Effect of High-Voltage Pulsed Discharges on Deflagration to Detonation Transition in Gases

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Introduction

Contemporary research in the field of gaseous detonations is closely related to the realization of the pulsed detonation engine (PDE) concept. For direct detonation initiation an ignition source of considerable energy is required. When initiated by a lower energy source in a sufficiently long tube, a deflagration to detonation transition (DDT) may occur through flame front acceleration at a distance of several tens of tube diameters. Thus, one of the key issues is the reduction of DDT length and time in smooth detonation tubes under minimum energy of initiation.

Non-equilibrium plasma of high-voltage nanosecond gas discharge was used for simultaneous pre-excitation of the gas and ignition delay time and DDT length reduction in [1]. The calculations performed for hydrogen-air and methane-air mixtures showed that the ignition threshold shifted by 400 K under energy deposition of 0.4 J/cm^3. It was also shown that the typical time of chemical energy release had to be shorter than that of gas-dynamic processes for detonation wave formation. Thus, for DDT length reduction it is desirable that sonic speed and, hence, temperature be as low as possible. It is the case in non-equilibrium plasma of high-voltage nanosecond gas discharge in the form of a fast ionization wave (FIW) which efficiently produces active species in a bulk volume within a short period of time (see [2]). This kind of discharge is also promising for detonation initiation from the point of view of Zeldovich's gradient mechanism [3]. In the current work, three setups have been assembled to study detonation initiation by different kinds of high-voltage pulsed discharges.

Initiation by distributed non-equilibrium nanosecond discharge

The experimental setup used for study of detonation initiation by a distributed high-voltage nanosecond discharge is described in [4]. The experiments were carried out in a detonation tube with inner diameter of 140 mm. The discharge section mounted at one end of the detonation tube was a distributed electrode system consisting of 131 discharge cell placed over the cross-section of the tube [5]. Each discharge cell included a pin-like high-voltage electrode inside a quartz tube covered from the outside with grounded foil. The diameter of discharge cells was 5 mm, the interelectrode gap was 80 mm. The electrodes were fed with a 60 ns pulse with 12 ns rise time. Voltage amplitude ranged from 4 to 70 kV, the corresponding energy input ranged from 70 mJ to 14 J. Observation made with an ICCD camera with nanosecond temporal resolution (LaVision Picostar 12 HR) showed that in air at 1 bar and less the discharge developed quasihomogeneously over the cross-section, exciting the gas in a bulk volume and in a large portion of discharge cells. Flame front velocity was calculated on the basis of the voltage profiles of 5 IR sensors installed along the tube. Shock wave velocity was measured simultaneously by two

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schlieren sensors. The experiments in detonation initiation were carried out in different stoichiometric mixtures at initial pressures from 0.15 to 1 bar. The results of the experiments are presented in figure 1 in terms of the dependences of flame front propagation velocity 400 mm (∼3 calibers) away from the discharge chamber upon initial mixture pressure for different mixture compositions.

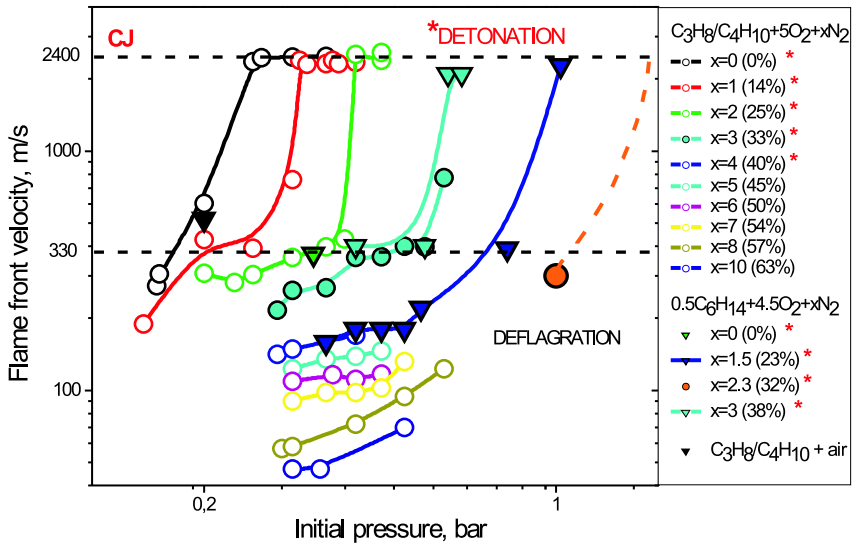

Figure 1: Flame front velocity dependence upon initial mixture pressure for different mixtures under ignition by a nanosecond discharge. C-J velocity is ∼2400 m/s for propane/butane mixtures (hollow symbols and solid lines) and ∼2100 m/s for hexane mixtures (solid symbols and dashed lines).

The DDT was registered 400 mm away from the discharge chamber or closer in all mixtures with nitrogen dilution level up to 38%. The energy input in these cases did not exceed 3 J. For undiluted stoichiometric propane-oxygen mixture, the DDT length and time amounted to 130 mm and 0.6 ms, respectively, under energy input of 70 mJ. This value of energy input corresponded to 4 J/m^2 of energy per unit cross-section. In $0.5C_6H_{14} + 4.5O_2 + 3N_2$ mixture (38% N_2), the DDT length under energy input of 3 J at initial pressure of 1 bar was 300 mm, the DDT time was 0.6 ms.

Initiation by localized microsecond spark discharge

Detonation initiation and flame propagation modes under microsecond initiation was studied in a detonation tube with inner diameter and length equal to 53 and 1000 mm, respectively. The geometry of the discharge chamber was analogous to the one used for nanosecond detonation initiation. The high-voltage electrode was a distributed electrode system consisting of 28 pins separated from each other and from the ground electrode by a ceramic insulator. Each pin formed a discharge cell with interelectrode gap of 50 mm. For shock and detonation waves velocity measurement, piezoelectric pressure transducers were used. Pulse parameters were the following: amplitude — 37 kV, width — 1–3 μs, rise time — ∼100 ns. The energy input in this case was limited by the energy stored in the generator, which was equal to 14 J. The ICCD imaging showed that in air at 1 bar a localized spark discharge formed after ∼50 ns. During the first 50 ns, a streamer phase was observed; the intensity of emission at this stage was extremely low. Homogeneous discharge phase was not observed at all in most of the discharge cells.

Experiments in detonation initiation by microsecond spark were carried out in two propane/butane mixtures ($C_3H_8/C_4H_{10} + 5O_2 + xN_2$ with x=0 and x=4) at initial pressures up to 1 bar. The results of

these experiments are presented in figure 2 (solid lines, solid symbols) in terms of dependences of shock wave velocity 600 mm away from the discharge chamber upon initial mixture pressure. The results are presented in comparison with the ones in the same mixtures obtained under initiation by the nanosecond discharge (dashed lines and hollow symbols). It is seen that in the case of the nanosecond discharge the DDT is observed at lower initial pressures, which indicates its essentially higher efficiency as a detonation initiator in comparison with the microsecond spark.

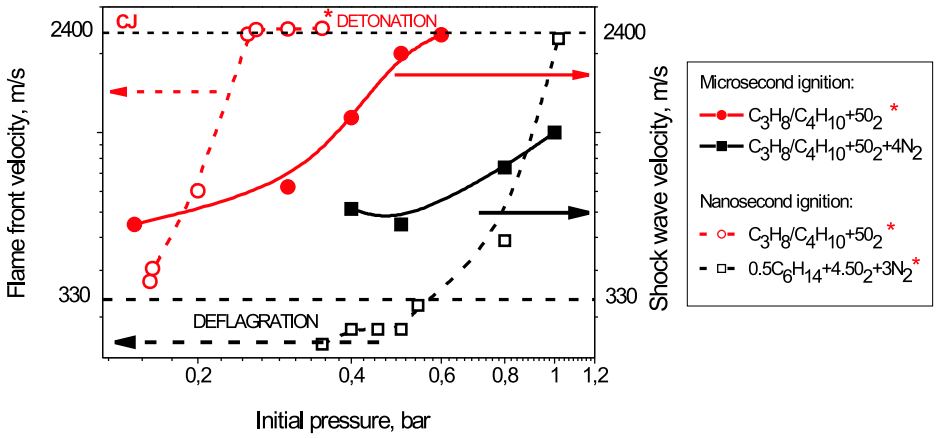

Figure 2: Flame front velocity dependence upon initial mixture pressure for different mixture compositions. Solid lines and solid symbols for microsecond initiation, dashed lines and hollow symbols for nanosecond initiation [4]. Same color corresponds to the same mixtures.

Initiation by nanosecond discharge in a single-cell geometry

For a detailed experimental study of deflagration to detonation transition, a detonation tube with a single-cell geometry of the discharge chamber and nanosecond initiation has been assembled (see Fig. 3). The discharge cell diameter was 6.5 mm, the interelectrode gap could be varied from 30 to 150 mm. The detonation tube mounted at the output of the discharge cell was of 20x20 mm square cross-section and was 300 mm long. A set of photodiodes and pressure transducers was installed in the sidewalls for accurate flame front and shock wave velocity measurements. Successful DDT was observed at 150 mm from the discharge chamber output at a minimum pressure of 0.3 bar under 160 kV pulse of 50 ns duration in stoichiometric propane-oxygen mixture; the DDT time did not exceed 200 μs. The ICCD imaging of the ignition and the DDT processes showed that the mixture ignited all over the discharge chamber volume within 5 μs after the discharge. The short ignition delay time was due to the high temperatures of the gas during the high-current phase of the discharge. The chemical energy stored inside the volume of the discharge chamber was comparable to the energy of direct detonation initiation for the case. This allowed the DDT to occur via a mechanism similar to the direct initiation of detonation. At the same time, the energy input in the discharge depended on the mixture density and composition and did not exceed 10 J. A successful detonation onset was also observed when no high-current phase of the discharge was observed, i.e. no discharge gap closure occurred, which was the result of a substantially lower amplitude of the high-voltage pulse ($\sim$50 kV). The energy input was also substantially lower in that case. This mode of discharge development and detonation initiation is under study at present.

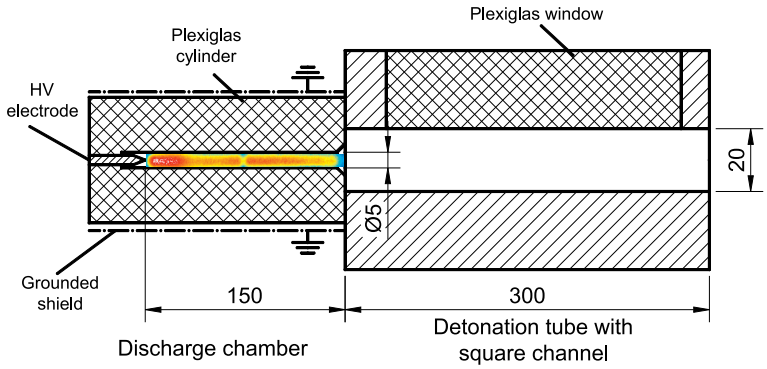

Figure 3: Scheme of detonation tube with single-cell geometry of the discharge chamber.

Conclusions

Under initiation by the distributed nanosecond discharge in a 140 mm diameter smooth detonation tube, a successful DDT was observed at 3 calibers from the discharge chamber in all the $C_3H_8/C_4H_{10} + 5O_2 + xN_2$ mixtures with N_2 concentrations up to 38%. The energy input did not exceed 3 J, the DDT time was less than 1 ms. Localized microsecond discharge was shown to be substantially less efficient in terms of detonation onset when compared with the distributed nanosecond discharge. A mechanism similar to direct initiation of detonation was realized in a single-cell geometry due to simultaneous ignition of the mixture over the volume of the discharge chamber under initiation energy less than 10 J. Effective detonation onset in the mode with no discharge gap closure and with low energy input also points at the possibility of Zeldovich's gradient mechanism realization.

Acknowledgments

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References

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