OPERATIONAL PRINCIPLES AND PERFORMANCE OF PULSE DETONATION ENGINE DEMONSTRATOR

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A liquid-fueled air-breathing pulse detonation engine (PDE) demonstrator with feasible energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of extra oxygen, and reasonable geometrical dimensions has been designed and tested. Due to acceptable weight and size characteristics of the PDE demonstrator, the proposed design can be considered as promising for practical applications.

1 INTRODUCTION

Pulse detonation engines apply a new principle of fuel chemical energy conversion to thrust: fuel is supposed to be burned out in repeatedly initiated propagating detonation waves. As compared to the conventional schemes of the operation process in ramjet and rocket engines, fuel burning in the propagating detonation waves exhibits several principal advantages. First, the thermodynamic efficiency of the detonation cycle exceeds considerably the efficiency of other known cycles [1, 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 boosters for acceleration to cruise flight conditions. Fourth, the use of several identical PDE units in the assembly allows for the thrust magnitude and vector control.

There exist several concepts of PDE design reviewed in [2]. 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 and/or fuel sensitizers to facilitate detonation initiation. The reason for this kind of preconditioning is very low detonability of liquid-fuel sprays in air and therefore extremely high energy requirement for direct detonation initiation [2–6]. As for the run-up distances for deflagration-to-detonation transition (DDT), for gaseous hydrocarbons like propane, they are known to be very long [7, 8]. In oxygen suspensions of liquid hydrocarbons, 20 to 100 tube diameters were required for the DDT [9]. Only the use of special means like combinations of Shchelkin spirals and tube coils allowed the DDT to be attained in air suspensions of liquid hydrocarbons [10].

The operational and safety considerations imply that the following preferences for practical PDEs should be met:

- propellants enter the combustion chamber in the form of liquid sprays as in conventional air-breathing liquid-fueled ramjets;
- prevaporization devices are avoided;
- devices for fuel premixing with air are avoided;
- the use of onboard oxygen is avoided;
- the use of fuel sensitizers is avoided;
- low-pressure fuel atomizers are used;
- igniters with low ignition energy are used; and
- compact geometrical dimensions are attained (e.g., less than 2 m in length).

The objective of the research summarized in this paper is to develop a laboratory-scale liquid-fueled air-breathing PDE demonstrator with feasible energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of onboard oxygen and fuel sensitizers, and reasonable geometrical dimensions. Various aspects of the operational process of the PDE demonstrator have been reported elsewhere [10–19].

2 GENERAL DESCRIPTION

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

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 design and performance of the atomizer have been reported elsewhere [13, 17]. Note that the atomizer provides very fine fuel drops (5–6 μm) at a distance of 70 mm from the nozzle. To ignite a two-phase flow issuing from the atomizer nozzle, an electrical igniter is used. The design and performance of the igniter have been also reported earlier [17]. Note that the discharge current duration through the igniter is

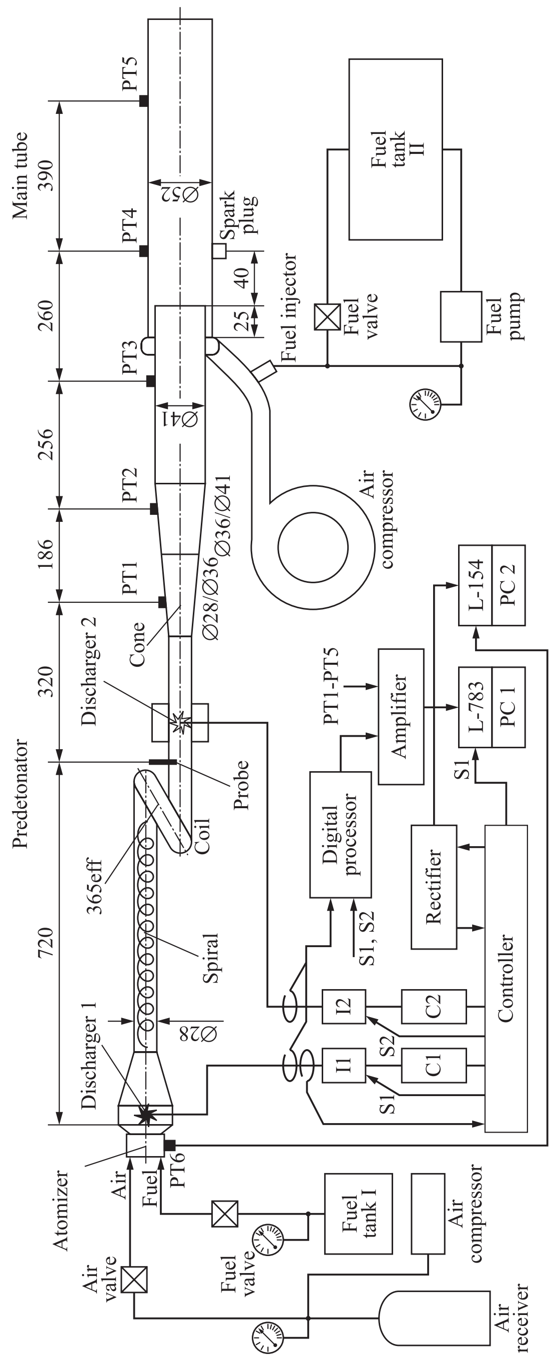


Figure 1 Schematic of PDE demonstrator. Dimensions are in millimeters

50 ± 5 μs. The igniter electrodes are placed at a distance of 60 mm downstream from the nozzle in a conical discharge chamber. To generate a relatively strong blast wave in the fuel–air mixture via flame acceleration, the Shchelkin spiral 400 mm long is inserted in the straight portion of the 28-millimeter tube. The spiral is wound from a steel wire 4 mm in diameter at a pitch of 18 mm. A single 28-millimeter tube coil of a length of 365 mm (measured along the tube axis) is attached downstream of the spiral section. The coil favors the gasdynamic focusing of the blast wave generated by the accelerating flame [10, 16]. The coil is followed by the second igniter, which ignites the reactive mixture at the instant the blast wave arrives at its electrodes. Thereby, the second igniter is used to facilitate detonation initiation according to a recently described mechanism [11–17]. The design and performance of the second and first igniters are similar. The synchronization of the triggering of the second igniter with the arrival of the blast wave is performed with a special activation probe. The design and performance of the probe have been described in [17]. Note that the second igniter is used only in the course of demonstrator start-up. The conical transition section is used to reliably transition the detonation wave to the 41-millimeter tube. The latter is inserted coaxially into the main 51-millimeter tube 540 mm long. The annular gap between the main tube and the predetonator is used for introducing the main stream of the fuel–air mixture. The other end of the main tube is open to the atmosphere. The total length of the PDE demonstrator with the predetonator and the main tube is 1.8 m.

The predetonator and main tube have separate fuel and oxidizer supply to make it possible to study various combinations of fuels and oxidizer gases. For example, the PDE demonstrator of Fig. 1 allows for implementing both the single- and dual-fuel concepts of the liquid-fueled air-breathing PDE [20, 21] or apply oxygen-enriched air in the predetonator. The fuels used in all the experiments reported herein are liquid n-hexane or liquid n-heptane. Atmospheric air was used as an oxidizer gas.

Air for the predetonator is fed to the atomizer from the 40-liter receiver connected with a compressor. Liquid fuel for the predetonator is fed to the atomizer from a pressurized fuel tank I.

Air for the main tube is supplied with the low-head centrifugal compressor. Liquid fuel for the main tube is fed with a standard low-pressure automobile fuel injector. The fuel supply system comprises a fuel tank II, as well as fuel pump and valve.

Both air and fuel supplies are continuous.

To feed the igniter circuits, a high-voltage rectifier is used. The rectifier provides the operational voltage to charge the capacitors C1, C2 via a digital controller. The controller, based on the preset program, activates the units I1 and I2 which, in their turn, activate the igniters.

Both the predetonator and main tube are equipped with piezoelectric pressure transducers (PT1 to PT6). The data acquisition system is composed of two analog-to-digital converters allowing for registration of the processes over two essentially different time scales, and two personal computers. The first converter (L-Card L-154) with a sampling frequency of 200 Hz registers the voltage at the capacitors and the air pressure in the atomizer (with the pressure transducer PT6). The second converter (L-Card L-783) with a sampling frequency of 840 kHz registers the signals of pressure transducers PT1 to PT5, as well as probe and ignition timing.

The velocity of 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 pressure transducers and probe timing. The maximal error in determining the shock and detonation wave velocity did not exceed 2.5%.

The electrical energy, E, deposited by the igniters was calculated based on the capacitance, C, and voltage, U, that is $E = CU^2/2$. Taking into account the residual energy in the capacitors after a discharge, the maximal error in determining the E value did not exceed 7%. Note that the efficiency at which the electrical energy E was deposited into the reactive medium was about 15%–20% [18].

The final design of the predetonator shown in Fig. 1 is based on several important preliminary findings. The tube diameter of the predetonator (28 mm) has been chosen based on the previous findings indicating that energy requirements for the initiation of the two-phase n-hexane–air detonation were minimal when the tube diameter approached the limiting value of 28 mm [17]. The straight tube with Shchelkin spiral followed by the section with one tube coil appeared to be a very promising configuration for the predetonator design according to [10]. In this configuration, the straight tube with Shchelkin spiral was used for generating blast waves propagating in the two-phase mixture at the velocities of 800 ± 50 m/s applying relatively low ignition energies on the order of 30 J. The use of a tube coil allowed for shock-to-detonation transition due to multiple reflections of the blast wave from the compressive surfaces inside the coil [10, 16]. The most intriguing finding was the existence of the 'detonation peninsular' in this predetonator design, which was very similar to that discovered earlier [11, 17]. At ignition energies ranging from 30 to about 50 J, the detonation initiation at the coil exit was highly reproducible and the detonation wave always transitioned to the main tube. At ignition energies ranging from about 50 to 130 J, the detonation wave not always transitioned to the main tube. At ignition energies ranging from 130 to 300 J, detonation was not detected at all. Similar results were obtained for liquid n-heptane–air mixtures. These effects should be attributed solely to the tube coil as the experiments in the tube with Shchelkin spiral did not lead to the detonation in this range of the ignition energy. Probably, at low ignition energy, the compression waves generated by the accelerating flame in the Shchelkin spiral formed a 'cumulating blast wave' (according to Shchelkin terminology [22]) inside the tube coil. Further reflections in the coil resulted in detonation initiation. At large ignition energies, the 'cumulating blast wave' formed outside the coil and decayed due to the lack of reflections.

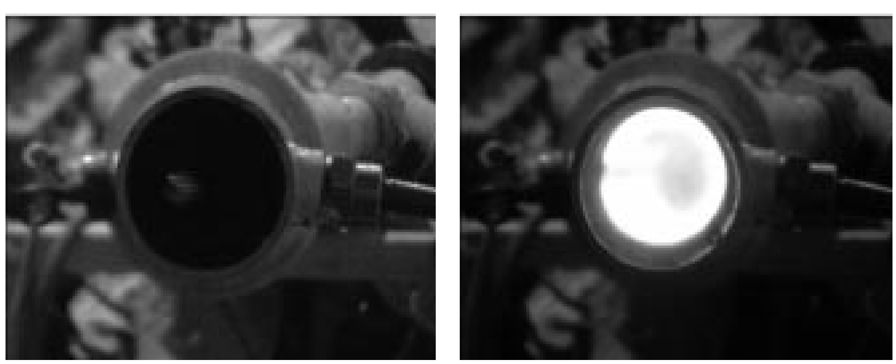
To improve the performance of the predetonator, the second igniter has been installed behind the tube coil and the activation probe. The idea of using the second igniter was discussed in detail elsewhere [11, 17]. The second igniter when triggered in phase with the blast wave arrival at its position widens the detonation peninsular considerably. This property appeared to be very important for detonation initiation control at engine start-up.

3 OPERATION AND PERFORMANCE

The PDE demonstrator of Fig. 1 was tested in a series of experimental runs. The objective of the tests was to obtain stable operation of the unit at different operation frequencies.

To ensure stable operation of the PDE with a near-stoichiometric fuel–air composition, a special starting procedure was used. Initially, voltage was applied at a frequency of 2 Hz to the start-up spark plug in the main tube. Then, air and fuel were fed to the main tube. After the fuel–air mixture was ignited, steady-state diffusion combustion in the main tube caused heating of the tube wall. Figure 2 shows the photographs of the start-up spark plug (Fig. 2*a*) and flame (Fig. 2*b*) in the main tube during the heating stage.

When the wall temperature reached 50 °C, air and fuel were supplied to the predetonator, the start-up spark plug was switched off, and by activating the



(*a*) (*b*)

Figure 2 Preheating the main tube during the starting procedure: (*a*) start-up spark plug triggering, and (*b*) onset of a two-phase diffusion flame

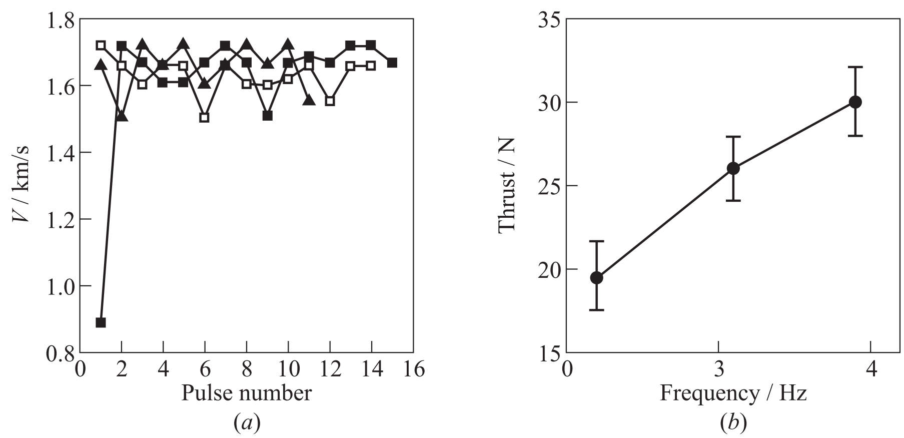
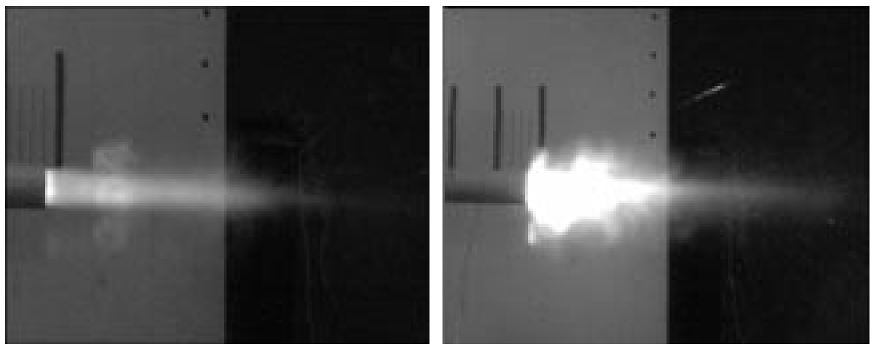


Figure 3 (*a*) Multipulse operation of the PDE demonstrator at the operation frequency of 3.9 Hz. Symbols show pulse-to-pulse variation of the mean velocity of the pressure wave at the measuring segment PT4–PT5 in the main tube for three independent runs. Total ignition energy per pulse is 30 J

first igniter at the given frequency, the operation mode of periodic combustion of the fuel–air mixture in the traveling detonation wave was attained. All the steps of starting the PDE demonstrator and attaining the operation mode were controlled by the digital controller. During the operation of the demonstrator the following parameters were monitored: the air and fuel flow rates in the predetonator and in the main tube, discharge current in dischargers ED1 and ED2, and air pressure in the air-assist atomizer. The dynamics of wave processes were recorded using piezoelectric pressure transducers PT1 to PT5 (Fig. 1).

In the detonation mode, the fuel and air flow rates measured in the predetonator were 0.4 ± 0.1 and 6.7 ± 0.5 g/s, respectively; and in the main tube, 3.8 ± 0.1 and 60 ± 7 g/s, respectively. The minimal energy required to initiate detonation in the predetonator was 24 J per cycle. At lower energies, ignition of the two-phase flow issuing from the atomizer failed. To further decrease the ignition energy, special means stabilizing ignition (e.g., recirculation zones) should be applied.

Figure 3*a* presents the blast wave velocities measured at the measuring segment PT4–PT5 during the operation of the PDE demonstrator in the detonation mode in three runs at a pulse repetition frequency of 3.9 Hz. The jet thrust was measured during the operation of the demonstrator at generation frequencies of 2.2, 3.1, and 3.9 Hz. Figure 3*b* presents the measured thrust vs. frequency. Thrust measurements have been performed using a standard pendulum technique. The thrust of the PDE is seen to increase linearly with the frequency.



(*a*) (*b*)

Figure 4 Pulse detonation engine nozzle plume produced by detonation (*a*) and deflagration (*b*)

The maximal measured thrust was 30 ± 2 N. The error ± 2 N is attributed to the tare forces from the air and fuel delivery systems. The maximal achieved demonstrator operation frequency was 8 Hz. The maximal estimated specific impulse was about 1000 s, which is about half of the specific impulse of modern ramjets. Note that this result has been obtained without special arrangements to ensure high performance. Moreover, due to continuous fuel supply, low operation frequencies, and short main tube, fuel combustion was incomplete.

It is seen from Fig. 3 that in all pulses, except for the first pulse in one of the runs, detonation in the main tube propagated at an average velocity of 1600–1700 m/s. Note that in case of detonation failure, the velocity at the measuring segment PT4–PT5 decreased to 900–1000 m/s. Figure 4 shows the typical photographic images of the plume produced by a detonation (Fig. 4*a*) and deflagration (Fig. 4*b*) at the demonstrator nozzle exit. In case of deflagration, the afterburning of fuel is observed in the plume.

4 CONCLUDING REMARKS

The liquid-fueled air-breathing PDE demonstrator was designed and tested. Unlike the existing design of PDE demonstrators (see [2]), in which a detonation wave in the predetonator is initiated using a fuel–oxygen mixture, the present demonstrator exhibits stable operation with periodic detonation without using additional oxygen. Owing to acceptable weight and size characteristics of the demonstrator, the proposed process design can be regarded as promising for practical applications. The main problem to be solved is to ensure the stable operation of a PDE that burns low-volatile fuel of the type of aviation kerosene rather than high-volatile fuel (n-hexane and n-heptane).

Taking into account that the efficiency of the electric dischargers used was 15%–20%, one can expect that the use of more efficient electrical igniters and application of special means of ignition stabilization will further allow one to decrease the initiation energy down to several joules per cycle. To increase the overall combustion efficiency and therefore the PDE performance, the length of the main tube and the operation frequency should be optimized.

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