Liquid-Fueled PDE with Externally Driven Shock-to-Detonation Transition

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Experimental studies aimed at diminishing the initiation energy of *n*-hexane spray detonation in a 28-millimeter tube by using two successively triggered electric dischargers, Shchelkin spiral, and tube coil are presented. As a result of the setup optimization, the critical initiation energy of *n*-hexane spray detonation was decreased by an order of magnitude to a value of 100 J. A liquid-fueled air-breathing PDE prototype comprising a 28-millimeter diameter predetonator tube and a 52-millimeter diameter main chamber with a total length of 1.8 m was fabricated and tested. Multipulse operation of the PDE prototype in the detonation mode was successfully demonstrated.

Introduction

The objective of the study is to further evaluate and experimentally realize the shock-booster concept of the pulse detonation engine (PDE) based on the findings reported in [1-5]. The concept implies that a relatively weak primary shock wave created by an ignition source is accelerated to a detonation in the course of its propagation along the PDE tube by the externally stimulated chemical energy deposition closely behind the lead shock front. In [1-5], external stimulation of chemical reactions behind the propagating primary shock wave was performed by using electric dischargers activated shortly (within 10–50 μs) after shock wave arrival at the discharger position.

The tests with two successively triggered dischargers [3-5] resulted in the following main findings: (1) there exist resonant conditions for successive triggering of two dischargers that have to be met for detonation initiation; (2) the minimal total detonation initiation energy is lower than that required for direct detonation initiation by a single discharger; and (3) the detonation peninsula at the “initiation energy vs. triggering time delay” plane is very narrow and indicates the necessity of careful synchronization of successive discharge triggering.

It has been shown that various means can be used to considerably decrease the initiation energy of spray detonation while keeping the predetonation distance and time both feasible for PDE applications. In the studies reported so far [1-5] multipulse *n*-hexane spray detonation was demonstrated in short (about 1 m long) smooth-walled tubes 28 and 52 mm in diameter with two successively triggered electric dischargers at minimal energy requirements of about 900 J per pulse in a 28-millimeter tube. As this energy level is still large, further studies were conducted to decrease it. The results presented in this paper indicate that the detonation initiation energy can be drastically decreased to a level of 100 J per cycle by introducing proper modifications in the detonation tube configuration.

Generation of a Primary Shock Wave with a Weak Igniter and Shchelkin Spiral

In the basic experimental setup presented in [5], the air-assist atomizer used for spraying liquid *n*-hexane in air provides a highly turbulent two-phase reactive flow in a PDE tube. Ignition of the flow with a powerful discharge results in the generation of a primary shock wave followed by the turbulent flame. Earlier experimental results obtained for single-discharge detonation initiation in a 52-millimeter diameter tube [3–5] indicate that the propagation velocities of both the lead shock wave and flame front are nearly independent of the discharge energy once the latter is less than about 50% of the critical initiation energy of detonation, $E_{\rm cr}$. This implies that the turbulence generated by the air-assist atomizer could play the important role in the primary shock generation at the discharge energies less than about $0.5\,E_{\rm cr}$. At higher discharge energies, flame propagation is increasingly affected by the discharge-generated shock wave. In view of it, enhancement of turbulence produced by the atomizer could potentially be used for decreasing the discharge energy required for a powerful primary shock wave to form.

To check this implication, a special experimental study has been performed in a 28-millimeter diameter tube with the Shchelkin spiral and two dischargers. The schematic of the experimental setup is shown in Fig. 1. The length of the spiral was 460 mm. The spiral was made of steel wire 4 mm in diameter and had an 18-millimeter pitch. The design and main characteristics of the atomizer and discharger ED1 are the same as reported elsewhere [3-5]. Note only that the mean arithmetic diameter of *n*-hexane drops produced by the

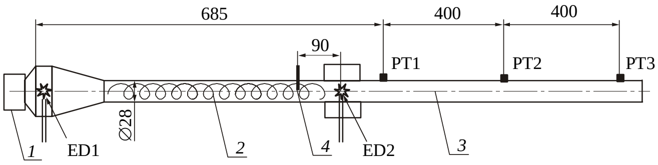


Figure 1: Detonation tube with the Shchelkin spiral between two dischargers: *1* — liquid fuel atomizer, *2* — Shchelkin spiral, *3* — tube, and *4* — discharge activation probe, ED1 — first discharger, ED2 — second discharger, PT1, PT2, and PT3 stand for pressure transducers. Dimensions in mm

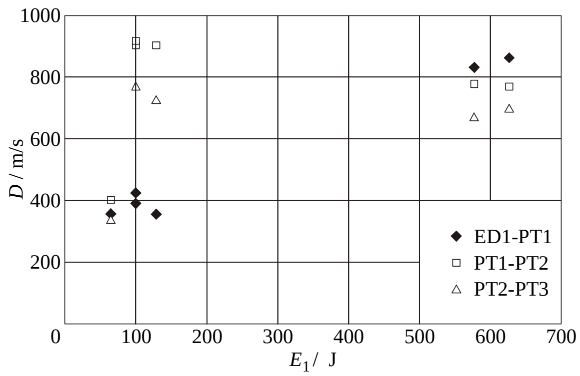


Figure 2: Measured shock wave velocities at various segments of the detonation tube of Fig. 1 depending on the energy of the first discharger ED1

atomizer is about 5–6 μm. Figure 2 shows the results of tests in terms of the primary shock wave velocity D vs. discharge energy E_1 dependency when only one discharger (ED1) was triggered in the run. The discharge energy was calculated based on the discharger voltage U and capacitance C_1 as $E_1 = 0.5C_1U^2$. At discharge energies less than 100 J, the propagation velocity of the primary compression wave is close to the sound speed in the initial mixture. Shock waves do not form. Increasing the discharge energy to 100–128 J results in the formation of a shock wave with a propagation velocity of about 910 m/s at the segment between the pressure transducers PT1 and PT2 and 770 m/s at the segment between PT2 and PT3. At the segment ED1–PT1, the propagation velocity of the arising shock waves is close to the sound speed. At the discharge energies of 576–625 J, the maximal shock wave velocity at the segment ED1–PT1 is 874 m/s. At the segments PT1–PT2 and PT2–PT3, the shock velocity decreases by 80 and 100 m/s, respectively. At high discharge energies, shock waves propagate at nearly constant velocity in the tube section with the spiral insert (‘spiral section’ for short).

Clearly, at the discharge energies of 100–128 J, the shock waves amplify most efficiently — from nearly the sound speed to about 910 m/s — in the spiral section. These values of the discharge energy can be treated as optimal for the tests with the Shchelkin spiral.

Detonation Initiation with Two Dischargers Separated by the Shchelkin Spiral

A shock wave generated by the first discharger ED1 and traveled through the spiral section can be further amplified to detonation intensities by the properly tuned triggering of the second discharger, ED2 (see Fig. 1) mounted downstream from the spiral section. This idea was tested on the setup of Fig. 1. The major energy was deposited in the second discharger ED2. Its design and main characteristics have been reported elsewhere [3-5]. Due to the fact that in the case with the spiral section the shock arrival time to the second discharger varied within the wide range — from 1400 to 2000 μs — a special discharge activation probe (labeled *4* in Fig.1) was used to provide the precise synchronization of the second discharger triggering time with the primary shock wave arrival. The probe was made of tungsten wire 0.8 mm in diameter and had a form of a rectangular frame 6x10 mm size positioned at the tube axis. The probe triggered the time-delay circuit in the digital controller, which, in its turn, triggered the second discharger. The probe was mounted at a distance of 90 mm upstream from the position of the second discharger. Electrical conductivity of the medium behind the propagating shock wave was sufficient for activating the probe with the saturation current of about 1 mA.

Several sets of experiments were made to check the possibility to amplify the primary shock wave exiting from the spiral section by the properly tuned triggering of the discharger ED2. In these experiments, 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. Note that the time delay $\Delta\tau$ was preset in a digital controller [3-5] prior to each run.

When the total initiation energy $E = 0.5(C_1+C_2)U^2$ was less than 600 J, detonation was not initiated at any $\Delta\tau$. When E was at a level of 650 J, a regular dependence of the shock wave velocity on the delay time $\Delta\tau$ became evident. In these experiments, C_1 was varied from 25 to 50 μF and C_2 was 225 μF. Voltage was varied from 2000 to 2300 V. Figure 3 shows the measured dependencies of the shock wave velocity on $\Delta\tau$ at E = 650 J. One very important implication follows from Fig. 3. It appears that detonation peninsula in the tests with the Shchelkin spiral is considerably wider than in tests without spiral (see [3-5]). Remind that without spiral, the width of the detonation peninsula was about 10 μs,

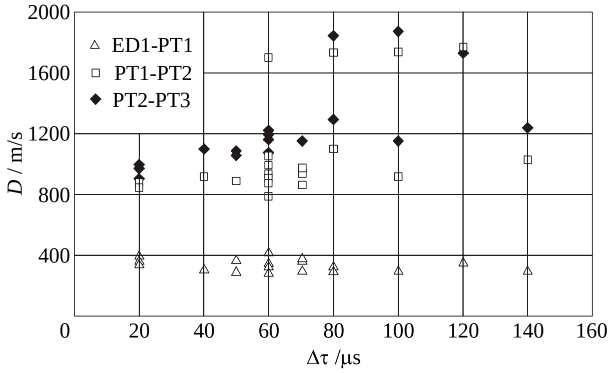


Figure 3: Measured dependencies of the shock wave velocity in the experiments with two dischargers ED1 and ED2 on the delay time between shock arrival at the discharge activation probe and second discharger triggering. The total energy of dischargers is 660 J

while the spiral insert widens the peninsula to about 60 μs . This is probably caused by the fact that the spiral modifies the pressure profile in the primary shock wave as compared with the cases without spiral. The pressure profile in the shock wave passing the spiral section becomes closer to stepwise contrary to the ‘triangular’ profile with fast pressure drop in the shock wave generated by a discharge. Moreover, with the spiral section, the dependencies of Fig. 3 become less sensitive to the fuel flow rate in the air-assist atomizer. These findings indicate that the use of the Shchelkin spiral make the shock-booster concept more feasible for practical applications.

Thus, it has been shown that the use of a sufficiently short spiral can result in the generation of a primary shock wave propagating at the velocity of about 900 m/s at the discharge energy exceeding 100 J in a 28-millimeter diameter tube. Such a shock wave can be further amplified to a detonation by using an additional discharger triggered in phase with the arrival of this shock wave at the discharger position. The optimal triggering time correlates with the time taken for the primary shock wave to travel from the discharge activation probe to the second discharger.

Further Modifications

Gap between Shchelkin Spiral and Second Discharger

Figure 4 shows the modified detonation tube. The basic difference in the setup of Fig. 4 from that of Fig. 1 is the availability of the tube segment free of the Shchelkin spiral between the end of the spiral and the second discharger ED2. The length of this segment is 110 mm. In addition, the distance between the probe and the second discharger was shortened from 90 to 65 mm.

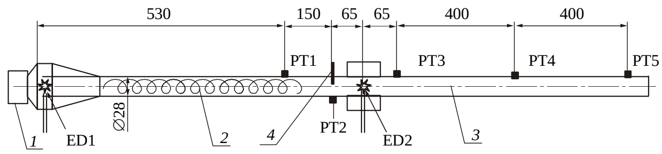


Figure 4: Modified detonation tube with the Shchelkin spiral between two dischargers: *1* — atomizer, *2* — Shchelkin spiral, *3* — tube, and *4* — discharge activation probe, ED1 — first discharger, ED2 — second discharger, PT1, PT2, PT3, and PT4 stand for pressure transducers. Dimensions in mm

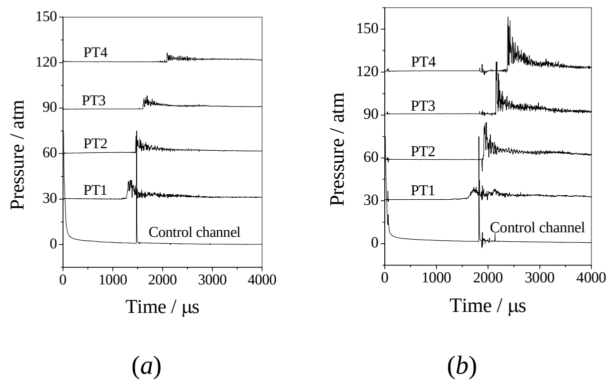


Figure 5: Pressure records obtained in the setup of Fig. 4 with triggering only one discharger ED1 of 200-joul energy (*a*) and two dischargers ED1 and ED2 with total energy of 512 J (*b*)

Figure 5*a* shows pressure records obtained in the setup of Fig. 4 with triggering only the discharger ED1 of 200 J (U = 2000 V, C_1 = 100 μF) rated energy. The spike on the control channel signal at the time of about 1500 μs corresponds to the probe-generated signal. This signal shows a short delay (about 15–20 μs) after the pressure signal at PT2 mounted in the same cross-section of the tube. At the spiral exit (PT1 record), the pressure wave exhibits a relatively smooth bell-like shape. Upon entering the spiral-free segment (record PT2) it transforms to the triangular shape with a distinct shock front. With further propagation along the tube, the shape of the pressure wave transforms to a nearly stepwise profile. At the distance from PT1 to PT4, the velocity of the pressure wave decreases from 915 to 820 m/s.

Figure 5*b* shows pressure records at successive triggering of dischargers ED1 and ED2. In this case, the minimal total initiation energy of a detonation is 512 J (U = 1600 V and C_1+ C_2 = 400 μF), which is lower than the critical initiation energy obtained at the setup of Fig. 1 (650 J). Decrease of the total energy to 450 J (by decreasing the voltage from 1600 to 1500 V) results in detonation failure, other conditions being equal.

Shchelkin Spiral Followed by Tube Coil

To further decrease the initiation energy of a detonation, the PDE tube was modified as shown in Fig. 6. An additional element, tube coil, was installed after the spiral section. As the tube coil introduces expansive and compressive surfaces for the propagating shock wave, it is expected that the interactions between various wave systems will promote the detonation onset [6].

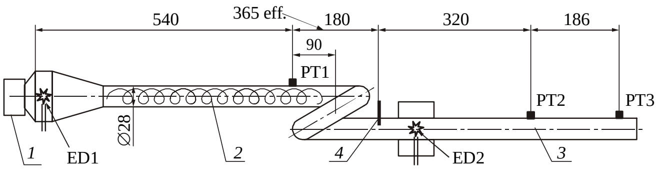


Figure 6: Modified detonation tube with the Shchelkin spiral and tube coil between two dischargers: *1* — atomizer, *2* — Shchelkin spiral, *3* — tube, and *4* — discharge activation probe, ED1 — first discharger, ED2 — second discharger, PT1, PT2, and PT3 stand for pressure transducers. Dimensions in mm

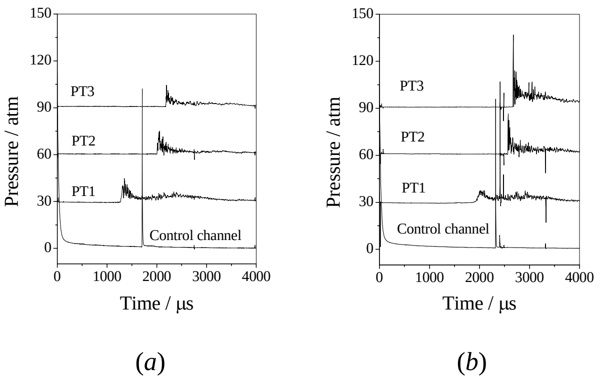


Figure 7: Pressure records obtained in the setup of Fig. 6 with triggering only one discharger ED1 of 144 J (*a*) and two dischargers ED1 and ED2 of total energy 132 J (*b*)

Figure 7*a* shows pressure records obtained in the setup of Fig. 6 with triggering only the discharger ED1 of 144 J (U = 2400 V, C_1 = 50 μF) rated energy. At this ignition energy detonation is not initiated. However when two dischargers, ED1 and ED2, are triggered successively with a total energy of 132 J ($C_1 = C_2$ = 25 μF, U = 2300 V) and $\Delta\tau$ = 80 μs, a detonation was detected at the tube segment PT2–PT3. In general, the use of two successively triggered dischargers separated by the Shchelkin spiral and tube coil resulted in a decrease of the detonation initiation energy in the 28-millimeter diameter tube to the value of about 100 J, i.e. by the order of magnitude as compared with the critical energy of direct detonation initiation by a single discharger [3-5]. In the setup of Fig. 6, the spray detonation is initiated at a distance of about 1 m, that is the predetonation length-to-diameter ratio is about 36. Both the energy requirements and the predetonation length can be considered feasible for PDE applications.

PDE Prototype

Based on the findings described above, the liquid-fueled air-breathing PDE prototype has been designed and fabricated. The schematic of the PDE prototype is shown in Fig. 8.

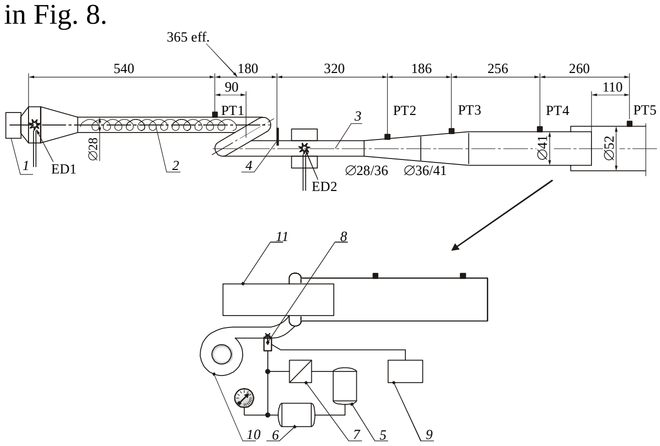
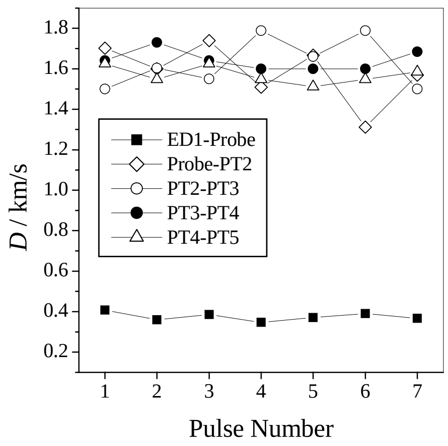


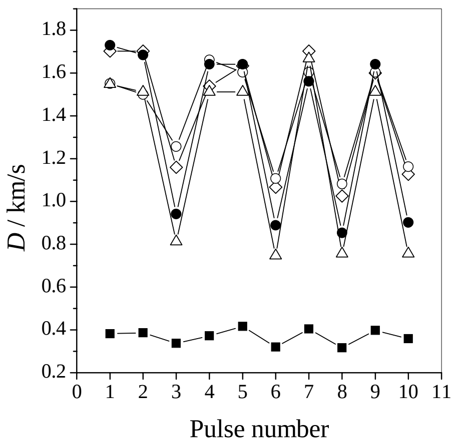
Figure 8: PDE prototype with the predetonator (upper figure) and main detonation chamber (lower figure). Predetonator: *1* — atomizer, *2* — Shchelkin spiral, *3* — tube, and *4* — discharge activation probe, ED1 — first discharger, ED2 — second discharger, PT1 to PT5 stand for pressure transducers. Main chamber: *5* — fuel tank, *6* — fuel pump, *7* — fuel valve, *8* — fuel injector, *9* — fuel pulse modulator, *10* — centrifugal compressor, and *11* — predetonator. Dimensions in mm

The PDE tube of Fig. 6 serves as a predetonator (upper part of Fig. 8). The predetonator is attached to the main detonation chamber (lower part of Fig. 8) 52 mm in diameter via two transition cones. The main chamber is equipped with the continuous-flow air supply system driven by an electric motor and a centrifugal compressor. Fuel (liquid *n*-hexane) is injected in the air manifold connected with the main chamber. Fuel supply may be either continuous or intermittent. In the preliminary tests conducted so far, the air manifold supplying the main chamber with the main fuel–air mixture was isolated to check the multipulse operation of the predetonator and transition of detonation to the main chamber via the transition cones.

Figure 9*a* shows the mean velocities at different segments of the PDE prototype in the multipulse operation mode at a frequency of 2 Hz as a function of the pulse number. In the run of Fig. 9*a*, a total detonation initiation energy by two dischargers is 132 J (U = 2300 V, $C_1 = C_2$ = 25 μF) and $\Delta\tau$ = 80 μs. The mean velocity at the segment from the first discharger to the



(*a*)



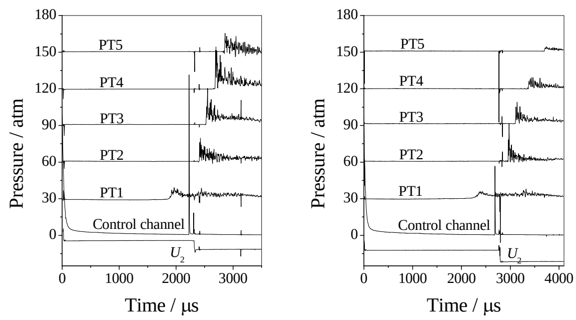
(*b*)

Figure 9: Multipulse operation of the PDE prototype of Fig. 8 with two electric dischargers. Symbols show cycle-to-cycle variation of the mean velocity of the pressure wave at different segments of the PDE. Operation frequency is 2 Hz. Total ignition energy per cycle is 132 J (*a*) and 121 J (*b*).

probe (ED1–Probe segment in Fig. 9*a*) is about 400 m/s and varies insignificantly from pulse to pulse. At other segments, the detonation wave was detected in all the pulses. The detonation wave propagation velocity varies from 1500 to 1800 m/s. The mean equivalence ratio in this run was about 1.2. The fuel consumption was measured by the weighting technique and encountered several experimental runs at similar initial conditions. Air consumption was calculated based on the pressure difference in the air bottle before and after the runs. It was noticed that the fuel consumption is higher at the beginning of device operation in the detonation mode, when the PDE tubes are cold. After several runs, when the tubes become heated, the mean fuel consumption in the detonation mode decreases towards a nearly stoichiometric value.

Decrease in the total initiation energy to 121 J by decreasing the voltage from 2300 to 2100 V other conditions been equal ($C_1 = C_2 = 25$ μF, $\Delta\tau = 80$ μs) resulted in the marginal multipulse operation mode of the PDE prototype. 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.

Figures 10*a* and 10*b* show the representative pressure records relevant to the pulse #3 in the diagrams of Figs. 9*a* and 9*b*, respectively. In addition to the record of the control channel and five records of pressure transducers PT1 to PT5, the voltage at the second (ED2) discharger, U_2, is plotted to identify the timing of discharge triggering after the signal generated by the probe (a spike at the control channel record). The drop of the voltage coincides with the second spike at the control channel record. The distance between the spikes corresponds to the triggering delay time $\Delta\tau$ preset in the controller.



(*a*) (*b*)

Figure 10: Representative pressure records corresponding to the runs of multipulse PDE operation of Fig. 9*a* (pulse #3) (*a*) and Fig. 9*b* (pulse # 3) (*b*)

Concluding Remarks

Experimental studies aimed at diminishing the initiation energy of *n*-hexane spray detonation in a 28-millimeter tube by using two successively triggered electric dischargers, Shchelkin spiral, and tube coil are presented. A powerful electric discharger used previously for generating a primary shock wave [1-5] was replaced by a primary shock wave generator comprising a low-energy (50–60 J) electric discharger and a Shchelkin spiral. A second, more powerful discharger was mounted at the exit of the spiral section and was activated in phase with the primary shock wave arrival at its position. This modification resulted in decreasing the critical detonation initiation energy to about 500 J. To further decrease the initiation energy of the detonation, a single tube coil was mounted between the exit from the spiral section and the second discharger. 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 the order of magnitude as compared with the energy (~1000 J) required for the direct initiation of the *n*-hexane spray detonation 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 configuration without the spiral [1-5]. This effect is attributed to the transformation of the pressure profile in the primary shock wave 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.

A liquid-fueled air-breathing PDE prototype comprising a 28-millimeter diameter predetonator tube of the optimized configuration and a 52-millimeter diameter main chamber with a total length of 1.8 m was fabricated and tested. Multipulse 2-hertz operation of the PDE prototype in the detonation mode was successfully demonstrated with the energy requirements of about 130 J per cycle. In these runs, the main PDE chamber was isolated from the main stream of the fuel–air mixture. Further studies will concentrate on the operational control of the PDE prototype with the supply of the main fuel–air mixture to the main PDE chamber. Also, the issues of decreasing the specific fuel consumption, and increasing the operation frequency will be addressed.

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