ISSN 0012-5016, Doklady Physical Chemistry, 2006, Vol. 410, Part 1, pp. 255–259. © Pleiades Publishing, Inc., 2006.
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PHYSICAL CHEMISTRY

Detonation Initiation by Shock Wave Interaction with the Prechamber Jet Ignition Zone

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Presented by Academician Al.Al. Berlin March 30, 2006

Received March 31, 2006

DOI: 10.1134/S0012501606090028

Detonation initiation in a stoichiometric propane–air mixture by controlled shock wave (SW) interaction with the cloud of hot combustible gas forming upon the discharge of a combustion product jet from the prechamber has been experimentally observed for the first time. It has been shown that detonation initiation requires the careful synchronization of the SW arrival at the cloud with the moment of spontaneous ignition in it.

Two classical methods of initiation of gaseous detonation are known: direct initiation by powerful sources [1] and the deflagration-to-detonation transition [2, 3]. Direct initiation leads to the formation of a strong primary SW in which the temperature, pressure, and compression phase duration are sufficient to excite fast exothermic reactions near the shock front. In this case, the detonation is formed after some (relatively short) transition period. For the deflagration-to-detonation transition, a primary SW need not be generated. Due to instability and hydrodynamic inhomogeneities, the flame initiated by a weak ignition source changes its shape during its propagation, leading to progressive thermal gas expansion and formation of an SW in the fresh fuel mixture. After some (relatively long) transition period, the gas in the region between the SW and the accelerating flame spontaneously ignites, which leads to detonation.

Previously, we experimentally demonstrated the possibility of another mode of detonation initiation, different from the classical methods, namely, by accelerating a weak primary SW by a traveling forced ignition pulse [4, 5]. In this case, fast exothermic reactions behind the shock front are excited by an external ignition source rather than by the SW itself. The external source, "moving" together with the SW, stimulates chemical transformations in an explosive mixture, thus promoting the shock-to-detonation transition. In [4, 5], detonation in a stoichiometric propane–air mixture under normal initial conditions in a smooth-walled tube 51 mm in diameter was initiated by successively triggering seven electric dischargers mounted at regular intervals along a booster section 12–14 tube diameters in length. The necessary condition for detonation initiation was careful synchronization of the triggering time of each discharger with the arrival of the primary SW at the corresponding cross section of the tube.

This work is a continuation of the studies begun in [4, 5]. As distinct from [4, 5], here, forced ignition in a gas in the SW front was attained by using a classical prechamber rather than a series of electric dischargers [6]. The basic idea of prechamber jet ignition is that the igniter is mounted not in the combustion chamber but in a small prechamber separated from the main chamber by one or several nozzles. Combustion in the prechamber leads to an increase in the pressure in it and to the discharge of a high-speed jet of hot combustion products into the main chamber. This jet, mixing with the fresh mixture in the main chamber, immediately ignites the gas in a considerable volume.

Figure 1 shows the scheme of the experimental setup. The main elements of the setup are a primary SW generator, a straight detonation tube 60 mm in diameter and 3.5 m in length, and a prechamber. The primary SW generator (an electric discharge chamber or solid-propellant gas generator) was placed at the end plane of the detonation tube. The other end was sealed. At some distance from the generator, the prechamber was connected to the wall of the tube through a threaded hole.

The prechamber is a steel cylindrical chamber 31 mm in diameter and 50 mm in length. An igniter was placed at one end plane of the prechamber, and the other end plane was supplied with a detachable conical nozzle with a cone angle of 120° and two round holes 5 mm in diameter, connecting the prechamber with the tube volume (see the inset in Fig. 1). The nozzle wall was 1 mm thick. The axes of the nozzle holes were in one plane with the tube axis.

The measurement system included eight high-frequency piezoelectric pressure transducers PT1–PT8 of the LKh600 type and an FEU-39 photomultiplier. The

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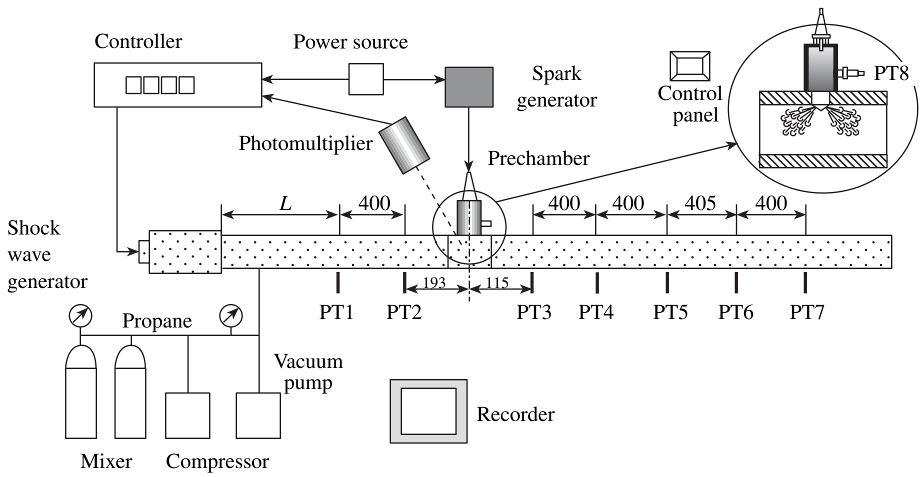

Fig. 1. Scheme of the experimental setup.

pressure transducers were mounted along the tube and at the lateral wall of the prechamber. They were used to determine the time of the SW arrival at the corresponding cross section of the detonation tube and to measure wave dynamics in the prechamber and in the SW that propagated through the cloud of prechamber gases (hereinafter, the prechamber cloud). In the cross section where the prechamber was located, the tube wall had a window for measuring the glow with the use of the photomultiplier. The axis of the cone of vision of the photomultiplier was perpendicular to the axes of the prechamber and detonation tube. The signals from the pressure transducers and photomultiplier were inputted into a personal computer through an L-Card L-783 analog-to-digital converter.

Before each run, the tube and prechamber were evacuated and then filled with a stoichiometric propane–air mixture under normal initial conditions (293 ± 2 K, 0.1 MPa). In preliminary runs, the primary SW generator and prechamber generator were tested and the measurement procedure was optimized. In generator tests, we studied the primary SW propagation along the tube without gas ignition in the prechamber. The mean SW velocity at different segments of the tube was calculated from the known distance between the transducers and the time it took the shock front to travel this distance. The error of determination of the mean SW velocity was no more than 2.5%. The prechamber tests were carried out without an SW. The parameters of detachable nozzles were changed in such a way as to ensure a noticeable time delay between the discharge of combustion products from the prechamber and the spontaneous ignition of the mixture in the tube. When the prechamber with two round nozzle holes 5 mm in diameter was used, the delay between the ignition of the mixture in the prechamber and the spontaneous ignition of the prechamber cloud was 35–40 ms. The first threshold evidence for an increase in pressure in the tube due to the prechamber ignition appeared within ~5 ms after the flash of the mixture was recorded with the photomultiplier. The flash was recorded by the photomultiplier as an exponential increase in glow intensity by three orders of magnitude in ~3 ms. The moment of the flash was taken to be the moment when the multiplier signal achieved a level of 0.13 V. After the spontaneous ignition of the prechamber cloud, the mixture in the tube burnt in 200–250 ms.

In the experiments on studying the interaction of the SW with the prechamber cloud, all recording means were activated by an electronic controller at the moment of mixture ignition in the prechamber. Then, after a specified delay, the primary SW generator was switched on. The SW propagated along the tube and arrived at the prechamber cross section either before or after the flash in the prechamber cloud. In all cases, before the SW arrival, the local overpressure in the prechamber cloud did not exceed 1 kPa. To quantify the SW interaction with the cloud, we used the time delay between the SW arrival at the prechamber cross section and the moment of the flash recorded by the photomultiplier (hereinafter, the time delay τ). The triggering time of the primary SW generator was specified based on the results of the preliminary tests described above.

Two series of runs were carried out with different primary SW generators: an electric discharge generator (series 1) and a solid-propellant gas generator (series 2). In each series, the distance L between the SW generator and the prechamber and the primary SW intensity were varied (series 1*a*, 1*b*, 2*a*, and 2*b*).

The electric discharge generator generated an SW with a very short compression phase since the characteristic energy release time in the electric discharge was 20–40 μs. Figure 2 shows the plots of the mean primary SW velocity V as a function of the distance X traveled by the SW along the tube in series 1*a* (solid lines) and 1*b* (dashed lines). In series 1*a*, the distance L from the electric discharger to the prechamber was 0.4 m and the discharge energy was 1.6 kJ. In series 1*b*, L = 1.434 m and the discharge energy was 2.5 kJ. The cross section with $X = 0$ corresponds to the position of the prechamber axis. The dotted horizontal line corresponds to the calculated Chapman–Jouguet detonation velocity in the stoichiometric propane–air mixture (1804 m/s). Curves *1* and *6* were plotted based on the results of the preliminary runs without gas ignition in the prechamber. As is seen, in the runs of series 1*a*, the mean primary SW velocity monotonically decreases from about 1100 m/s at $X = 0$ to 620 m/s at $X = 2.35$ m. In series 1*b*, V decreases from 810 m/s at $X = 0$ to 680 m/s at $X = 2.1$ m.

In both series 1*a* and 1*b*, at "negative" delay times (the SW arrived at the prechamber cross section ahead of the flash, $\tau < 0$), the SW attenuation curves roughly coincided with curves *1* and *6*.

In series 1*a* at $\tau = 10.3$ ms (curve *5*) and in series 1*b* at $\tau > 2.3$ ms (curves *10–15*), an increase in the mean SW velocity was observed when the SW propagated through the prechamber cloud; downstream of the cloud, the SW velocity decreased. At $\tau \approx 10$–11 ms (curves *5*, *14*, and *15*), the mean SW velocity increased to 1500–1800 m/s, i.e., to the detonation velocity in the stoichiometric propane–air mixture. It is worth noting that this increase in velocity is mainly caused by the interaction of the SW with the interface between a cold and a hot gas and by its propagation through the hot gas [3].

As distinct from the series 1*a* runs, in which the mean velocity of the SW monotonically decreased after it had left the prechamber cloud to 700–870 m/s at $X = 2.3$ m, in the series 1*b* runs, the mean SW velocity increased to 810–960 m/s at $X = 2.1$ m. The maximum increase in the mean velocity ($\Delta V = 100$ m/s) was observed at time delays $\tau \approx 3$–7 ms (curves *11–13*). As compared to basic curve *6*, the increase in the mean SW velocity at $X = 2.1$ m in series 1*b* was as large as $\Delta V = 200$–300 m/s. The observed SW amplification effects after its interaction with the prechamber cloud indicate that the energy release occurs close to the shock front. Indeed, pressure transducers PT3–PT7, located downstream of the prechamber, recorded clearly defined secondary blast waves overtaking the primary SW.

In the runs of series 2, the primary SW was created by a solid-propellant gas generator, a cylindrical combustion chamber equipped with a detachable flow control nozzle and a bursting diaphragm. A porous cotton powder charge of 1.50–2.25 g was placed into the gas generator. The charge was ignited with a primer. The total combustion time of the powder was 1–2 ms. The use of the solid-propellant gas generator made it possible to increase the energy release duration as compared to the electric discharge and to obtain an SW with a considerably longer compression phase duration. The compression phase duration in an SW was determined by the nozzle diameter. The thickness and material of the diaphragm determined the initial SW velocity. The initial SW velocity was also varied by changing the distance from the solid-propellant gas generator to the prechamber: $L = 1.563$ m in series 2*a* and $L = 1.293$ m in series 2*b* (Fig. 1). In most runs of series 2*a* and 2*b*, the initial SW velocity was 700–850 and 1080–1120 m/s, respectively. In some runs of series 2*a*, a higher initial SW velocity was used: 1000 m/s $\leq V \leq$ 1250 m/s.

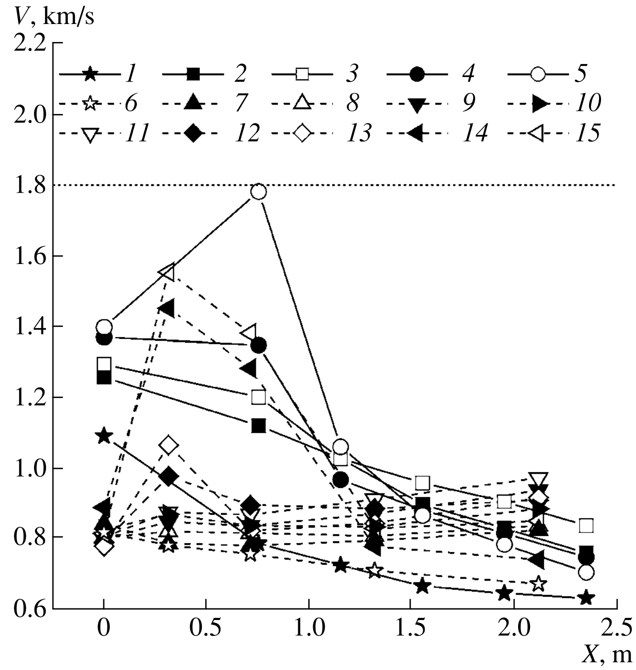

Fig. 2. Measured mean primary SW velocity as a function of the distance traveled by the SW along the tube at different delays of the SW arrival at the prechamber cloud in series 1. Series 1*a* (solid lines): (*1*) without a prechamber; τ = (*2*) 2.4, (*3*) 4.4, (*4*) 6.4, and (*5*) 10.3 ms; series 1*b* (dashed lines): (*6*) without a prechamber; τ = (*7–9*) 1.4, (*10*) 2.3, (*11*) 3.4, (*12*) 5.3, (*13*) 7.4, (*14*) 11.2, and (*15*) 11.5 ms. The cross section with $X = 0$ corresponds to the position of the prechamber axis. The dotted horizontal line corresponds to the Chapman–Jouguet detonation velocity in the stoichiometric propane–air mixture.

Figure 3 shows the plots of the mean velocity of the primary SW as a function of the distance traveled by the SW along the tube in series 2*a* (solid lines) and 2*b* (dashed lines). As in Fig. 2, the cross section at $X = 0$ in Fig. 3 corresponds to the prechamber axis and the dotted horizontal line corresponds to the Chapman–Jouguet detonation velocity in the stoichiometric propane–air mixture. Curves *1* and *9* were plotted based on the results of the preliminary runs without ignition of the gas in the prechamber. In the series 2*a* runs, the mean velocity of the primary SW (curve *1*) monotonically decreases from about 710 m/s at $X = -0.35$ m to 650 m/s at $X = 0.7$ m. As distinct from curve 1*b*, basic curve *9* for series 2*b* shows a slow SW amplification along the detonation tube: from 1100 m/s at $X = 0.35$ m to 1650 m/s at $X = 1.7$ m. A similar behavior of primary SWs in series 2*b* was observed at large negative time delays $\tau < -3$ ms.

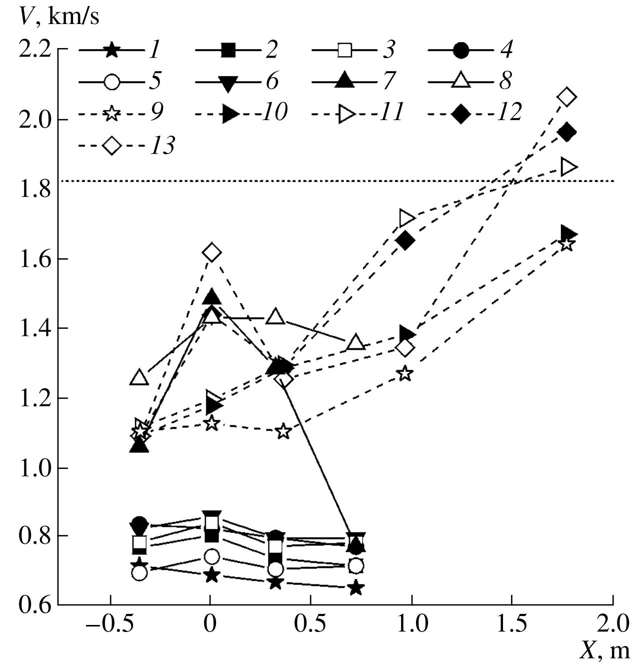

Fig. 3. Measured mean primary SW velocity as a function of the distance traveled by the SW along the tube at different delays of the SW arrival at the prechamber cloud in series 2. Series 2*a* (solid lines): (*1*) without a prechamber; τ = (*2*) –0.6, (*3*) –0.6, (*4*) –0.4, (*5*) 0.0, (*6*) 2.3, (*7*) 12.2, and (*8*) 31.0 ms; series 2*b* (dashed lines): (*9*) without a prechamber; τ = (*10*) –2.0, (*11*) 2.6, (*12*) 4.6, and (*13*) 5.6 ms. The cross section with $X = 0$ corresponds to the position of the prechamber axis. The dotted horizontal line corresponds to the Chapman–Jouguet detonation velocity in the stoichiometric propane–air mixture.

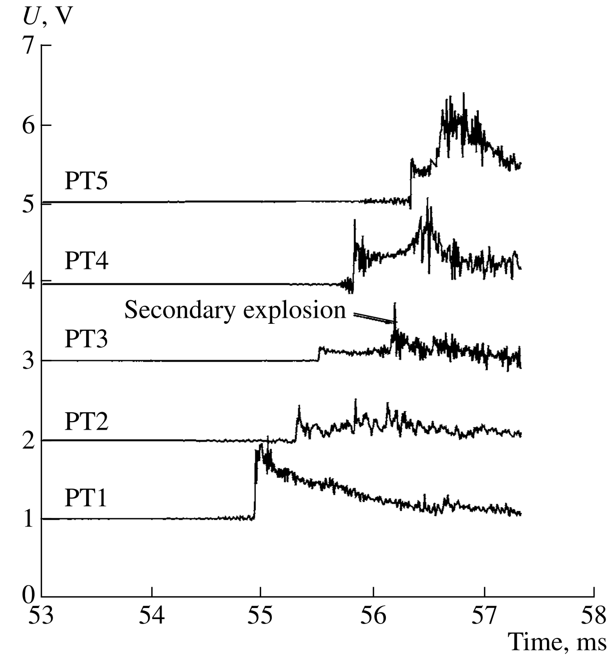

Fig. 4. Records of pressure transducers PT1–PT5 in the run of series 2*a* with τ = 12.2 ms (see curve *7* in Fig. 3).

In general, the results of the series 2*a* runs repeat the corresponding results of series 1*b*. For example, curve *6* in Fig. 3 roughly coincides with curve *10* in Fig. 2. These curves correspond to runs with close SW velocities at $X = 0$ (≈820–850 m/s) and equal time delays $\tau \approx 2.3$ ms.

In the runs of series 2*a* with the increased initial SW velocity (curves *7* and *8* in Fig. 3), secondary explosions were observed when the SW propagated through the prechamber cloud. Figure 4 shows the pressure record corresponding to τ = 12.2 ms (curve *7* in Fig. 3). The primary SW velocity at the measuring segment PT1–PT2 was 1057 ± 30 m/s. At the PT2–PT3 segment, the primary SW velocity increased to 1481 ± 40 m/s, then slowly decreasing to 1282 ± 30 m/s at the PT3–PT4 segment and to 770 ± 15 m/s at the PT4–PT5 segment. The pressure recorded by PT3 indicates that a secondary blast occurs behind the shock front and the secondary blast wave approaches the primary SW (see the records of PT4 and PT5), propagating with a mean velocity of 2200–2300 m/s.

The most interesting results were obtained in series 2*b* runs with ignition of the mixture in the prechamber. At τ = 2.6–5.6 ms (curves *11*–*13* in Fig. 3), the mean SW velocity increased to 1850–2100 m/s, which exceeds the Chapman–Jouguet detonation velocity. This means that the shock-to-detonation transition takes place downstream of the prechamber cloud through the formation of an overdriven detonation wave. The shortest predetonation distance ($X \approx 1.3$–1.5 m) is achieved at small positive time delays (τ = 2.6 and 4.6 ms, curves *11* and *12* in Fig. 3). At τ = 5.6 ms (curve *13* in Fig. 3), after passing through the prechamber cloud, the primary SW first propagates with the same mean velocity as at negative τ values (τ = –2 ms, curve *10* in Fig. 3). However, at the distance $X \approx 1.0$–1.7 m, the mean SW velocity sharply increases to 2100 m/s due to the coalescence of the primary SW and the secondary blast wave formed in the prechamber cloud.

Thus, synchronization of the SW arrival at the prechamber cloud with the moment of the flash in the cloud promotes the shock-to-detonation transition. In the series 2*b* runs, the shock-to-detonation transition for an SW with a Mach number of about 3.2 required a distance of about 1.3–1.5 m (22–25 tube diameters). This distance should be compared with the distance required for detonation initiation in the tube without ignition of the gas in the prechamber. It is worth noting that detonation in the tube without ignition of the gas in the prechamber was not observed (curve *9* in Fig. 3). If we extrapolate curve *9* to its intersection with the dotted straight line at $V = 1804$ m/s, we obtain an estimated value of 2.2 m (37 tube diameters) for the predetonation distance. This means that, due to the SW interaction with the prechamber cloud, the predetonation distance decreased by about a factor of 1.5. The possibility of this decrease in the predetonation distance was determined by the initial intensity and compression phase duration of the primary SW, as well as by the time of the SW arrival at the prechamber cloud. Both the early and late SW arrival at the cloud did not noticeably change the SW dynamics in the detonation tube. The decrease in the predetonation distance was observed only when the SW arrival was carefully synchronized with the moment of the flash in the cloud. The physical mechanism of this "resonance" interaction with the cloud is presumably associated with the enhanced sensitivity of an explosive mixture in the cloud preconditioned for self-ignition. Under these conditions, compression and heating of the mixture in an SW with a Mach number of about 3.2 turned out to be sufficient to excite fast exothermic reactions near the shock front and to initiate detonation.

This interpretation of our findings is supported by the experimental data in [7], where the effect of preliminary cool-flame oxidation on predetonation flame propagation in pentane–oxygen mixtures was studied and a sharp (up to 1.5–2.0 times) decrease in the predetonation distance as a function of the ignition time of a preconditioned mixture was found.

The classical mechanism of flame acceleration by interaction with an SW resulting in a multifold increase in the flame surface [2, 3] could also play a certain role in the observed phenomena. However, the fact that a significant decrease in the predetonation distance was observed only at some "resonance" delay of the SW arrival at the prechamber cloud points to the minor role of this mechanism. Nevertheless, at large delays of the SW arrival, when this effect was not observed, the pressure transducers located downstream of the prechamber recorded secondary explosions behind the primary SW. These secondary explosions can initiate detonation in longer detonation tubes than that used in this work.

ACKNOWLEDGMENTS

This work was supported in part by the International Science and Technology Center, project no. 2740.

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