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Initiation of Gaseous Detonation by a Traveling Forced Ignition Pulse

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As assessed by Ya.B. Zel'dovich in [1], jet engines using detonation fuel combustion should be thermodynamically more efficient than engines operating on fuel deflagration. At the present time, the possibility of fuel combustion in periodically generated detonation waves (DWs) to produce thrust is being extensively studied [2]. One of the most challenging problems on the road to designing pulse detonation engines is to provide conditions for the reliable initiation of DWs in fuel–air mixtures over short distances on the order of 1 m.

Zel'dovich and Kompaneets in 1955 considered the problem of initiation of gaseous detonation by means of forced ignition by distributed external sources mounted along a channel with a fuel gas [3]. If the apparent velocity of the ignition pulse displacement is constant and equal to the velocity of detonation in the gas, a DW should eventually arise. Numerical calculations in [4–6] showed that a DW does emerge if the energy deposition is synchronous with a propagating shock wave (SW). It does not matter whether the energy is supplied by external sources or conditions for autoignition are set up in the gas. In this paper, we report on the first experimental proof of the idea put forward in [3].

In our experiments, we used a sealed smooth-walled tube 51 mm in diameter and 1.5 m in length. The tube consisted of a booster section 1 m long and a measuring section 0.5 m long. An electric discharger was placed at the end plane of the booster section. Beginning with cross section 1, at a distance of 26 mm from the end plane, additional electric dischargers were mounted along the booster section at intervals of 100 mm (cross sections 2, 3, etc.). The electric power supply of each discharger included a high-voltage capacitor. The discharge triggering signal came to the dischargers from a multichannel controller. This controller made it possible to specify in advance the triggering delay time for each of the dischargers. The discharge current duration was 100 μs. The tube was filled with a stoichiometric propane–air mixture up to a pressure of 1 atm. To measure wave dynamics, piezoelectric pressure transducers and ionization probes were used. For these transducers and probes, ports were designed into the tube along its full length at 100-mm intervals, the ports in the booster section being located in the same cross sections as the dischargers. The diagnostics system includes oscilloscopes, frequency meters, and a PC. The experiments were run with the aim to select the triggering times of successive discharges in such a way as to provide a maximum amplification of a weak primary SW propagating along the tube and to initiate a DW. The primary SW arose on triggering of the end-plane discharger and the discharger in cross section 1.

Figure 1 shows the space–time diagram of our experimental results. The voltage on the battery of capacitors was 2500 V. The capacitance of the end-plane discharger was 200 μF; the capacitance of the discharger in cross section 1 was 400 μF, and the capacitance of each of the remaining dischargers was 100 μF. The dashed lines marked as 342 m/s and 1800 m/s correspond to the characteristic values of the sound velocity and the Chapman–Jouguet detonation velocity in the fuel gas. The black circles correspond to the experimental optimal triggering times for the dischargers, and the white circles correspond to the time of the arrival of the SW at the corresponding cross section. When two, three, etc., up to seven, dischargers were switched on in the same experiment, detonation in the tube was not observed. Only when eight dischargers were successively triggered in the same experiment, did the primary SW velocity gradually increase from 850 ± 12 to 1770 ± 25 m/s; i.e., beginning with cross section 7 or 8 (at a distance of 0.6–0.7 m from section 1), a DW arose in the booster section. In the measuring section, the DW propagated with a constant velocity of 1700–1800 m/s, which was not impacted by additional discharges, as followed from the records of the pressure transducers and ionization probes. Figure 2 shows the records of pressure at cross sections 11 and 13 (at a distance of 1.0–1.2 m from cross section 1). The mean DW velocity over this segment (200 mm) was 1745 ± 25 m/s. To produce a DW, the dischargers should be switched on ahead of the arrival of an SW at the corresponding cross section of the tube. The required ignition advance was

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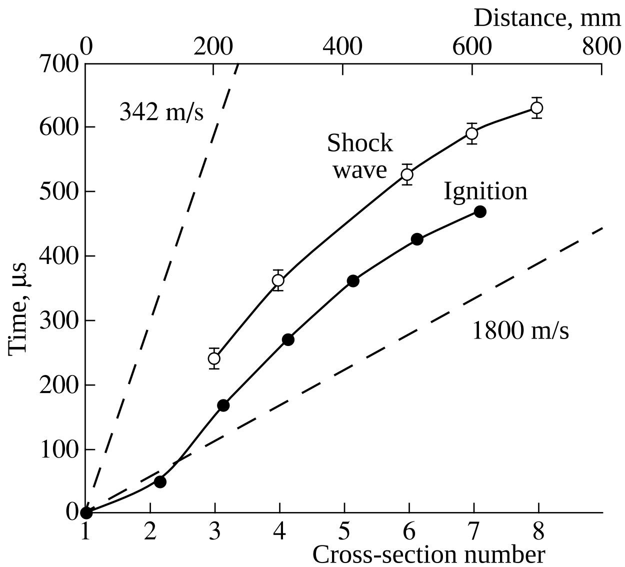

Fig. 1. Experimental *x–t* diagram of SW amplification in a stoichiometric propane–air mixture. Detonation arises in cross section 7.

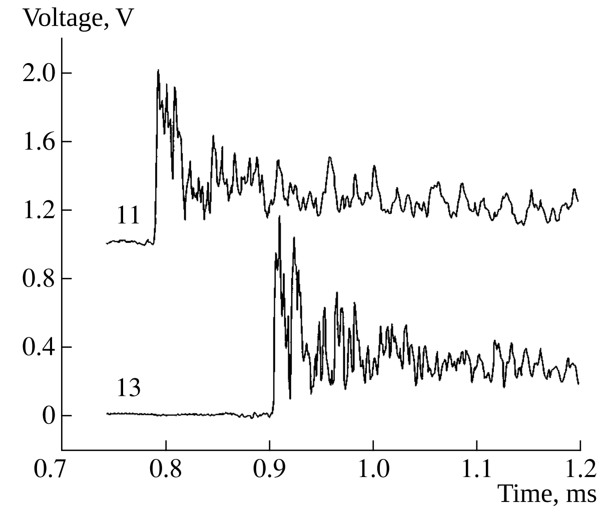

Fig. 2. Pressure records for cross sections 11 and 13.

80–100 μs, which correlated with the discharge current duration.

In addition, the sensitivity of the process to small deviations of the discharger triggering delay time was studied. The startup of the discharger in cross section 4 with a delay of 320 μs instead of the optimal value 270 μs (Fig. 1) resulted in the failure of DW initiation, other conditions being equal. The same result was obtained when the triggering time of the dischargers in cross sections 5, 6, and 7 deviated from the corresponding optimal value by 50 μs. These facts point to the resonance character of the process.

Thus, our experiments demonstrated that detonation in a fuel gas can be initiated by a traveling forced ignition pulse, which is formed by successively triggering several dischargers with thoroughly adjusted delay times. This mode of initiation of detonation differs significantly from conventional methods, direct initiation or deflagration-to-detonation transition. In direct initiation by one source, detonation arises after the stage of attenuation of a very strong primary SW; therefore, the major part of the energy of the initiator and fuel gas is lost for compression, heating, and thermal dissociation of reaction products behind the SW. It takes a distance of 1.0–1.5 m for a self-supporting planar detonation front to arise [7]. For the deflagration-to-detonation transition to take place, the flame should be accelerated to an apparent velocity on the order of 1000 m/s. To attain such a velocity in a propane–air mixture, a smooth-walled tube more than 260 diameters in length [8] or a tube with turbulizing elements in the form of regular obstacles more than 60 diameters in length [9] is required. In this mode of detonation initiation, some energy is also lost for compression and heating of a large volume of combustion products.

When a traveling ignition pulse is used, the energy of the fuel gas is completely supplied to the shock front, so that the SW is rapidly amplified up to the intensities sufficient for initiation of detonation. To obtain detonation at the shortest distances, the ignition pulse should move with acceleration. In our experiments, the DW arose at distances of 0.6–0.7 m, corresponding to 12–14 tube diameters. The primary SW was relatively weak and had the velocity (over the distance between cross sections 2 and 4) $M \cong 2.0–2.5$. The overall nominal energy of electric discharges for the conditions in Fig. 1 is 1.68 MJ/m^2, which is lower than the value 3 MJ/m^2 reported in [7] for the critical energy of detonation initiation by a flat charge of a high explosive. Inasmuch as the efficiency of conversion of the electric discharge energy into the SW energy is low compared to the high-explosive efficiency (as a rule, 10% [10]), the actual total critical initiation energy appears to be much smaller.

Based on our findings, we draw three conclusions that allow us to treat this method of initiation of a DW as a candidate for use in pulse detonation engines. First, it provides acceptable distances before the appearance of a DW in a smooth-walled tube. Second, the energy of each of the individual ignition sources is much smaller than the critical energy required for direct initiation of detonation by one source. Third, the resulting total energy of ignition sources appears to be considerably lower than the critical energy of direct initiation of detonation.

REFERENCES

1. Zel'dovich, Ya.B., *Zh. Tekh. Fiz.*, 1940, vol. 10, no. 17, pp. 1453–1461.
2. Frolov, S.M., *Tyazh. Mashinostr.*, 2003, no. 9, pp. 19–22.

3. Zel'dovich, Ya.B. and Kompaneets, A.S., *Teoriya detonatsii* (Theory of Detonation), Moscow: Gostekhteorizdat, 1955.
4. Zel'dovich, Ya.B., Librovich, V.B., Makhviladze, G.M., and Sivashinskii, G.I., *Prikl. Matem. Teoret. Fiz.*, 1970, no. 2, pp. 76–84.
5. Zel'dovich, Ya.B., Gelfand, B.E., Tsyganov, S.A., *et al.*, *Progress Astronaut. Aeronaut.*, 1988, vol. 114, pp. 99–123.
6. Lee, J.H.S. and Moen, I.O., *Progr. Energ. Combust. Sci.*, 1980, vol. 6, no. 4, pp. 359–389.
7. Borisov, A.A., *Gaseous and Heterogeneous Detonations: Science to Applications*, *Science*, Moscow: ENAS, 1999, pp. 3–24.
8. Veyssiere, B., Kerampran, S., Proust, C., and Gilles, S., *Proc. XIX ICDERS*, Hakone, 2003, Paper no. 154, ISBN 4-9901744-1-0.
9. Santoro, R.J., Lee, S.-Y., Conrad, C., *et al.*, *Advances in Confined Detonations*, Moscow: Torus Press, 2002, pp. 243–254.
10. Nettleton, M.A., *Gaseous Detonations*, London: Chapman and Hall, 1987.