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Combined Strategies of Detonation Initiation in a Liquid-Fueled Air-Breathing PDE

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ABSTRACT

The results of the experimental studies aimed at evaluating the practical feasibility of a liquid-fueled air-breathing pulse detonation engine (PDE) demonstrator are presented. To reduce the initiation energy of *n*-hexane and *n*-heptane spray detonation, a 28-millimeter-diameter, 1-meter long predetonator transitioning via a conical and abrupt transition sections to a 52-millimeter-diameter, 0.6-meter long main tube is used. The fuel–air predetonator comprises the air-assist liquid-fuel atomizer, two electric (arc) dischargers, Shchelkin spiral, and tube coil. The atomizer provides the entire flow rate through the predetonator. The first discharger repeatedly generates the primary shock wave in a continuous two-phase flow. The second discharger is mounted at the exit of the tube coil and is activated in phase with the primary shock wave arrival at its position by a digital controller. The minimal attained rated energy of detonation initiation is about 30 J at the discharge efficiency of 15%–20%. The continuous two-phase flow in the main tube is provided by the centrifugal air compressor and a standard automobile fuel injector. To start the PDE in the multipulse detonation mode, the main tube is first operated on a continuous deflagration for a short time. The predetonator is activated after the tube wall attains the preset temperature. Multipulse 10-hertz operation of the setup in the detonation mode was successfully demonstrated at the total fuel–air ratio close to stoichiometric. Thrust measurements have been performed using a pendulum technique. It has been shown that the operation process is relatively low sensitive to variations in the fuel–air ratio and operation frequency.

NOMENCLATURE

Symbols

C [F]	capacitance
E [J]	energy
U [V]	voltage
V [m/s]	shock wave velocity

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*** Senior Researcher

Abbreviations

DDT	Deflagration-to-Detonation Transition
PC	Personal Computer
PDE	Pulse Detonation Engine

INTRODUCTION

During the last decade, there has been a growing interest to the development of a new type of jet propulsion engines that is PDE [1]. Such engines apply a new principle of fuel chemical energy conversion to thrust: fuel is supposed to be burned out in repeatedly propagating detonation waves. As compared to the conventional schemes of the operation process in ramjet and rocket engines fuel burning in propagating detonation waves exhibits several principal advantages. First, the thermodynamic efficiency of the detonation cycle exceeds considerably the efficiency of other known cycles of heat machines [2]. Second, PDE can potentially operate on both special fuels and conventional fuels used in aerospace applications. Third, in contrast to many existing concepts of jet engines, PDE has a simple design and does not require sophisticated and expansive compressors and turbopump machinery. Moreover, PDE is potentially robust as it contains no moving parts and self-sufficient as a PDE-based vehicle requires no booster for acceleration to cruise flight conditions. Fourth, the use of several identical PDE units in the assembly allows the thrust magnitude and vector control.

There exist several concepts of PDE design reviewed in [1]. Most of the concepts imply fuel preconditioning (prevaporization, preheating, partial decomposition, blending, etc.) prior to injection to a detonation chamber of a PDE and the use of oxygen to facilitate detonation initiation. The reasons for this kind of preconditioning are the low detonability of liquid fuel sprays in air and therefore extremely high energy requirement for direct detonation initiation [3–6] and very long run-up distances for deflagration-to-detonation transition (DDT) for vapor–air mixtures.

The objective of the research summarized in this paper is to develop a laboratory-scale liquid-fueled

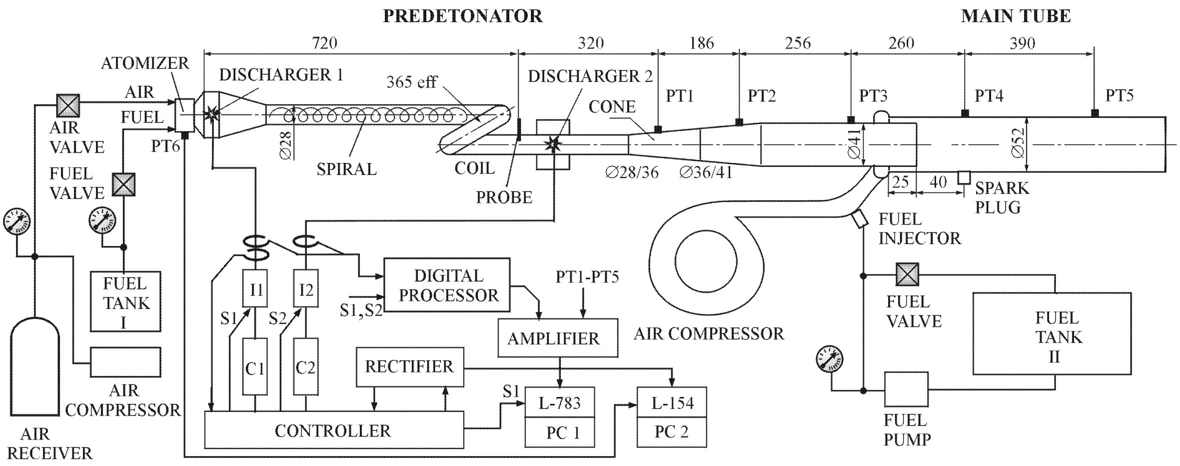


Fig. 1: Schematic of PDE demonstrator. Dimensions in millimeters

air-breathing PDE demonstrator with feasible energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of oxygen, and reasonable geometrical dimensions. Various aspects of the operational process of the PDE demonstrator have been reported elsewhere [7–11].

PDE DEMONSTRATOR

The schematic of the PDE demonstrator is shown in Fig. 1. Its main parts are the predetonator and the main tube.

The predetonator and main tube have separate fuel and oxidizer supply to make it possible to study various combinations of fuels and the oxidizing gas. For example, the PDE demonstrator of Fig. 1 allows for implementing both the single-fuel and dual-fuel concepts of the liquid-fueled air-breathing PDE [12, 13].

The predetonator is a combination of two tubes 28 and 41 mm in diameter connected by a transition cone. At one end of the 28-millimeter tube an air-assist continuous-flow liquid fuel atomizer is attached. The atomizer provides very fine fuel drops (5–6 ìm) at a distance of 70 mm from the nozzle. The atomizer performance has been described in detail in [10]. The electrical discharger I used for fuel–air mixture ignition is mounted in a conical discharge chamber 60 mm downstream from the atomizer nozzle. The discharge current duration through the discharger is 50 ± 5 ìs. Discharg e design and performance is described in [10]. To promote DDT in the fuel-air mixture, the Shchelkin spiral 400 mm long is inserted in the straight portion of the 28-millimeter tube. The spiral is wound from the steel wire 4 mm in diameter with a pitch of 20 mm. Downstream from the spiral section, a single 28-millimeter tube coil 140 mm in diameter (along the tube centerline) is attached. The coil is used to promote cumulating of flame-generated compression waves and detonation onset (see below). To provide reliable detonation onset, the second electrical discharger is mounted downstream from the coil exit. The discharger is activated with a certain delay time by a special probe to ensure energy deposition in phase with blast wave arrival at its position. Note that the second discharger is used only in the course of engine start-up (see below). The transition cone ensures transition of the detonation wave to the 41-millimeter tube. The latter is inserted in the main tube 52 mm in diameter with a uniform radial gap. The total length of the PDE demonstrator is 1.8 m.

The air and liquid fuel in the main tube are supplied by the centrifugal compressor and standard (low-pressure) automobile injector. The drop size provided by the injector is relatively large (100–150 μm).The open end of the main tube is equipped with a nozzle.

The energy supply is provided by a rectifier. A digital controller controls charging of the capacitors C_1 and C_2 based on the preset program and activates the units I1 and I2, which in their turn activate the dischargers. The energy deposition by the electric dischargers results in ignition of the fuel spray and generation of shock and detonation waves in the facility.

The predetonator and main tube are equipped with piezoelectric pressure transducers (PT1, PT2, PT3, PT4, and PT5). Pressure transducer PT6 registers air pressure in the air-assist atomizer. The data acquisition system comprises two analog-to-digital converters and two PCs.

The fuels used in all the experiments reported herein are liquid *n*-hexane or liquid *n*-heptane. The initial temperature of air and liquid fuel was 293 ± 4 K.

The section below describes the experimental findings which underlie the operation principle of the predetonator.

PREDETONATOR

Performance of Tube with Schelkin Spiral

Figure 2 shows the schematic of the straight predetonator tube 28 mm in diameter with a Schelkin spiral 400 mm long wound from steel wire 4 mm thick with a pitch of 20 mm. The external spiral diameter was equal to the internal tube diameter. The spiral was mounted at the outlet of the conical discharge chamber. Figure 3 shows the measured mean shock wave velocity *V* as a function of discharge energy E_1 at different measuring segments: ED1–PT1 (between the discharger and pressure transducer PT1), PT2–PT3 (between pressure transducers PT2 and PT3), PT3–PT4 (between pressure transducers PT3 and PT4), PT4–PT5 (between pressure transducers PT4 and PT5). The energy, E_1, deposited by the discharge is calculated based on the capacitance, C_1, and voltage, *U*, that is $E = CU^2/2$.

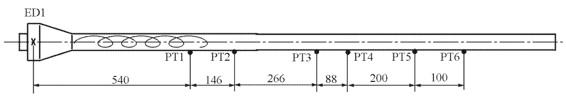


Fig. 2: Straight predetonator tube with Schelkin spiral

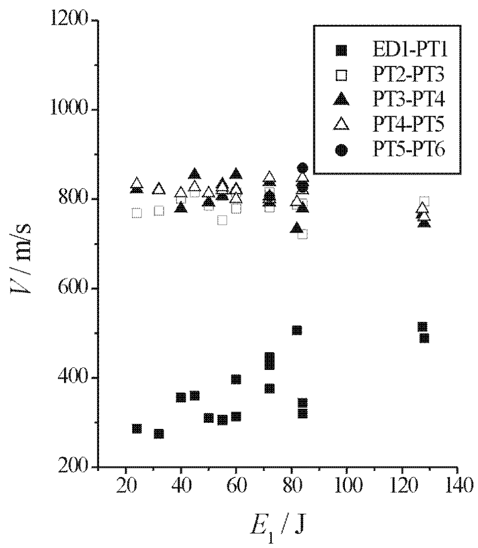


Fig. 3: Mean shock wave velocity at various measuring segments in a tube of Fig. 2 as a function of discharge energy. Fuel: *n*-hexane

The maximal shock wave velocity at the exit from the spiral is about 800 m/s at E_1 varying from 20 to 130 J. After issuing from the spiral the shock wave propagates at nearly constant velocity of 800 ± 50 m/s in a tube section 0.7–0.8 m long. Poor repeatability of the measurements at the segment ED1–PT1 is noteworthy. At this segment the pressure wave is bell-shaped without an apparent shock front.

Variation of spiral wire diameter (between 4 and 7 mm) and spiral length (between 400 and 700 mm) exerts no significant effect on the explosion dynamics.

Peformance of Tube with Coils

It is known that tube bends can promote detonation onset due to shock wave interaction with compressive and expansive surfaces [14, 15]. To study the effect of tube bends on detonation initiation, a series of experiments was conducted in a tube 28 mm in diameter with several coils as shown in Fig. 4.

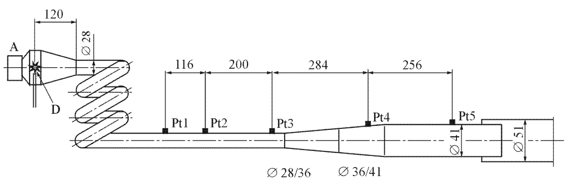


Fig. 4: Predetonator tube with three coils and a transition section to a main tube

The tube section with one to three coils was attached to the outlet of the conical discharge chamber. The diameter of the tube coil was 140 mm. A straight 28-millimeter tube is attached to the other end of the coil section, which transitions to a 41-millimeter tube via a conical expansion. The latter tube is inserted with an annular gap in the main detonation tube 52 mm in diameter.

Figure 5 shows the results of experiments in the tube of Fig. 4.

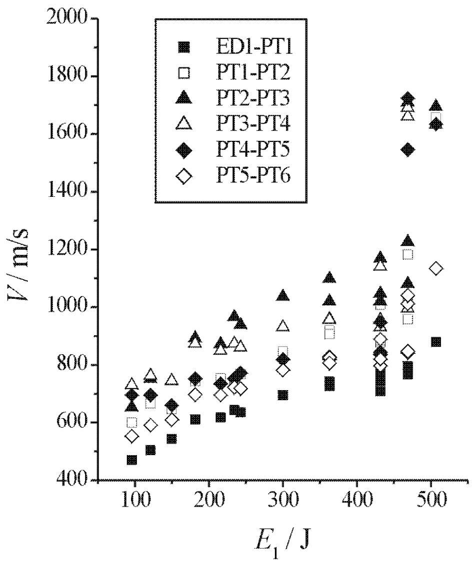


Fig. 5: Mean shock wave velocity at various measuring segments in a tube of Fig. 4 as a function of discharge energy. Fuel: *n*-hexane

Increase in the discharge energy from 95 to 470 J results in the gradual increase of the shock wave velocity at the exit from the coil section (measuring segment PT1–PT2). At the discharge energy exceeding 470 J a detonation wave was detected at measuring segments PT1–PT2, PT2–PT3, PT3–PT4 and PT4–PT5. The measured detonation velocity is 1630–1720 m/s (Fig. 6). The detonation wave propagated at this velocity via the conical expansion and along the main tube.

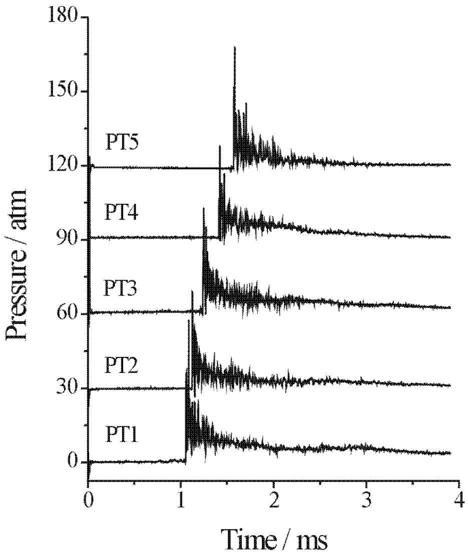


Fig. 6: Pressure histories registered by pressure transducers PT1 to PT5 in a tube of Fig. 4 at discharge energy of 507 J. Fuel: *n*-hexane

This experimental series indicates that detonation can be initiated in a relatively short smooth-walled tube with a coil section comprising of three loops. The minimal detonation initiation energy of about 500 J is by a factor of 2 smaller that the discharge energy required for direct detonation initiation in a straight, smooth-walled tube 28 mm in diameter [10]. Note that in tubes with one and two-loop coil sections detonation was not detected at discharge energies below 600 J.

Figure 5 indicates that detonation is initiated when the mean shock wave velocity in the coil section (measuring segment ED1–PT1 in Fig. 4) is close to 800 m/s. This velocity is attained at the discharge energy of about 470 J. Recalling that the same level of shock wave velocities is obtained at the exit from the Schelkin spiral in a straight tube (see Figs. 2 and 3) we suggest an efficient 'spiral–coil' combination to decrease the minimal discharge energy required for detonation initiation.

<u>Peformance of Tube with Spiral – Coil Combination</u>

The schematic of the tube 28 mm in diameter implementing the findings described above is shown in Fig. 7. The spiral 400 mm long is wound from the steel wire 4 mm in diameter with a pitch of 20 mm. A single-loop coil section is attached to the outlet of the spiral section.

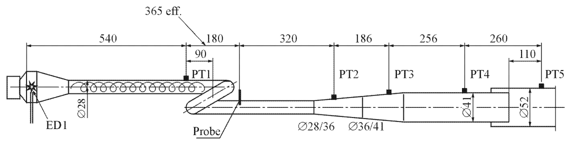


Fig. 7: Predetonator tube with the Schelkin spiral, single-loop coil, and transition section to a main tube

As in Fig. 4, the coil section is connected to a straight tube transitioning via the conical expansion to the 41-millimeter tube which is coaxially inserted into the main tube 52 mm in diameter. In addition to pressure transducers PT1 to PT5 a special probe was mounted in the tube at the exit from the coil (see Fig. 7). The probe was used both for measuring purposes and for triggering the second discharger in the PDE demonstrator of Fig. 1.

Figure 8 shows the results of experiments in the tube of Fig. 7 in terms of the mean shock wave velocities vs. discharge energy at various measuring segments.

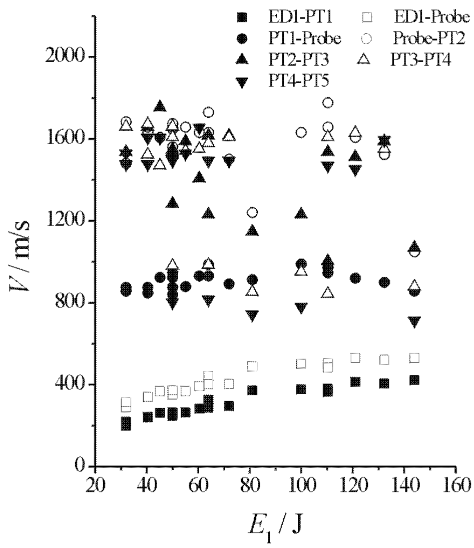


Fig. 8: Mean shock wave velocity at various measuring segments in a tube of Fig. 7 as a function of discharge energy. Fuel: *n*-hexane

At low ignition energies (below 25–30 J) the *n*-hexane and *n*-heptane sprays were not ignited by the discharger, as the discharge plasma was presumably blown-up with the high-speed two-phase flow issuing from the atomizer nozzle. At discharge energies ranging from 30 to 50 J the detonation wave was detected at measuring segments PT3–PT4 and PT4–PT5. The detonation arose in the tube coil at a distance of about 1 m downstream from the discharger (~28 tube calibers), transitioned to the 41-millimeter tube and then to the main tube 52 mm in diameter. The mean detonation velocity was 1500–1700 m/s. The occurrence of the detonation within this range of the discharge energy was regular from run to run.

At discharge energies ranging from 50 to 130 J the transition of detonation to the main tube was not always reproducible. Moreover, at discharge energies exceeding 130 J (up to 300 J) the detonation was not detected at all. Similar results were obtained in the experiments with *n*-heptane sprays.

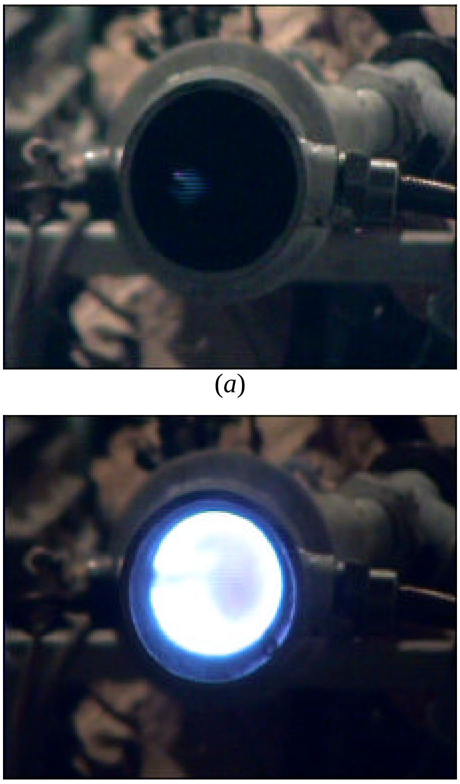
The existence of the detonation 'peninsula' at low discharge energies (30–50 J) can be attributed solely to the effect of the coil, because the Schelkin spiral alone does not give rise to detonation at such discharge energies (see Fig. 3). Presumably the coil acts as an element, which promotes the gasdynamic focusing of compression waves generated by the accelerating flame. At low discharge energies the compression waves are capable of catching up with each other and with the primary shock wave inside the coil and undergo various reflections promoting the detonation onset. At high discharge energies, the characteristic time taken for the compression waves to catch up with the primary shock wave is longer and wave 'cumulating' (according to Schelkin terminology) occurs outside the coil.

Thus, the use of the spiral–coil combination allowed us to decrease the detonation initiation energy in the two-phase *n*-hexane–air and *n*-heptane–air mixtures to the value of about 30 J. With such a discharge energy it was possible to reliably transition the detonation to the 52-millimeter tube from the short predetonator. This energy is by a factor of 100 less than the energy of direct detonation initiation in a straight smooth-walled tube 52 mm in diameter [10].

PDE START-UP AND OPERATION

A special starting procedure of the PDE demonstrator was required. It is based on the observation that the hot tube walls facilitate detonation initiation. Of particular importance was to heat up the main tube as the drop size provided by the low-pressure fuel injector was relatively large.

First, the spark plug installed in the main tube (see Fig. 1) was triggered for several seconds at a discharge frequency of 2 Hz (Fig. 9*a*). Then the fuel and air supply to the main tube was activated giving rise to a diffusion flame (Fig. 9*b*). When the flame heated up the main tube to a preset temperature of about 50 ^{o}C, the spark plug in the main tube was switched off. Simultaneously fuel and air supply to the predetonator were activated followed by pulse energy deposition to dischagers I and II. After a preset number (usually 5–7) of detonation pulses, the second discharger was deactivated as the detonation was repeatedly obtained using solely discharge I. The entire operation process was controlled by the digital controller.



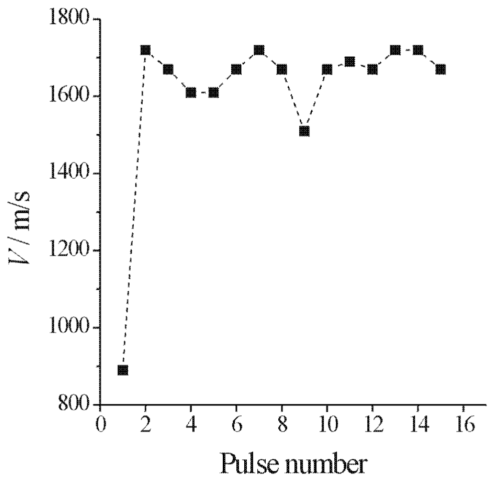
(*a*)

(*b*)

Fig. 9: Preheating the main PDE tube during the starting procedure: (*a*) initial spark plug triggering, (*b*) onset of a two-phase diffusion flame

In the pulse detonation mode, the mass flow rates of fuel and air were respectively 0.4 ± 0.1 and 6.7 ± 0.5 g/s in the predetonator and 3.8 ± 0.1 and 60 ± 7 g/s in the main tube. The minimal energy required for detonation initiation was 30 J. The efficiency of the electrical dischargers used was at the level of 15%–20%. Thus the use of more efficient igniters can potentially decrease the initiation energy to several Jules per cycle.

Figure 10 shows the examples of measured mean shock wave velocities at segment PT4–PT5 of the PDE demonstrator in the multipulse operation mode at a frequency of 3.9 Hz as a function of the pulse number. In the stable mode, the detonation wave was detected in all pulses except for the first pulse (Fig. 10*a*). The detonation wave propagation velocity varied from 1500 to 1720 m/s. The mean equivalence ratio in the run of Fig. 10a was about 1.3 ± 0.1. In the marginal detonation mode, the detonation wave was detected only in a part of pulses (Fig. 10*b*). In some pulses, the shock wave velocity droped down to 850–900 m/s. The mean equivalence ratio in the run of Fig. 10*b* was about 1.1 ± 0.1.



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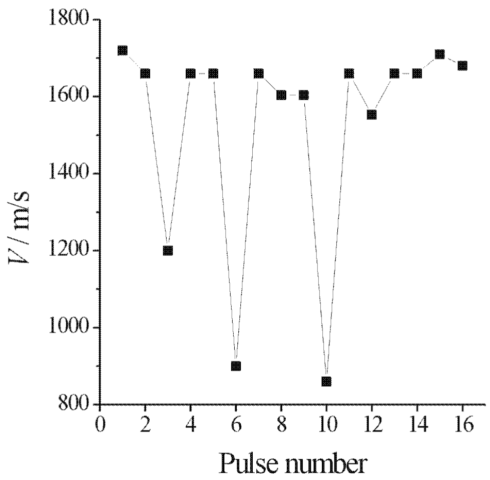
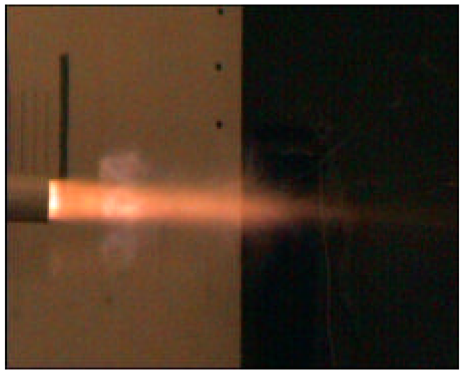


(*b*)

Fig. 10: Multipulse operation of the PDE demonstrator at frequency of 3.9 Hz. Symbols show pulse-to-pulse variation of the mean shock wave velocity at the measuring segment PT4–PT5. (*a*) stable detonation mode, (*b*) marginal detonation mode. Fuel: *n*-hexane

It was noticed that the fuel consumption required for stable detonation mode was higher at the beginning of device operation, when the PDE tubes were cold. After several pulses, when the tubes were becoming hot, the required mean fuel consumption for the detonation mode decreased towards a nearly stoichiometric value. It is seen, for example, from Fig. 10*b*: after 10 pulses in the marginal mode the stable mode of PDE operation is observed. Such a performance is explained by the formation of the liquid fuel film at the internal surfaces of the device. When the surfaces are heated up, the film quickly evaporates and lower fuel mass flow rates are required for supporting the detonation.



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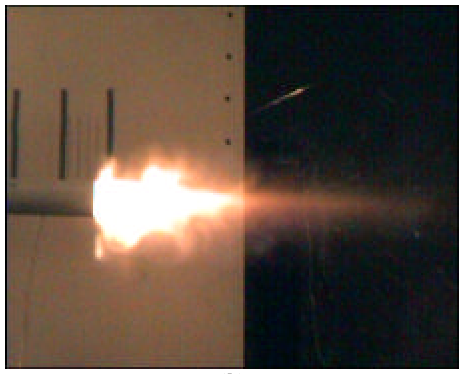

(*b*)

Fig. 11: PDE nozzle plume produced by detonation (*a*) and deflagration (*b*)

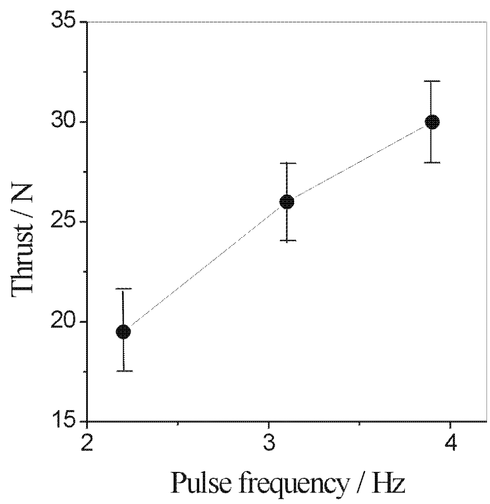

Fig. 12: Measured PDE thrust as a function of the operation frequency. Fuel: *n*-hexane

Figure 11 shows the typical photographic images of the plume produced by a detonation (Fig. 11*a*) and deflagration (Fig. 11*b*) at the PDE nozzle exit. In case of deflagration, the afterburning of fuel is observed in the plume.

Figure 12 shows the results of thrust measurements depending on the operation frequency (2.2, 3.1, and 3.9 Hz). Each point corresponds to 5–6 experimental runs. As could be expected, the thrust is a linear function of frequency. The maximal measured thrust in Fig. 12 is 30 ± 2 N. Due to the air supply system used, detonations were increasingly irregular at operation frequencies exceeding 4–5 Hz (up to 10 Hz). Therefore thrust measurements at these conditions were less reproducible.

SUMMARY

A liquid-fueled air-breathing PDE demonstrator comprising a 28-millimeter diameter predetonator tube of the optimized configuration and a 52-millimeter diameter main tube with a total length of 1.8 m was designed, fabricated, and tested. Multipulse PDE operation in the detonation mode was successfully demonstrated with liquid *n*-hexane and *n*-heptane as fuels with the energy requirements for detonation initiation of about 30 J per cycle. Thrust measurements using the pendulum technique were made. The linear dependence of the PDE thrust on the operation frequency was obtained. The main problem to be solved in future studies is to replace *n*-hexane and *n*-heptane by a regular jet propulsion fuel.

ACKNOWLEDGEMENT

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