SHOCK-TO-DETONATION TRANSITION DUE TO SHOCK INTERACTION WITH THE ZONE OF PRECHAMBER-JET IGNITION

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A new principle of detonation initiation due to controlled interaction of a propagating shock wave (SW) with the cloud of hot explosive gas formed by prechamber flame jets in the stoichiometric propane–air mixture was demonstrated experimentally. Detonation initiation was shown to be conditioned by synchronization of cloud autoignition with its shock-induced compression.

1 Introduction

There exist two classical approaches for gaseous detonation initiation, namely, direct initiation with a strong source [1] and deflagration-to-detonation transition (DDT) [2, 3]. In the course of direct initiation, a strong primary SW is generated. The temperature, pressure and compression phase duration in such an SW are sufficient for triggering fast exothermic chemical reactions in the close vicinity to the lead shock front. In this case, a detonation forms after a certain relatively short transition period. For the DDT, there is no need in the strong primary SW. The flame arising from a weak ignition source changes shape due to various instabilities and nonuniformities, thus leading to progressive thermal expansion of the reactive mixture and formation of an SW. After a certain relatively long transition period, autoignition of the mixture occurs in the region between the SW and the accelerating flame, leading to a detonation.

The other approach, different from those mentioned above, was suggested in [4, 5]. A possibility to initiate detonation due to acceleration of an initially weak SW by a travelling ignition pulse was demonstrated experimentally. In this case, fast exothermic reactions behind a lead shock front were triggered by the external ignition source rather than by the SW itself. The external ignition source, travelling with the SW, triggered chemical reactions in the explosive gas, thus promoting fast shock-to-detonation transition (SDT). In [4, 5], successive triggering of seven electric discharges, mounted equidistantly along the tube, was sufficient for initiating a detonation in the stoichiometric propane–air mixture at normal initial conditions at a distance of 12 to 14 tube diameters. A necessary condition for detonation initiation was careful synchronization of the triggering time of each electric discharge with the SW arrival to its position. The research outlined in this paper continues the studies reported in [4, 5]. Contrary to [4, 5], forced ignition of the reactive mixture behind the propagating SW was achieved using a classical prechamber [6] rather than a series of electric discharges. The basic idea of prechamber jet ignition is to move the spark plug from the main combustion chamber to a small supplementary chamber (prechamber) separated from the main chamber by one or several nozzles. Mixture ignition and combustion leads to pressure buildup in the prechamber and formation of high-speed turbulent jets of hot combustion products issuing in the main chamber. These jets engulf the reactive mixture in the main chamber and ignite it with a certain delay nearly simultaneously in a large volume.

2 Experimental Setup

Figure 1 shows the schematic of the experimental setup. The main elements of the setup are an SW-generator, straight detonation tube 60 mm in diameter and 3.5 m long, and a prechamber. The SW-generator (electrodischarge chamber or solid-propellant gas generator) was mounted at one end of the detonation tube. The other end of the tube was closed. The prechamber was screwed to the lateral wall of the tube at a certain distance from the SW-generator.

The prechamber was a steel cylindrical chamber 31 mm in diameter and 50 mm long. A standard spark plug was fixed at one end of the

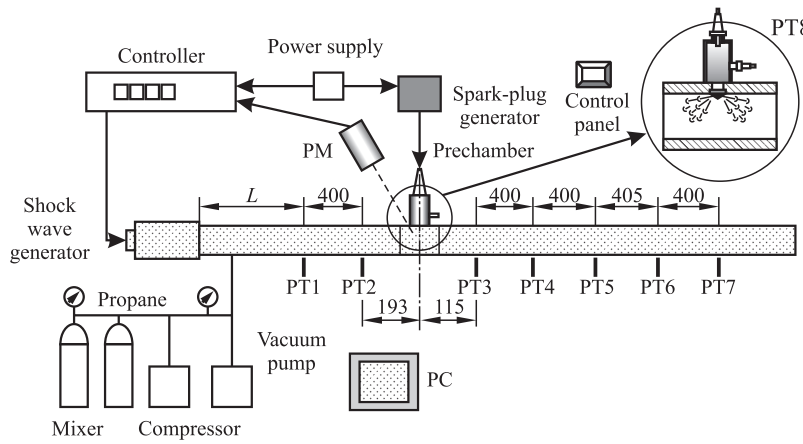

Figure 1 Schematic of the experimental setup. Dimensions are in millimeters

prechamber, while the other end was equipped with a changeable conical nozzle with the apex angle of 120° (see the insert in Fig. 1) and two round orifices 5 mm in diameter connecting the prechamber with the volume of the detonation tube. The thickness of the nozzle wall was 1 mm. The axes of the nozzle orifices and the tube were positioned in the same plane.

The measuring system included 8 high-frequency piezoelectric pressure transducers PT1 to PT8 and a photomultiplier (PM). The pressure transducers were mounted along the tube and in the lateral prechamber wall. They were used to register the SW arrival time to the corresponding tube cross section and for the analysis of wave processes in the prechamber and in the SW traversing the cloud of prechamber gases. From now on, the cloud of prechamber gases will be referred to as the prechamber cloud. For detecting the luminosity of combustion products by the PM, a provision was made for an optical window. The window was made in the lateral tube wall in the same section with the prechamber. The axis of the window was normal to the tube and prechamber axes. The data acquisition system comprised the analog-to-digital converter and a PC.

3 Experimental Procedure

Before each run, the tube and prechamber were evacuated and filled with the stoichiometric propane–air mixture at normal initial conditions (a temperature of 293 ± 2 K and pressure of 0.1 MPa). In the preliminary experiments, the SW-generators of both types and prechambers were tested and the measuring procedure was established. The tests with SW-generators were aimed at measuring the parameters of the shock waves propagating along the detonation tube without mixture ignition in the prechamber. The mean SW velocity at the measuring segments was calculated based on the known distance between the pressure transducers and the time interval between the registration of lead shock fronts. The error in determining the mean SW velocity was estimated as 2.5%. The preliminary tests with the prechambers were aimed at providing ignition of the prechamber cloud with a significant delay after the prechamber jets issued from the nozzles. These tests were conducted by trying different nozzle units without activating the SW-generator. With the nozzle unit containing two round orifices 5 mm in diameter, the delay time between mixture ignition in the prechamber and prechamber cloud autoignition in the tube was about 35–40 ms. Upon prechamber cloud autoignition, detected by the PM, it usually took about 5 ms for pressure transducers to detect the resolvable pressure rise. The luminosity accompanying autoignition was registered by the PM as an exponential rise of the signal intensity by three orders of magnitude within about 3 ms. Therefore, the autoignition event was conditionally attributed to an instant when the PM signal attained a value of 0.13 V. A local overpressure at the prechamber nozzle did not ususlly exceed 1 kPa. After cloud autoignition, the reactive mixture in the tube burned out completely during about 200–250 ms.

In the experiments on SW – prechamber cloud interaction, all measuring units were activated by a digital controller upon spark plug triggering in the prechamber. The SW-generator was activated after a certain preset time delay resulting in the formation of a primary SW. The SW propagated along the tube and arrived at the prechamber nozzle position either before or after prechamber cloud autoignition. For the quantitative description of the SW – prechamber cloud interaction, a concept of SW arrival delay time with respect to the autoignition event registered by the PM was introduced. In the following, this delay time will be referred to as the SW arrival delay τ. The activation time of the SW-generator was chosen based on the preliminary tests described above.

4 Experimental Results

Two experimental series, Series 1 and Series 2, were performed, which differed by the type of the SW-generator used. In these series, the electrodischarge SW-generator and solid-propellant SW-generator were used, respectively. In each series, the distance between the SW-generator and the prechamber, L (Series 1a and 2a), as well as the primary SW velocity (Series 1b and 2b) were varied.

4.1 Series 1

The electrodischarge SW-generator formed the shock waves of very short compression phase duration as the characteristic time of energy release in the electric discharge was 20–40 μs. Figure 2 shows the measured dependencies of the mean SW velocity, V, on the distance X travelled by the shock along the tube in Series 1a (solid curves) and 1b (dashed curves). In Series 1a, the distance L from the electric discharge to the prechamber was 0.4 m and the stored discharge energy was 1.6 kJ. In Series 1b, $L = 1.434$ m and the stored discharge energy was 2.5 kJ. The section $X = 0$ corresponded to the prechamber axis position. The dotted horizontal line shows the calculated velocity of Chapman–Jouguet (CJ) detonation in the stoichiometric propane–air mixture at normal initial conditions (1804 m/s). Curves *1* and *6* were plotted based on the preliminary tests without mixture ignition in the prechamber. The mean velocity of the primary SW decreased monotonically from 1100 m/s at $X = 0$ to 620 m/s at $X = 2.35$ m in Series 1a and from 810 m/s at $X = 0$ to 680 m/s at $X = 2.1$ m in Series 1b.

In both Series, 1a and 1b, the decay of the SW velocity at "negative" SW arrival delay (i.e., at SW arrival prior to cloud autoignition, $\tau < 0$) was virtually the same as that shown by the corresponding curves *1* and *6*.

In Series 1a, at the SW arrival delay of $\tau = 10.3$ ms (curve *5*), and in Series 1b, at $\tau > 2.3$ ms (curves *10*–*15*), the increase in the mean SW velocity when the SW was traversing the prechamber cloud,

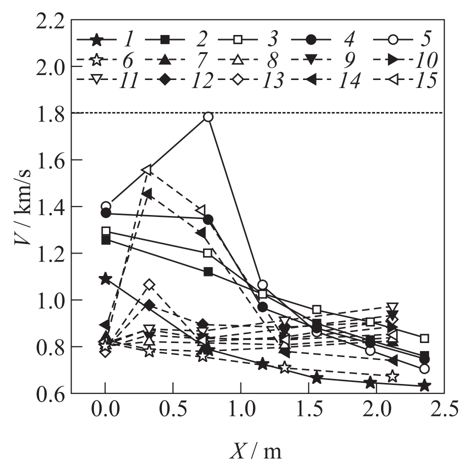

Figure 2 Measured dependencies of the mean velocity of the primary SW on the distance travelled along the tube at different SW arrival delay to the prechamber cloud in Series 1. Series 1*a* (solid curves): *1* — without prechamber, *2* — $\tau = 2.4$ ms, *3* — 4.4, *4* — 6.4, and *5* — $\tau = 10.3$ ms; Series 1*b* (dashed curves): *6* — without prechamber, *7*, *8*, and *9* — $\tau = 1.4$ ms, *10* — 2.3, *11* — 3.4, *12* — 5.3, *13* — 7.4, *14* — 11.2, and *15* — $\tau = 11.5$ ms. Section $X = 0$ corresponds to the prechamber axis location. Horizontal dotted line corresponds to the theroretical CJ detonation velocity in the stoichiometric propane–air mixture

followed by the velocity decrease after it passed through the cloud, was observed. Moreover, at SW arrival delays $\tau \approx 10$–11 ms (curves *5*, *14*, and *15*), the mean SW velocity increased to 1500–1800 m/s, i.e., up to a level of the CJ detonation velocity in the stoichiometric propane–air mixture. Note that this velocity rise was caused mainly by the transition of the SW through the interface between cold and hot gases and further propagation in the hot gas [3]. Contrary to the tests in Series 1*a* with the gradual decrease in the SW velocity to 700–870 m/s at $X = 2.3$ m after the SW left the prechamber cloud, the tests in Series 1*b* exhibited the growth of the mean SW velocity up to 810–960 m/s at $X = 2.1$ m. The maximal mean velocity increase (approximately by $\Delta V = 100$ m/s) was observed at SW arrival delays $\tau \approx 3$–7 ms (curves

11–13). As compared to the baseline curve *6*, the increase in the mean SW velocity at $X = 2.1$ m attained a value of $\Delta V = 200$–300 m/s in Series 1*b*. The observed effects of SW amplification after interaction with the prechamber cloud imply the existence of the energy release zone in the close vicinity to the lead shock front. As a matter of fact, pressure transducers PT3 to PT7 located downstream the prechamber, detected pronounced secondary pressure waves catching up with the primary SW.

4.2 Series 2

In Series 2, the primary SW was generated by a solid-propellant SW-generator, a cylindrical combustion chamber equipped with the changeable nozzle and a bursting diaphragm. Before the test, a small amount (up to 1.50–2.25 g) of porous cotton propellant was placed in the chamber. The propellant was ignited by a primer. The total time of propellant combustion was 1–2 ms. The use of the solid-propellant gas generator made it possible to increase the duration of energy release compared to the electrodischarge SW-generator and obtain shock waves with a much longer compression phase. The compression phase duration of the resultant SW was determined by the nozzle diameter. The thickness and material of the bursting diaphragm determined the initial SW velocity. The initial SW velocity was also varied by changing the distance between the SW-generator and the prechamber. This distance was $L = 1.563$ m in Series 2*a* and $L = 1.293$ m in Series 2*b* (see Fig. 1). The tests in Series 2*a* and 2*b* were performed mainly with the shock waves of initial velocity $V = 700$–850 and 1080–1120 m/s, respectively. In addition, the tests with the elevated initial SW velocities, $1000 \leq V \leq 1250$ m/s, were made within Series 2*a*.

Figure 3 shows the measured dependencies of the mean SW velocity on the distance travelled along the tube in Series 2*a* (solid curves) and 2*b* (dashed curves). Similar to Fig. 2, the section $X = 0$ in Fig. 3 corresponds to the prechamber axis position, and the horizontal dotted line corresponds to the theoretical CJ detonation velocity in the stoichiometric propane–air mixture.

Curves *1* and *9* were plotted based on the results of preliminary tests without mixture ignition in the prechamber. It is seen that in Series 2*a*, the mean velocity of the primary SW (curve *1*) dropped

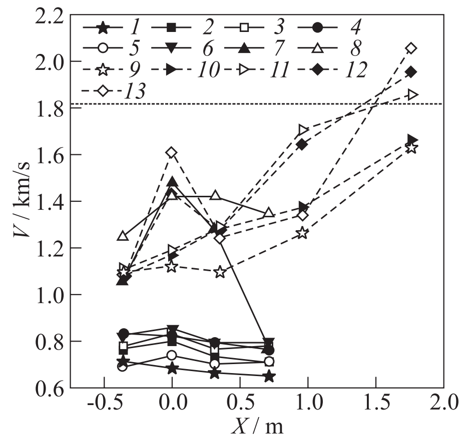

Figure 3 Measured dependencies of the mean velocity of the primary SW on the distance travelled along the tube at different SW arrival delay to the prechamber cloud in Series 2. Series 2*a* (solid curves): *1* — without prechamber, *2* and *3* — $\tau = -0.6$ ms, *4* — -0.4, *5* — 0.0, *6* — 2.3, *7* — 12.2, and *8* — $\tau = 31.0$ ms; Series 2*b* (dashed curves): *9* — without prechamber, *10* — $\tau = -2.0$ ms, *11* — 2.6, *12* — 4.6, and *13* — $\tau = 5.6$ ms. Section $X = 0$ corresponds to the prechamber axis location. Horizontal dotted line corresponds to the theoretical CJ detonation velocity in the stoichiometric propane–air mixture

monotonically from about 710 m/s at $X = -0.35$ m to 650 m/s at $X = 0.7$ m. Contrary to curve *1*, the baseline curve *9* in Series 2*b* shows gradual acceleration of the SW along the tube from 1100 m/s at $X = 0.35$ m to 1650 m/s at $X = 1.7$ m. Similar behavior of primary shock waves in Series 2*b* was registered at large "negative" SW arrival delays $\tau < -3$ ms.

The results of tests in Series 2*a* repeated in general the results of similar tests in Series 1*b*. For example, curve *6* in Fig. 3 virtually coincides with curve *10* in Fig. 2. These curves correspond to the tests with close values of the SW velocity at $X = 0$ ($\approx$ 820–850 m/s) and similar values of the SW arrival delay of $\tau \approx 2.3$ ms.

In the tests of Series 2*a* with the elevated initial SW velocities (curves *7* and *8* in Fig. 3), secondary explosions were detected when the

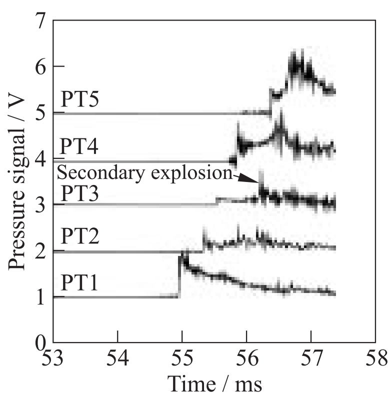

Figure 4 Records of pressure transducers PT1 to PT5 in the test of Series 2*a* with the SW arrival delay time $\tau = 12.2$ ms (see curve *7* in Fig. 3)

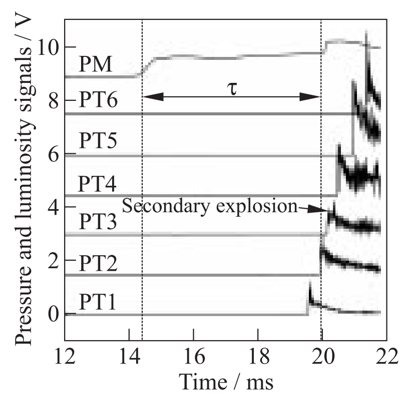

Figure 5 Records of pressure transducers PT1 to PT6 and photomultiplier (PM) in the test of Series 2*a* with the SW arrived delay time τ = 5–6 ms (see curve *13* in Fig. 3)

SW was traversing the prechamber cloud. Figure 4 shows the pressure records corresponding to τ = 12.2 ms (curve *7* in Fig. 3). The SW velocity at the measuring segment PT1–PT2 was 1057 ± 30 m/s. At the segment PT2–PT3, the primary SW accelerated to 1481 ± 40 m/s, and then decelerated to 1282 ± 30 m/s at the segment PT3–PT4 and to 770 ± 15 m/s at the segment PT4–PT5. The pressure record of PT3 indicates that a secondary explosion occurred behind the primary shock wave. The secondary SW propagated at a velocity of 2200–2300 m/s rapidly approaching the primary one (see pressure records of PT4 and PT5).

The most interesting were the tests with mixture ignition in the prechamber in Series 2*b*. At SW arrival delays τ from 2.6 to 5.6 ms (curves *11*–*13* in Fig. 3), acceleration of a primary SW to the mean velocity of 1850–2100 m/s, exceeding the CJ detonation velocity, was detected. Such high values of the mean SW velocities indicate that downstream the prechamber cloud, the SDT occurred via the stage of overdriven detonation formation. The shortest predetonation distance

($X \approx$ 1.3–1.5 m) was attained at short positive SW arrival delays (τ = 2.6 and 4.6 ms, curves *11* and *12* in Fig. 3). At the delay of $\tau = 5.6$ ms (curve *13* in Figs. 3 and 5), the primary SW, after passing the cloud, propagated initially at the velocity typical for the "negative" delays τ ($\tau = -2$ ms, curve *10* in Fig. 3). However, at a distance of $X \approx$ 1.0–1.7 m, a sharp increase in the mean SW velocity up to 2100 m/s occurred due to collision of the secondary SW formed in the prechamber cloud with the primary SW.

Concluding Remarks

Thus, synchronization of SW arrival to the prechamber cloud with cloud autoignition made it possible to accelerate the SDT phenomenon. In the tests of Series 2*b*, for the transition of the SW of Mach number 3.2 to a detonation, a distance of about 1.3–1.5 m (22–25 tube diameters) was required. This distance should be compared with that needed for detonation onset in the tube without mixture ignition in the prechamber. Note that in the tests without mixture ignition in the prechamber, a detonation was not observed (see curve *9* in Fig. 3). If curve *9* is extrapolated to the dotted line $V = 1804$ m/s, the estimate of 2.2 m (37 tube diameters) for the predetonation distance could be obtained. This means that SW – prechamber cloud interaction resulted in the reduction of the predetonation distance by a factor of 1.5. The possibility of such a reduction was determined by the initial SW velocity and compression phase duration, as well as by the SW arrival time to the prechamber cloud. Early or late SW arrival to the cloud did not lead to a significant change in SW evolution. The effect of predetonation distance reduction was detected only at careful synchronization of SW arrival to the prechamber cloud with cloud autoignition.

The physical mechanism of such a resonant interaction of the SW with the prechamber cloud is most probably connected with the enhanced sensitivity of the explosive mixture in the cloud, preconditioned to autoignition. In such conditions, mixture compression and heating in the SW with the Mach number of about 3.2 appeared to be sufficient for triggering fast exothermic reactions in the close vicinity to the lead shock front and detonation onset. This mechanism has much in common with the SWACER-mechanism suggested in [7].

The interpretation of the present experimental findings is also in line with the early experimental data of Shchelkin and Sokolik [8] who studied the effect of preliminary cool-flame oxidation of n-pentane–oxygen mixtures on the predetonation distance. Shchelkin and Sokolik discovered a sharp reduction (up to a factor 1.5 to 2) of the predetonation distance depending on the ignition timing of the preconditioned explosive mixture.

In the phenomena observed herein, a proper role could be also played by the classical mechanism of flame acceleration due to SW flame interaction leading to a multiple increase in the flame surface area [2, 3]. However, the fact that the considerable reduction of the predetonation distance was obtained only at a certain (resonant) delay time of SW arrival to the prechamber cloud indicates the minor role of this mechanism. Nevertheless, at long SW arrival delays, when the effects under discussion were less pronounced, the pressure transducers located downstream the prechamber registered secondary explosions behind the primary SW. These explosions might promote the detonation onset in tubes longer than that used in the present study.

Acknowledgments

This work was partly supported by the International Science and Technology Center, project No. 2740.

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