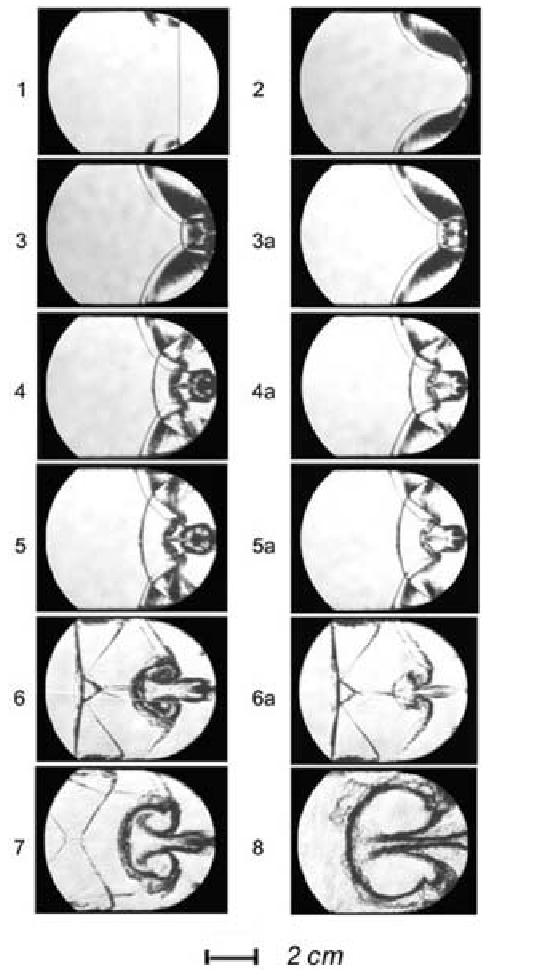

Fig. 4. Semi-cylindrical reflector. Mach number $M = 2.34$. Reactive mixture (frames 1–8); inert mixture (frames 3a–6a). Time between frames: 1–2–3–4: 20 μs, 4–5: 10 μs, 5–6: 60 μs, 6–7: 50 μs, 7–8: 180 μs

wave propagates from the reflector, and the combustion front with a complicated shape appears behind this shock wave. A part of the combustion front is positioned at the slip lines in the cavity of the reflector and behind the reflected shock wave. In the inert mixture, there exists a vortex-shaped structure in the vicinity of the apex (frame 2a). In the case of mild ignition, only combustion products without visible gradients of density exist near the vicinity of the apex. Thus, a mild ignition under the focusing condition leads to the appearance of a flame front with a complicated shape, and the configuration of this front depends on the reflector type.

3.2 Strong ignition

The regime of self-ignition behind a reflected shock wave resulting in direct initiation of a detonation is referred to as a strong mode. This regime is realized in the parabolic reflector at Mach numbers of the incident shock wave $M > 2.38$. The relevant schlieren pictures are presented in Fig. 7. Self-ignition takes place between frame 1 (just

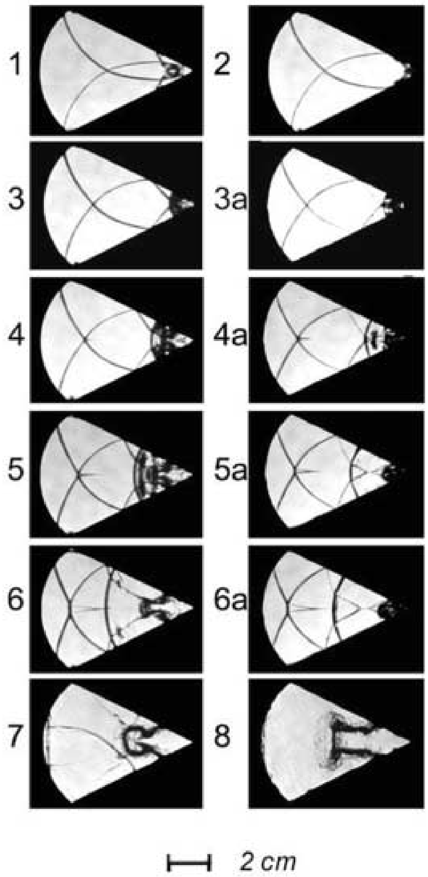

Fig. 5. Wedge reflector 53°. Mach number $M = 2.34$. Reactive mixture (frames 1–8); inert mixture (frames 3a–6a). Time between frames: 1–2–3–4–5: 10 μs, 5–6: 20 μs, 6–7: 90 μs, 7–8: 200 μs

before reflection) and frame 2, after that the detonation front is formed. At the beginning of propagation, this front is curved. Near the reflector exit, it becomes flat. Pressure profiles plotted in Fig. 8 show that the difference between maximum values of the pressure in the reactive and inert mixtures is more significant than in the case of the mild ignition mode (Fig. 3). For example, at the distance of 60 mm from the apex of the reflector, the maximum value of the pressure in the reactive mixture is more than 2 times higher than in the inert mixture and corresponds to detonation.

Detonation is initiated inside the wedge 90° at Mach number $M \geq 2.52$. It is clear from Fig. 9 that the detonation wave propagates inside the reflector cavity through the regions with different initial conditions corresponding to the complex flow-field behind the incident shock wave. Therefore, it is incorrect to test the stability of the detonation inside the cavity without a detailed evaluation of the flow parameters ahead of the detonation wave. The latter is the topic of another investigation and is beyond the scope of the present work.

At the same time, flow parameters are uniform and correspond to the parameters behind the incident shock wave in the region outside of this reflector. The detona-

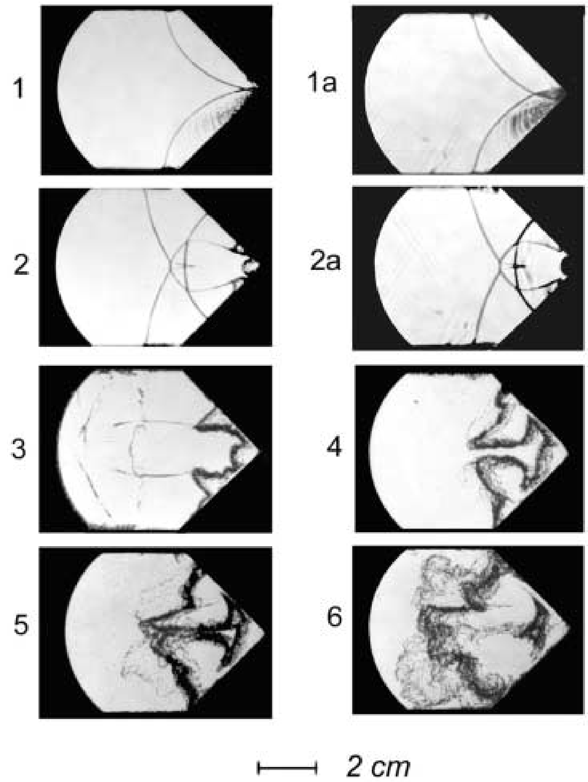

Fig. 6. Wedge reflector 90°. Mach number $M = 2.1$. Reactive mixture (frames 1–6); inert mixture (frames 1a - 2a). Time between frames: 1–2: 40 μs, 2–3: 180 μs, 3–4: 360 μs, 4–5–6: 220 μs

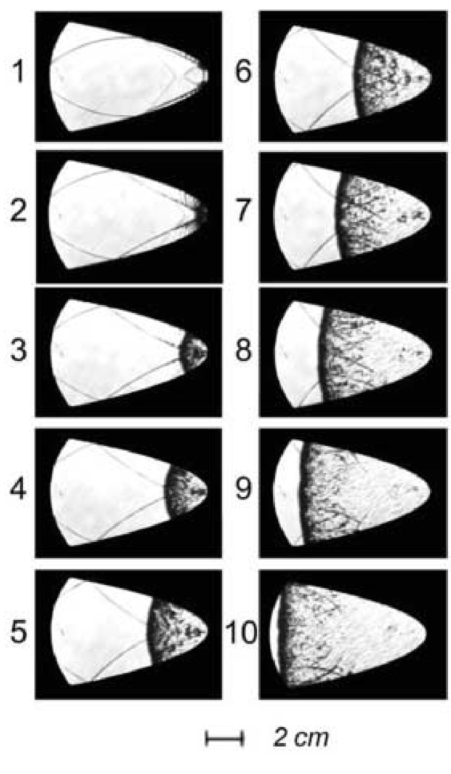

Fig. 7. Parabolic reflector. Mach number $M = 2.4$. Time between frames 7 μs

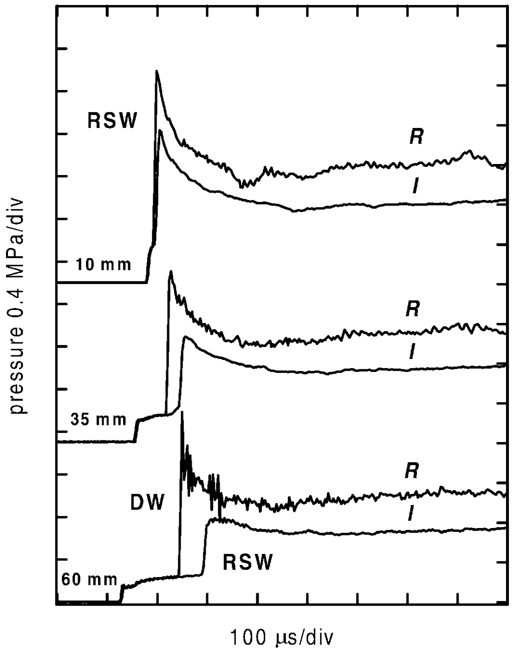

Fig. 8. Pressure records at different distances from the apex inside the parabolic reflector in the reactive (R) and inert (I) mixtures. Initial pressure 0.023 MPa and Mach number of the incident shock wave $M = 2.42$. RSW: reflected shock wave, DW: detonation

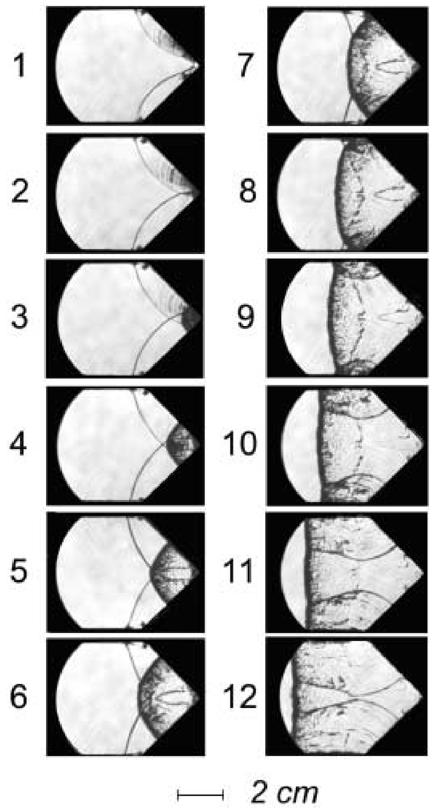

Fig. 9. Wedge reflector 90°. Mach number $M = 2.55$. Time between frames 6 μs

tion velocity in this part of the tube can be defined as $D = W + u$, where W is the visible velocity of detonation propagation outside the reflector, and u is the flow velocity behind the incident shock wave. Visible velocity can be measured on the set of schlieren pictures. Alternatively, this velocity can be calculated by processing shock-arrival times. Experimentally defined detonation velocities are compared with the calculated C-J velocity for the wedge 90° in Fig. 10. The values of pressure and temperature behind the incident shock wave were used as initial conditions for calculation of the C-J velocity.

Figure 10 demonstrates that the detonation becomes steady at the distance of one and a half of the characteristic tube size from the reflector apex, and its velocity is practically equal to the calculated one.

As it was specified above, there is a range of Mach numbers of the incident shock wave in which the so-called transient modes of ignition in hydrogen-air mixtures can be realized. The specific feature of this regime is the presence of powerful spikes of pressure behind the reflected shock wave, as shown in Fig. 11. Looking at the pressure-time diagram, one can suppose that the shock wave (SW in Fig. 11) propagates in the direction of the reflector apex. It is reasonable to assume that the source of this wave is an explosion process (detonation initiation for example) taking place between the reflected shock wave and the reflector. The distance L^* from the reflector apex, where this process is located, can be estimated both directly from photos and using the $x - t$ diagram, assuming that the initiation takes place near the front of the reflected shock wave. Figure 12 demonstrates the pressure profiles recorded by the same transducer for different experiments for the cases corresponding to detonation initiation, both in the reflector apex at $M = 2.52 - 2.55$ and at different distances L^* from the reflector at $M = 2.34 \div 2.47$. It is seen that these profiles are nearly identical to each other. The dependence of L^* on the Mach number of the incident shock wave is plotted in Fig. 13 for the wedge 90° and the semi-cylinder. As seen from Fig. 13, three characteristic regions exist for this dependence.

Region 1 in Fig. 13 corresponds to the direct detonation initiation inside the reflector cavity in the vicinity of the apex as it was demonstrated above. This case is similar to detonation initiation with the help of a HE charge. The decrease of the incident shock wave Mach number leads to detonation initiation outside the reflector at distances not more than two times the characteristic tube sizes (see region 2, Fig.13). The calculations (Bartenev et al.1999) and experiments with an inert mixture show that, in region 2 after focusing, only a system of weak bow shocks exist behind the reflected shock wave. Figure 14a presents the photos corresponding to shock wave reflection with $M = 2.47$ at the wedge 90°. The location scheme of pressure transducers and the window is shown in Fig. 14b. The corresponding pressure profiles are shown in Fig. 15. From the given photos, one can see the presence of a system of weak bow shocks behind the reflected shock wave. On some of these shocks, there is ignition followed by burning of the mixture. The detonation wave arises at the center of the tube between the frames 4 and 5 (Fig. 14a) at a distance of approximately 77 mm from

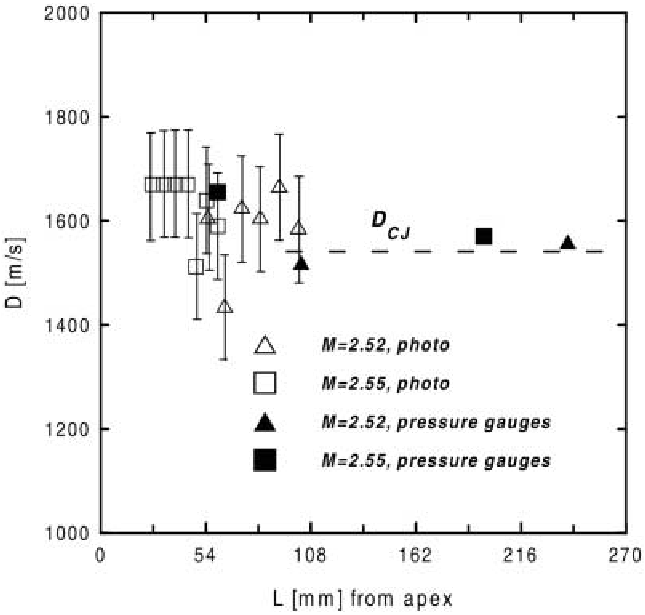

Fig. 10. Comparison of calculated (dashed line) and measured (points) detonation velocity for wedge reflector 90° at different incident shock wave Mach numbers

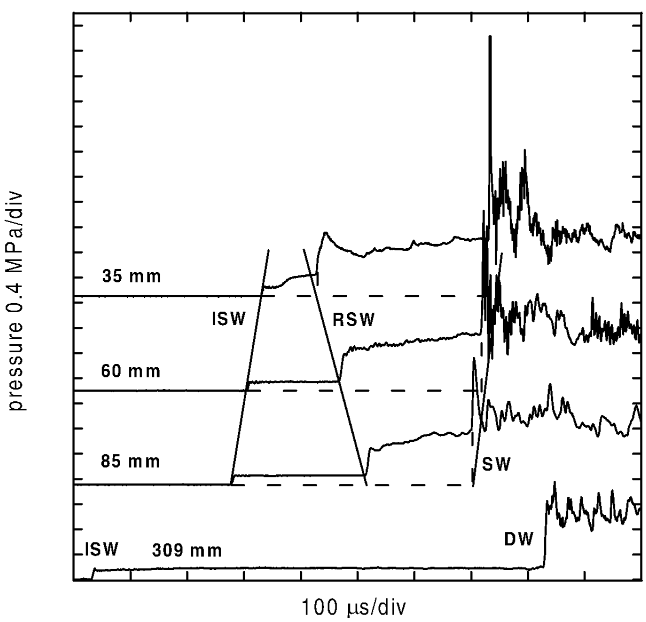

Fig. 11. Pressure records at different distances from the apex of wedge reflector 90°. Initial pressure 0.026 MPa and Mach number of the incident shock wave $M = 2.45$. ISW, RSW and DW: incident, reflected and detonation wave, SW: shock wave propagates in the direction of the reflector apex

the apex of the reflector after collision of two weak shocks accompanied by a flame. After that, the detonation wave is formed, and then moves out of the reflector. Simultaneously, the shock wave appears, and this wave propagates through the partially burned mixture to the top of the reflector. The analysis of the photos and the pressure history shows that the high intensity of pressure spikes behind the reflected shock wave is caused by the process of reflection

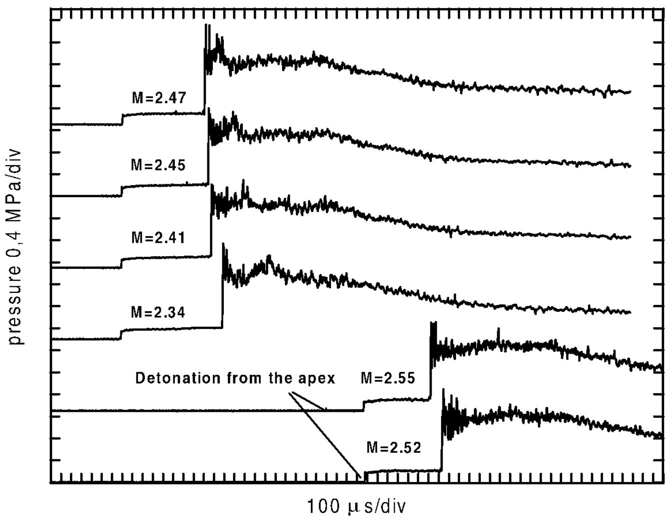

Fig. 12. Pressure records for detonation initiation at the apex of wedge reflector 90° ($M = 2.52$–2.55) and outside ($M = 2.34$–2.47)

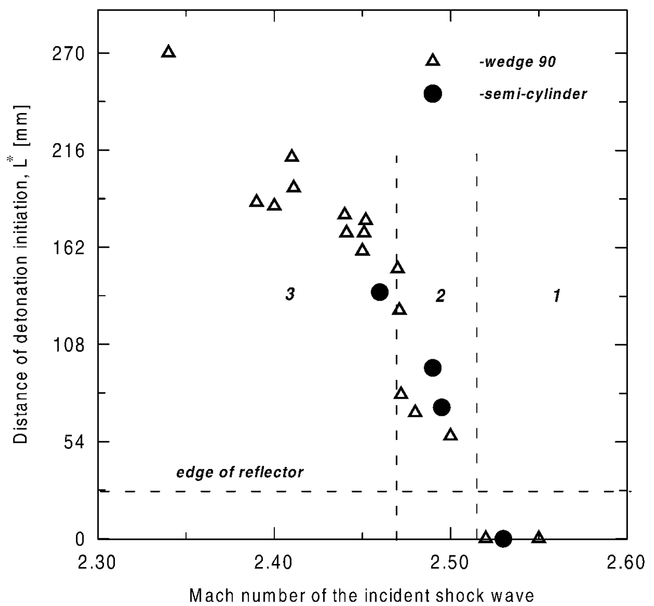

Fig. 13. Distance of detonation initiation L^* vs incident shock wave Mach number

of oblique waves (see the pressure recorded by transducer PG3). This new type of detonation initiation, which occurs under focusing conditions, has been established in the current study. The peculiarity of this phenomenon is that the area behind the reflected shock wave is characterized by the simultaneous presence of a system of weak shocks and flame fronts at the top and bottom wall. This mode of detonation initiation is an example of DDT under focusing condition.

The further decrease of the intensity of incident shock wave leads to a change of the detonation initiation mechanism, this being region 3. The indirect evidence of this change is bad reproducibility of results on the boundary between regions 2 and 3. Consider the example of this mechanism occurring at $M = 2.45$. As it is seen from

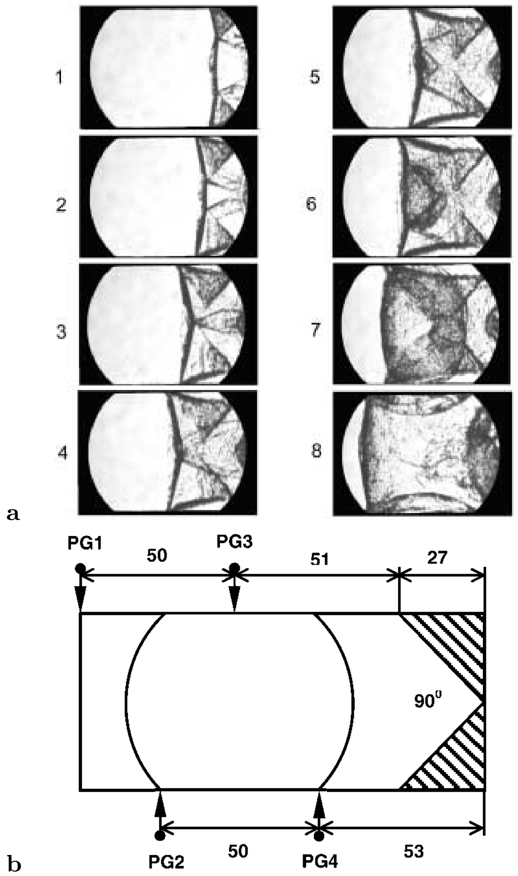

Fig. 14. a Schlieren pictures for detonation initiation outside the wedge reflector 90°. Mach number $M = 2.47$. Time between frames $10\,\mu$s. **b** Geometry of the experiment

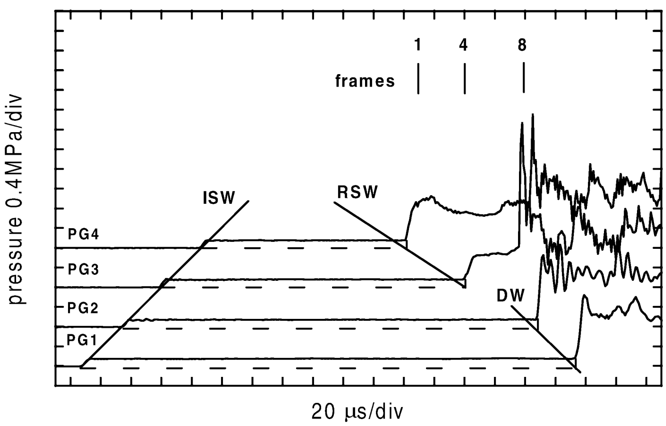

Fig. 15. Pressure records for Fig. 14

the photo in Fig. 16 (frames 1, 2), ignition takes place inside the reflector cavity, and then the combustion front is formed. Frames 3, 4 show the appearance and development of turbulent combustion zones in the vicinity of tube walls behind the reflected shock wave. From about $170\,\mu$s (frames 5, 6), a shock wave that moves to the reflector is detected. Also seen in these frames is the significant growth of the combustion zones. The shock wave propagating to the reflector can be considered as a quasi-retonation wave in partially burnout mixture. Near the walls, where the reaction is complete, this wave is oblique. The estimation for the case presented in Fig. 16 shows that the detonation is initiated at L^* of about 167 mm from the reflector apex. This experiment gives us an example of another kind of the DDT under focusing conditions. Region 3 is a good example of the well-known detonation initiation due to propagation and development of a complicated shape flame front in the flow-field behind the reflected shock wave (Oppenheim, 1985). In this case the reflector serves as a powerful initiator of the turbulent combustion front, thus decreasing significantly the minimal initiation energy in the comparison with the flat end wall.

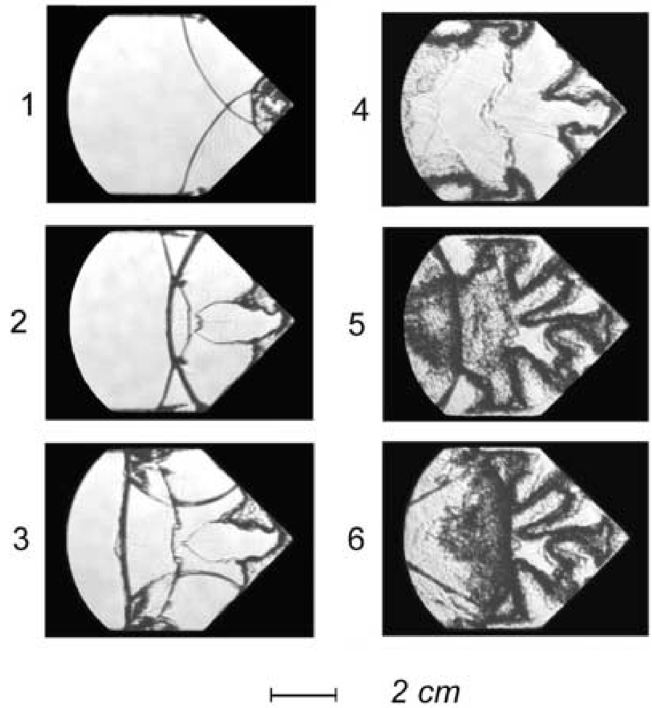

Fig. 16. Wedge reflector 90°. Mach number $M = 2.45$. Time between frames: 1–2: $40\,\mu$s, 2–3: $30\,\mu$s, 3–4: $90\,\mu$s, 4–5: $170\,\mu$s, 5–6: $10\,\mu$s

4 Conclusions

The experiments performed demonstrate that flame fronts with different configurations were realized after the mild ignition caused by focusing. These configurations depend on the reflector type. Strong ignition leads to direct detonation initiation inside the reflector cavity in the vicinity of the reflector apex.

It is shown that the absence of detonation initiation inside the reflector cavity does not exclude the possibility of detonation initiation outside the reflector cavity (at some distance from the reflector) due to self-ignition near/behind the reflected shock wave. The self-ignition in this case is promoted by additional compression and preheating of the mixture by turbulent multi-front combustion behind the reflected shock wave. It is possible to define a set of attributes peculiar to the given kind of initiation, namely: a) presence of an area of preheated mixture behind the incident shock wave, b) presence of a zone of turbulent combustion inside the reflector cavity and c) presence of zones of combustion behind the reflected shock wave outside the reflector cavity, the later zones developing in time and capable to meet at the center of the tube. The process considered is an example of DDT under focusing conditions.

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