COMBUSTION CHAMBER WITH INTERMITTENT GENERATION AND AMPLIFICATION OF PROPAGATING REACTIVE SHOCKS

S. M. Frolov, V. Ya. Basevich, and V. S. Aksenov

N. N. Semenov Institute of Chemical Physics
Russian Academy of Sciences
Moscow, Russia

Introduction

There exist several design concepts of a liquid-fueled air-breathing pulse detonation engine (PDE) described in detail in the recent review [1]. One of the concepts has been suggested and studied in [2–5] and is referred to as the shock-booster concept. It implies that the propagating primary shock wave (SW) is accelerated by in-phase ignition of the reactive mixture stimulated by external ignition sources. In this concept, both the intensity of the primary SW and spatial distribution of the postshock parameters determine the demands to the external ignition sources in terms of their power and activation timing required for the most efficient acceleration of the primary SW to detonation. The objective of this study is the experimental evaluation of feasibility of the shock-booster concept for PDE applications.

Experimental Setup

The schematic of the setup is shown in Fig. 1. The main elements of the setup are the 28-millimeter diameter tube (labeled *3* in Fig. 1) with two electric dischargers ED1 and ED2, air-assist atomizer *1*, Shchelkin spiral *2*, tube coil, and transition cone to a 41-millimeter diameter tube followed by the abrupt transition from a 41- to a 52-millimeter diameter tube. Air is fed to the atomizer from an air receiver of 40-liter volume. Liquid fuel is fed to the atomizer from a pressurized fuel tank. Both air

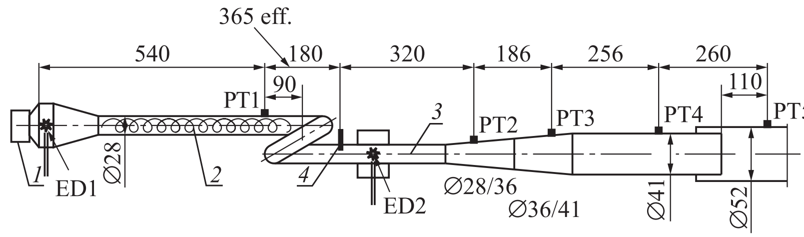

Figure 1 Schematic of the experimental setup. ED1 and ED2 stand for electric dischargers. PT1 to PT5 stand for piezoelectric pressure transducers. Dimensions in mm. *1* — atomizer, *2* — Shchelkin spiral, *3* — tube, and *4* — discharge activation probe

and fuel supply can be either continuous or intermittent. The fuel used in all the experiments reported herein is liquid *n*-hexane.

The design and main characteristics of the atomizer and dischargers are the same as reported elsewhere [3–5]. The characteristic duration of the discharge current in dischargers ED1 and ED2 is 25 μs. In the experiments, the discharger ED1 was used for generating the primary SW. The discharger ED2 was used to accelerate the primary SW to the detonation intensity. To provide precise synchronization of the triggering time of the discharger ED2 with the primary SW arrival at its position, a special discharge activation probe (labeled *4* in Fig. 1) was used. The probe triggered the time-delay circuit in a special digital controller, which, in its turn, triggered the discharger ED2. The probe was mounted at a distance of 90 mm upstream from the position of the discharger. The rated electric energy deposited by the dischargers was controlled by varying their capacitances C_1 and C_2 and voltage U and was determined as $E = E_1 + E_2 = 0.5CU^2$, where $C = C_1 + C_2$. The maximal voltage in the experiments did not usually exceed 2000 V. After a discharge, the residual voltage of the capacitors did not exceed 400 V, i.e., the residual energy was less than 4% of the rated energy E. The error in determining the capacitor voltage, $\Delta U/U$, was estimated as less than 1%. The uncertainty in the C_1 (or C_2) value was also less than 1%. Thus, the uncertainty in determining the energy E_1 (or E_2), calculated as $\Delta E_1/E_1 = \Delta C_1/C_1 + 2\Delta U/U$, did not exceed 3% at a voltage of 2000 V. Taking into account the residual energy in the capacitor, the maximal error in determining the E_1 (or E_2) value based on the formula given above did not exceed 7%.

The atomizer provided the flow rate of air of about 30 g/s and very fine spraying of liquid fuel with a mean arithmetic diameter of about 5–10 μm. Measurements of the flow structure in the setup indicate that the discharger ED1 was located in the two-phase flow region during the experiments. When working with liquid n-hexane, the discharger ED2 was located in a gas-phase flow region due to fast evaporation of n-hexane. Note that the measurements without ignition revealed the existence of the liquid fuel film deposited on the inner tube wall up to the tube coil. The initial temperature of air and liquid fuel was 293 ± 4 K. In the course of the experiments, the tube temperature varied from 293 ± 4 K at the beginning of the run and did not exceed 310 K at the end of the run. The initial air pressure in the tube was 0.1 MPa. Fuel consumption was determined by measuring fuel level in the fuel tank and encountered several experimental runs at similar initial conditions. Air consumption was calculated based on the pressure difference in the air receiver before and after the runs. The mean equivalence ratio in the runs with detonation initiation was 1.3 ± 0.1, that is the fuel-air mixture was always fuel rich. This effect is attributed to the partial deposition of the injected fuel on the inner wall of the tube.

The Shchelkin spiral is 460 mm long and is made of steel wire 4 mm in diameter with a pitch of 18 mm. The tube coil introduces expansive and compressive surfaces for the propagating primary SW and the interactions between various wave systems promote SW amplification in the reactive medium. The effective length of the coil measured along the tube axis is 365 mm.

The transition cone is used to gradually transition the detonation from the 28-millimeter diameter tube to a larger tube 41 mm in diameter. The annular gap between the latter tube and the main detonation chamber 52 mm in diameter is designed to be used for supplying the fuel–air mixture to the PDE.

To measure pressure histories in various sections of the setup and to determine the corresponding SW propagation velocity, five piezoelectric pressure transducers PT1 to PT5 (see Fig. 1) were used. The mean velocity of the shock and detonation waves was calculated using the formula $V = X/\Delta t$, where X is the length of the measuring segment and Δt is the time interval determined from the records of the pressure transducers. The systematic error in determining X was ± 0.5 mm. The time interval Δt was determined at the half-amplitude levels of the pressure-transducer signals. Due to the finite dimensions of the sensitive elements of the transducers (8 mm), the duration of the shock and detonation front registration was not less than 3 μs. The characteristic sampling time of each measuring channel was 1.2 μs which allowed the resolution of the wave front with 2 to 3 pixels. Thus, an uncertainty in determining the arrival time at the position of the sensitive element did not exceed ± 1.2 μs, and therefore the time interval Δt was determined with an uncertainty of ± 2.4 μs. The detonation velocity in the n-hexane–air mixture is at the level of 1700–1800 m/s. Hence, the maximal error in determining the time interval Δt was about $\pm 2\%$ at the shortest measuring segment and the maximal error in determining the detonation velocity at this measuring segment did not exceed 2.5%. The SW velocities in the experiments were smaller than the detonation velocity. Therefore the error of determining the SW velocity was smaller than that for the detonation velocity.

Results and Discussion

Several series of experiments have been conducted. In the first series, the performance of the setup was tested in a single-pulse mode with one discharger (ED1). In the second, multipulse experiments with one discharger (ED1) were made. In the third, experiments with two successively triggered dischargers (ED1 and ED2) were conducted in a single-pulse mode. Finally, multipulse operation of the setup with two successively triggered dischargers was checked. Some results of the tests are described below.

Single-Pulse Experiments with One Discharger. Figure 2 shows the results of experiments in terms of the dependencies of the SW propagation velocity, V, vs. the rated energy, E_1, of the discharger ED1.

At the ignition energy E_1 ranging from 32 to 132 J, a detonation was detected at tube segments PT2–PT3 and PT3–PT4 in some experimental runs. Detonation initiation was accidental with a probability of about 50%. For example, Figs. 3a and 3b show the pressure records in two runs with eventually identical initial conditions and $E_1 = 64$ J.

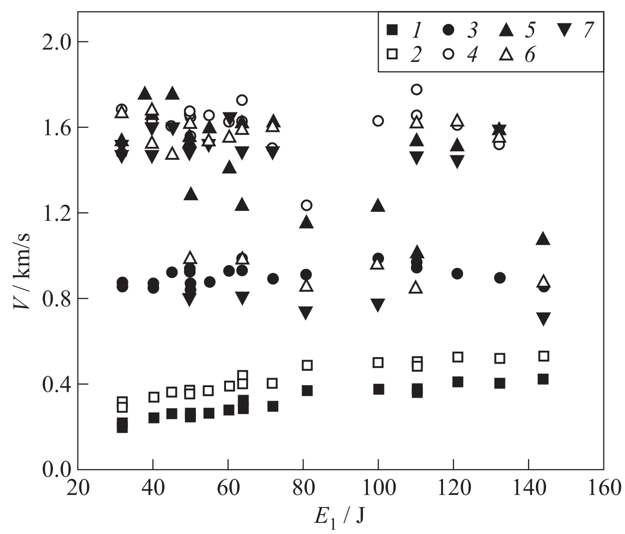

Figure 2 Measured dependence of the mean SW velocity V at different measuring segments of the tube vs. the ignition energy E_1: *1* — ED1–PT1, *2* — ED1–Probe, *3* — PT1–Probe, *4* — Probe–PT2, *5* — PT2–PT3, *6* — PT3–PT4, and *7* — PT4–PT5

Clearly, pressure transducers PT2, PT3, and PT4 register a detonation wave in Fig. 3*a*, whereas in Fig. 3*b*, the detonation registered by the pressure transducer PT2 decays. This effect can be attributed to uncontrolled differences in fuel spraying conditions in the two runs. The spikes on the control channel (CC) records at time instants of about 2.05 (Fig. 3*a*) and 2.3 ms (Fig. 3*b*) correspond to the probe-generated signal.

As seen from Fig. 1, the mean SW velocity at the segments ED1–PT1 and ED1–Probe increases gradually with the ignition energy and attains the value of 420 and 530 m/s, respectively, at $E_1 = 144$ J. At the pressure transducer PT1, the lead front of the pressure wave is smeared at all ignition energies tested. The mean SW velocity in the tube coil (segment PT1–Probe) varies from 840 to 990 m/s and nearly independent of the ignition energy in the range from 32 to 144 J. Note that energy requirements for detonation initiation in the setup of Fig. 1 without tube coil are considerably higher and attain a value of about

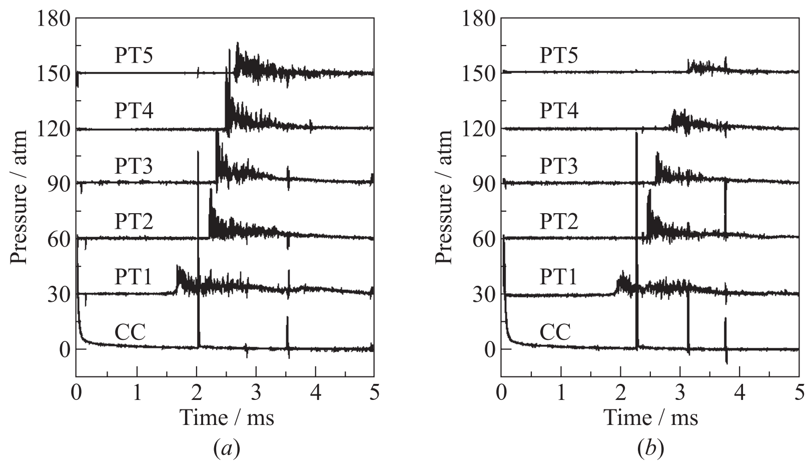

Figure 3 Pressure records at pressure transducers PT1 to PT5 in two runs with $E_1 = 64$ J: (a) detonation, and (b) no detonation. CC stands for the control channel record

1 kJ. Thus, the use of the tube coil appeared to be crucial for decreasing the initiation energy.

Multipulse Experiments with One Discharger. Figure 4 shows the mean velocities at different measuring segments of the setup in the multipulse operation mode at a frequency of 1.5 Hz as a function of the pulse number. In the run of Fig. 4, the rated energy of the discharger ED1 was about 55 J ($U = 2100$ V, $C_1 = 25$ μF) per pulse. The mean velocity of the pressure wave at the segment ED1–Probe is about 300–350 m/s and varies insignificantly from pulse to pulse. At other measuring segments, the detonation wave was detected in six of total twelve pulses, substantiating the finding in the single-pulse experiments as to the accidental character of the detonations. The detonation wave propagation velocity varies from 1510 to 1760 m/s.

Single-Pulse Experiments with Two Dischargers. As the experiments with one electric discharger (ED1) showed poor reproducibility

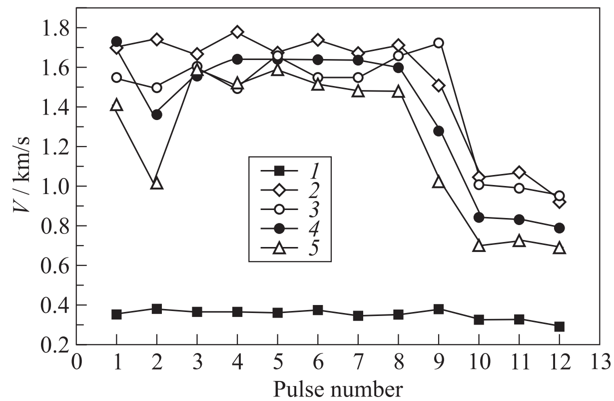

Figure 4 Multipulse operation of the setup of Fig. 1 with a single electric discharger ED1. Symbols show pulse-to-pulse variation of the mean velocity of the pressure wave at different measuring segments of the setup. Operation frequency is 1.5 Hz. The ignition energy is 55 J per pulse: *1* — ED1–Probe, *2* — Probe–PT2, *3* — PT2–PT3, *4* — PT3–PT4, and *5* — PT4–PT5

of detonations in single-pulse and multipulse operations of the setup, the second discharger (ED2) was additionally used to improve the performance. In the experimental series with single pulses, the capacitances of the dischargers, C_1 and C_2, voltage U, and the time delay $\Delta\tau$ of the second discharger triggering relative to the probe activation were varied. The time delay $\Delta\tau$ was preset in the digital controller prior to each run. When the total rated energy E of the dischargers exceeded 130 J, the detonation was reliably and reproducibly initiated at $\Delta\tau$ ranging from 40 to 80 μs. At $\Delta\tau$ values beyond this range, the detonation initiation process, if detected, was not reproducible. Figure 5 shows the example of pressure records relevant to this experimental series. In addition to the record of the CC and five records of pressure transducers PT1 to PT5, the voltage curve V2 for the second discharger is plotted to identify the timing of discharge triggering after the signal generated by the probe (a strong spike at the CC record). The drop of the voltage coincides with the second spike at the CC record. The time interval between the spikes corresponds to the triggering delay time $\Delta\tau$ preset in the controller.

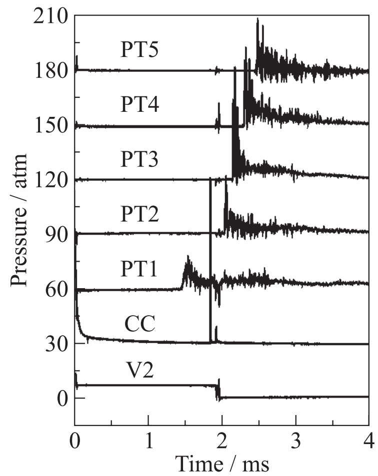

Figure 5 Pressure records relevant to the single-pulse operation of the setup with two successively triggered dischargers ED1 and ED2 at a total rated energy of $E = 135$ J ($C_1 = 50$ μF, $C_2 = 25$ μF, $U = 1900$ V, and $\Delta\tau = 80$ μs). V2 curve stands for the voltage record at the discharger ED2

Multipulse Experiments with Two Dischargers. Figure 6*a* shows the mean velocities at different measuring segments of the setup in the multipulse operation mode with two dischargers at a frequency of 2 Hz as a function of the pulse number. In the run of Fig. 6*a*, a total detonation initiation energy of two dischargers is 132 J ($U = 2300$ V, $C_1 = C_2 = 25$ μF) and $\Delta\tau = 80$ μs.

The mean velocity at the segments PT2–PT3, PT3–PT4, and PT4–PT5 ranges from 1500 to 1800 m/s. Thus, the second discharger triggered at a properly chosen time serves as an efficient means for detonation initiation control. Decrease in the total initiation energy to 121 J by decreasing the voltage from 2300 to 2200 V, other conditions been equal ($C_1 = C_2 = 25$ μF, $\Delta\tau = 80$ μs), resulted in the marginal multipulse operation mode of the setup. This mode is characterized with a sort of regular detonation go–no go pulses. The propagation velocity of the pressure waves in this run oscillates in the range from 800 to 1700 m/s.

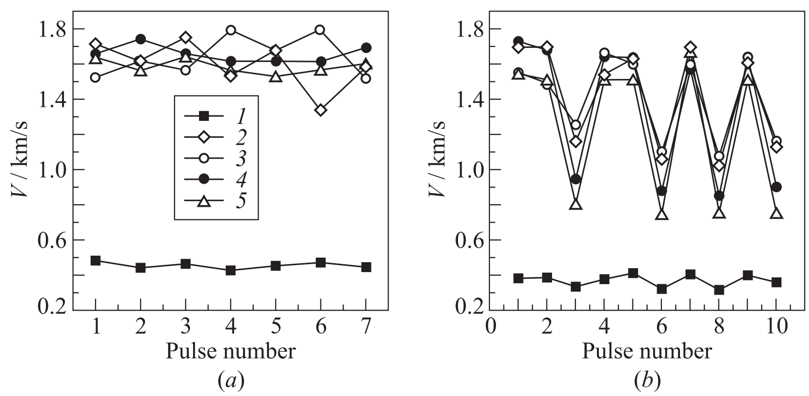

Figure 6 Multipulse operation of the setup of Fig. 1 with two electric dischargers. Symbols show pulse-to-pulse variation of the mean velocity of the pressure wave at different measuring segments of the setup. Operation frequency is 2 Hz. Total ignition energy per pulse is (*a*) 132 J and (*b*) 121 J: *1* — ED1–Probe, *2* — Probe–PT2, *3* — PT2–PT3, *4* — PT3–PT4, and *5* — PT4–PT5

Concluding Remarks

The results of the experimental studies aimed at evaluating the practical feasibility of the shock-booster PDE concept are presented. To reduce the initiation energy of an n-hexane spray detonation, a 28-millimeter tube transitioning via a conical and abrupt transition sections to a 52-millimeter tube was used. A powerful electric discharger utilized previously for generating a primary SW [2–5] was replaced by a primary SW generator comprising a relatively low-energy (50–60 J) electric discharger, Shchelkin spiral, and tube coil. A second discharger was mounted at the exit of the tube coil and was activated in phase with the primary SW arrival at its position. Due to interactions between various wave systems in the tube coil formed at expansive and compressive surfaces, the total critical energy of detonation initiation with two successively triggered dischargers was decreased to about 100 J, i.e., by an order of magnitude as compared with the energy ($\sim$ 1 kJ) required for the direct initiation of the n-hexane spray detonation in the straight 28-millimeter diameter smooth-walled tube by a single electric discharger. The other important advantage of the modified configuration of the detonation tube is the relatively low sensitivity of the detonation initiation process to the triggering time delay $\Delta\tau$ of the second discharger as compared to the previous configurations without the Shchelkin spiral [2–5]. This effect is attributed to the transformation of the pressure profile in the primary SW from the 'triangular' shape in a smooth-walled tube to a nearly stepwise shape in a tube with the spiral. These two findings make the shock-booster concept of the PDE feasible for practical applications. Multipulse 2-hertz operation of the setup in the detonation mode was successfully demonstrated with the energy requirements of about 132 J per pulse. It has been shown that the second discharger triggered at a properly chosen time can serve as an efficient means for detonation initiation control.

Acknowledgments

This work was partly supported by the Russian Foundation for Basic Research and the U.S. Office of Naval Research.

References

1. Roy, G. D., S. M. Frolov, A. A. Borisov, and D. W. Netzer. 2004 (in press). Pulse detonation propulsion: Challenges, current status, and future perspective. *Progress Energy Combustion Sciences*.
2. Frolov, S. M., V. Ya. Basevich, V. S. Aksenov, and V. S. Polikhov. 2003. Detonation initiation by controlled triggering of electric discharges. *J. Propulsion Power* 19(4):573–80.
3. Frolov, S. M., V. Ya. Basevich, V. S. Aksenov, and V. S. Polikhov. 2003. Initiation of confined spray detonation by electric discharges. In: *Confined detonations and pulse detonation engines*. Eds. G. Roy, S. Frolov, R. Santoro, and S. Tsyganov. Moscow, Russia: TORUS PRESS. 157–74.
4. Frolov, S. M., V. Ya. Basevich, V. S. Aksenov, and S. A. Polikhov. 2003. Initiation of pulse detonation in sprays by means of successively triggered electric discharges. *16th ONR Propulsion Meeting Proceedings*. Eds. G. D. Roy and A. Gundersen. University of Southern California, Los Angeles. 162–67.
5. Frolov, S. M., V. Ya. Basevich, V. S. Aksenov, and S. A. Polikhov. 2004. Detonation initiation in liquid fuel sprays by successive electric discharges. *Doklady Physical Chemistry* 394. Part 2:39–41.