Experimental Investigation of Gradient Mechanism of Detonation Initiation

Aleksandr E. Rakitin[1,2], **Andrei Yu. Starikovskii**[2,3]

[1]NEQLab Research BV, Delft, The Netherlands

[2]Physics of Nonequilibrium Systems Lab, MIPT, Dolgoprudny, Russia

[3]Drexel Plasma Institute, Drexel University, Philadelphia, PA

1 Introduction

The current investigation of the mechanisms of gaseous detonation initiation is related to the problem of the pulsed detonation engine (PDE) concept realization. The concept of detonation initiation through a gradient mechanism was theoretically introduced by Zeldovich [1] and, more recently, numerically studied in [2]. According to Zeldovich's work, an ignition delay time gradient formed due to a corresponding temperature gradient leads to the onset of a spontaneous combustion wave. The mixture first ignites at the point with the lowest delay and then propagates by spontaneous ignition with a velocity D_{sp} determined by the shape of the gradient. When D_{sp} falls into the interval between the speed of sound and D_{CJ}, the spontaneous wave can become coupled with the compression wave and thus evolve into a detonation wave through shock amplification and acceleration.

Relying on these results, Zhukov and Starikovskii carried out experiments on detonation initiation using discharge chambers with distributed electrode systems [3, 4]. It was found that detonation was initiated efficiently by such a distributed nanosecond discharge, strongly depending on the nitrogen dilution level and initial mixture pressure. To clarify the mechanisms leading to DDT promotion under non–equilibrium non–uniform excitation, a detonation tube with a single–cell discharge chamber has been assembled [5], which proved the feasibility of the gradient mechanism as well as its efficiency. The current paper focuses on further study of this mechanism with regard to its future application in pulsed detonation engines.

2 Experimental setup

The scheme of the four–cell Plexiglas discharge chamber is shown in Fig. 1. Each cell contains a pin–like high–voltage electrode (1) which is immersed into a 6.5 mm–diameter channel (2). The length of the channels is 150 mm. The four channels are led into a square detonation tube (2×2 cm) through a converging reducer (3). The diameter of the channels inside the reducer is 9 mm. The convergence angle is 24 deg. The diameter of the reducer outlet is 20 mm, which matches with the inlet of the detonation tube. The reducer is manufactured of aluminium and is grounded, serving as the ground electrode. The whole Plexiglas discharge section is also covered with grounded shield (4). The shield includes a

Correspondence to : arakitin@neqlab.com

longitudinal gap for visual observation of the processes inside one channel. Discharge propagation is also enhanced by four grounded plates (5) which are fixed into narrow slits inside the chamber between the discharge channels. The plates stretch along the whole chamber, increasing the capacitance of the electrode system and the transverse reduced electric field in the channels. In comparison to the single–cell geometry in [5], the volume of the excited mixture may be up to four times larger.

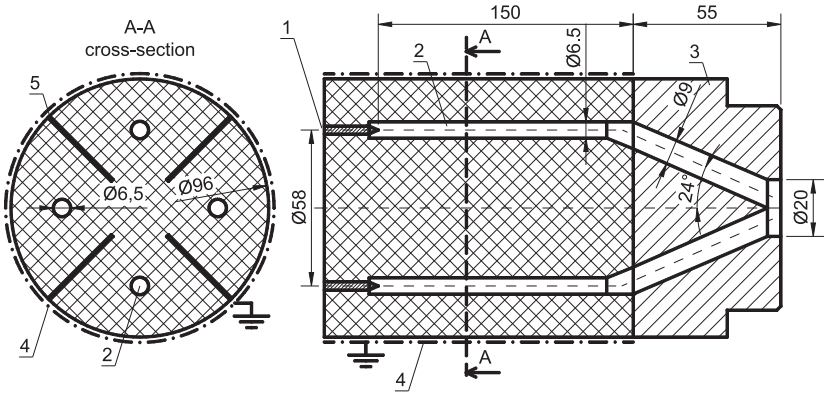

Figure 1: Four–cell discharge chamber: the scheme. (1) — high–voltage electrode, (2) — discharge channel with a diameter of 6.5 mm, (3) — converging reducer, (4) — coaxial grounded shield, (5) — grounded plates.

A set of infra–red sensors (IR) and pressure transducers (PT) was used in the DDT experiments. The sensors are positioned 80, 170, 260, and 305 mm from the discharge channel outlet and the reducer inlet. The experiments were carried out in two different mixtures: $C_3H_8 + 5O_2$ (undiluted) and $C_3H_8 + 5O_2 + 4N_2$ (40% nitrogen). The high–voltage pulse amplitude was 40—60 kV, the rise time was 20 ns, and the pulsewidth was 50 ns.

3 Ignition inside the four–cell discharge chamber and DDT

Under mixture pressure values in the range of 0.2—1 bar, the discharge developed as a streamer propagating in each of the channels. The energy input typically amounted to 0.2—0.3 J under these conditions. Under such low energy inputs only the gas in the region next to the high–voltage electrode was notably excited. The overall resuls based on the IR and PT data for the streamer mode in the undiluted propane–oxygen mixture are plotted in the x–t diagram in Fig. 2 (left figure). The negative position region corresponds to the discharge channel and, thus, to the ignition area. The data points in the channel were obtained with high–speed multi–frame ICCD imaging inside one of the channels.

All the traces show that a detonation wave was formed before the first sensor. The accelerating x–t trajectory of the combustion wave inside the discharge chamber points at the realization of the gradient mechanism. It is seen that the DDT time decreases with pressure rise under close energy input values. This is due to the similar dependency of ignition delay time upon mixture pressure. On the other hand, the DDT time also decreases with energy input rise. For a clear comparison, the data points for the experiment in a transient mode at 0.2 bar under 2 J of energy input are plotted in the same figure (blue squares in Fig. 2). Under an initial pressure of 0.2 bar, the arrival time of the detonation wave to the position of the first sensor decreased from 400 μs under the initiation energy of 0.35 J to 260 μs under 2 J. Another comparison can be made with detonation initiation by streamer discharge in the single–cell discharge chamber [5]. The x–t diagram for the case at 1 bar of initial pressure is also plotted in Fig. 2 as grey circles. The higher energy input of 2 J together with the smaller volume of the excited gas in the single–cell DC results in a slightly shorter delay than in the experiment in the four–cell DC at the same

initial pressure. However, the DDT distance is below 3 transverse tube sizes in all the tests in streamer mode. The increased initial pressure together with the gradient mechanism also allowed to obtain CJ detonation in the diluted mixture under energy inputs as low as 0.2—0.3 J. The results are presented in Fig. 2 (right figure) for three pressure values of 0.63, 0.8, and 1 bar. At 0.63 bar, the shock/flame velocity remained ∼1000 m/s, which corresponds to a fast deflagration mode. A CJ detonation wave was first observed at a minimum of 0.8 bar of initial pressure. The temporally resolved ICCD imaging confirmed the role of the gradient mechanism in detonation initiation. The spontaneous combustion wave again originated from the region next to the high–voltage electrode and then accelerated along the channel. However, it is seen that the spontaneous combustion wave only accelerates up to ∼800 m/s inside the discharge cell. The following transition into a detonation wave early on in the tube is most likely due to the focusing effect of the converging reducer. It is important that the combustion waves in each of the four discharge cells are formed simultaneously and under equivalent conditions. This is ensured by the nature of the nanosecond discharge, developing independently in each cell during the streamer phase.

At the initial pressure of 1 bar, the DDT pattern inside the tube was rather similar to that at 0.8 bar, the shock waves arriving at the first sensor simultaneously, whereas a shorter delay was expected under a higher pressure. The effect of pressure rise could be compensated by a lower energy input (0.2 J for 1 bar experiment compared to 0.3 J for the case at 0.8 bar) or by a slightly different discharge development which would alter the gradient shape. Additionally, an x–t diagram of the experiment at 1 bar in the same mixture in the single–cell DC ([5]) is plotted in the same figure for comparison (grey triangles). The data points are based on the IR data and correspond to the flame wave propagation. Even though the initiation energy was by an order of magnitude higher (2 J), only a deflagration wave with a velocity of 600 m/s was observed. Furthermore, in this case the shock wave propagated ahead of the flame wave with a slightly higher velocity. That resulted in a decoupling of the shock–flame complex and in an eventual deceleration of both waves.

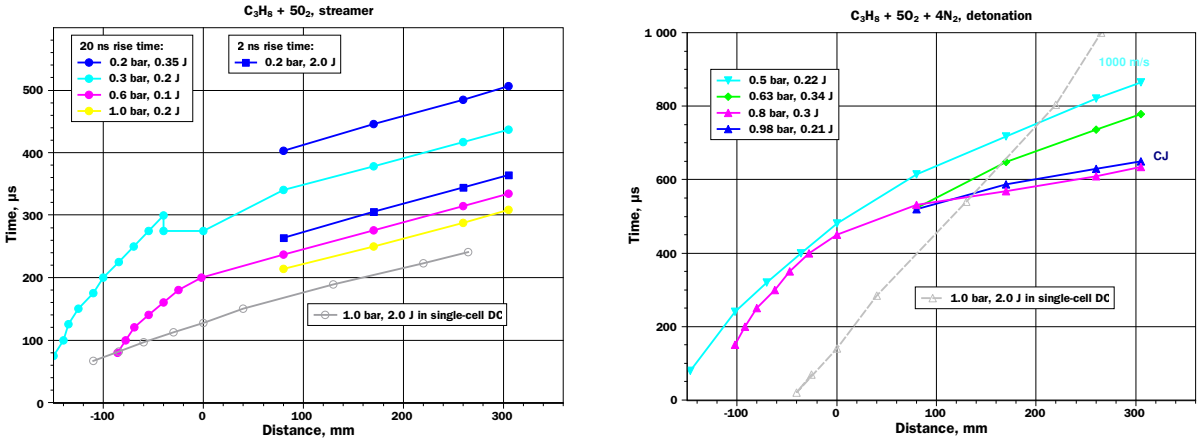

Figure 2: X–t diagrams of DDT at various pressures. Left: $C_3H_8 + 5O_2$. Right: $C_3H_8 + 5O_2 + 4N_2$.

4 Discussion and conclusions

A smooth square detonation tube with a transverse size of 20 mm has been assembled and used to study DDT mechanisms under initiation by high–voltage nanosecond discharges in all the experiments. Stoichiometric fuel–oxidizer mixtures were used at initial pressures from 0.2 to 1 bar. The diagnostics included pressure transducers, IR sensors, a back-current shunt, and an ultra–fast multi–frame ICCD camera.

A gradient mechanism of deflagration–to–detonation transition similar to that proposed by Zeldovich has been observed experimentally under streamer initiation in a four–cell discharge chamber. The four–cell geometry allowed to obtain streamer discharge under low amplitudes of the high–voltage pulse in a wide pressure range. Typical pulse energy input in the streamer mode was 0.2—0.3 J, while amounting to 1.9 J in the transient mode under low pressures. In an undiluted propane–oxygen mixture, detonation inside the tube was observed at pressures from 0.1 bar and higher. The discharge propagated as a streamer or as a transient streamer in this pressure range. The simultaneous use of the multi–frame ICCD camera in the discharge channel and of the combined infra–red/pressure diagnostics inside the tube allowed to observe the whole DDT pattern. Detonation was initiated through the gradient mechanism in all these cases. That resulted in extremely short DDT distances of less then 4 tube sizes (80 mm, minimal measurable distance in the experiment). The DDT times varied from 0.2 and 0.5 ms depending on the initial pressure and the energy input.

The second series of experiments was carried out in a less sensitive and less energetic mixture of propane–oxygen diluted with 40% of nitrogen. A fast deflagration wave with a propagation velocity of over 1000 m/s was observed at pressures of 0.5 and 0.63 bar. The gradient mechanism combined with the focusing effect of the converging reducer has been shown to be the governing one in these modes as well. The focusing of the four independently formed combustion waves is possible due to the nanosecond–scale rise time of the high–voltage pulse.

It is important to notice that no low–speed flame propagation modes have been observed: under all conditions and discharge propagation modes, the initial flame velocity in the discharge cells exceeded at least 600 m/s, even after significant ignition delay times as under 0.8 bar of initial pressure in Fig. 2. It follows from that that the initial flame propagation mode is one of a phase wave, rather than that of a conventional turbulent deflagration wave.

The achieved understanding of the gradient mechanism of detonation initiation, together with the expertise in high–voltage pulsed discharges, may now be applied to the design of air–breathing PDEs.

Acknowledgment

This research was partially supported by European Office of Aerospace Research and Development/ Civilian Research and Development Foundation (Project GAP RUP2–1512–MO–06).

References

[1] Y. B. Zeldovich, V. B. Librovich, G. M. Makhviladze, G. I. Sivashinskii, On the onset of detonation in a nonuniformly heated gas, J. Appl. Mech. Tech. Phys. 11 (2) (1970) 264–270.

[2] E. S. Oran, V. N. Gamezo, Origins of the deflagration–to–detonation transition in gas–phase combustion, Combustion and Flame 148 (1–2) (2007) 4–47.

[3] V. P. Zhukov, A. Y. Starikovskii, Effect of a nanosecond gas discharge on deflagration to detonation transition, Combustion, Explosion, and Shock Waves 42 (2) (2006) 195–204.

[4] V. P. Zhukov, A. E. Rakitin, A. Y. Starikovskii, Effect of high–voltage pulsed discharges on deflagration to detonation transition, Journal of Propulsion and Power 24 (1) (2008) 88–93.

[5] A. E. Rakitin, A. Y. Starikosvkii, Mechanisms of deflagration–to–detonation transition under initiation by high–voltage nanosecond discharges, Combustion and Flame 155 (2008) 343–355, doi:10.1016/j.combustflame.2008.05.019.