LIQUID-FUELED AIR-BREATHING PDE DEMONSTRATOR

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The pulse detonation engine (PDE) demonstrator was designed and tested. Unlike the existing design of PDE demonstrators, in which a detonation wave in the predetonator is initiated using a fuel–oxygen mixture, the present demonstrator exhibits stable operation with periodic detonation of liquid fuel (n-hexane or n-heptane) without using oxygen. The design of the demonstrator is based on several new findings. The use of special means like the combinations of Shchelkin spirals and tube coils allowed the deflagration-to-detonation transition (DDT) to be attained in air suspensions of liquid hydrocarbons apparently for the first time. The DDT is solely attributable to the use of the new element – tube coil. One of the most intriguing findings is the existence of the 'detonation peninsular' in the predetonator comprising the Shchelkin spiral followed by the tube coil. A new method for detonation initiation in sprays of the liquid fuel in air by successive triggering of two igniters was also applied. The use of a tube with a nearly limiting diameter, Shchelkin spiral, tube coil, and two igniters enhanced considerably the practical feasibility of the predetonator by decreasing the detonation initiation energy to several tens of joules per pulse and extending the detonation initiation limits. Multipulse operation of the PDE demonstrator in the stable detonation mode was successfully demonstrated at the total fuel–air ratio close to stoichiometric. Thrust measurements have been performed using a pendulum technique.

Introduction

In 1940 Zel'dovich has shown that detonative combustion is thermodynamically more efficient than constant-volume and constant-pressure combustion [1]. Two principle schemes of practical implementation of detonation cycle are possible. One applies a concept of fuel combustion in a stabilized detonation front. The other applies a concept of fuel combustion in repeatedly generated detonation waves traversing the combustion chamber [2]. The device implementing this cycle and referred to as a PDE is the focus of this paper. In comparison with existing combustion design

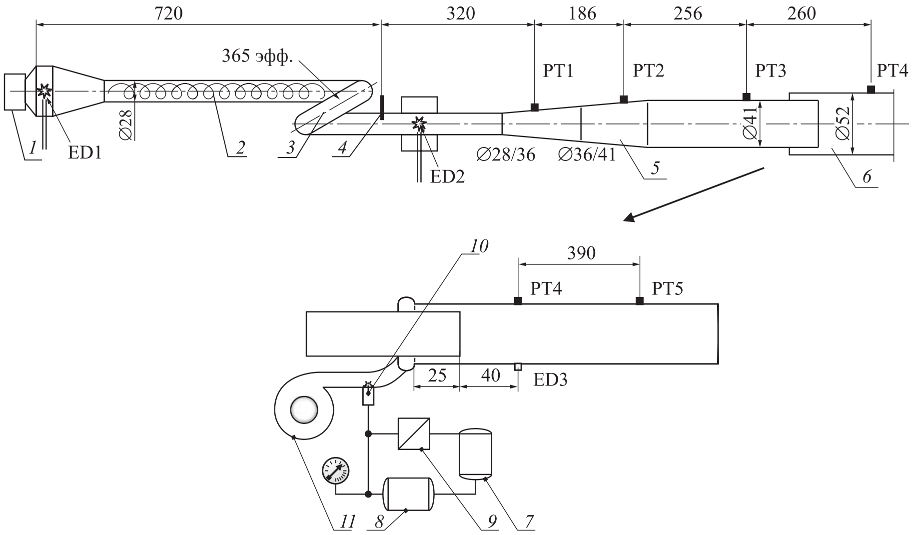


Fig. 1

in air-breathing and jet engines, the detonation combustion of fuel in a traveling wave has a number of fundamental advantages. First, the thermodynamic efficiency of the detonation cycle is much higher than that of other cycles, especially at low pressures in the combustion chamber. Second, a PDE can burn both special fuels and conventional (liquid) jet propulsion fuels. Third, unlike many existing jet engines, a PDE has a simple design (requires no expensive compressors and turbopumps) and is reliable (has no moving elements) and self-sufficient (needs no boosters to reach the operation mode). And finally, using the multitube design of a PDE allows one to improve the thrust performance by simply increasing the number of chambers. Inasmuch as the practical implementation of detonation combustion of fuel saves energy resources, stationary power plants operating on this principle are also being developed.

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 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 and very long DDT run-up distances even for gaseous hydrocarbons–air mixtures.

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 oxygen, and reasonable geometrical dimensions. Various aspects of the operational process of the PDE demonstrator have been reported elsewhere [3–9].

PDE demonstrator

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

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 liquid fuel atomizer *1* is attached. The design and performance of the atomizer have been reported elsewhere [9] Note that the atomizer provides very fine fuel drops (5–6 μm) at a distance of 70 mm from the nozzle. To ignite the two-phase flow issuing from the atomizer nozzle an electrical igniter *ED1* is used. The design and performance of the igniter have been also reported in [9]. The discharge current duration through the igniter is 50 ± 5 μs. The igniter electrodes are placed at a distance of 60 mm downstream of the nozzle in a conical discharge chamber. To generate a relatively strong shock wave in the fuel–air mixture via flame acceleration, the Shchelkin spiral *2* 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.

Downstream of the spiral section, a single 28-millimeter tube coil *3* of a length of 365 mm (measured along the axis) is attached. The coil favors the gasdynamic focusing of the shock wave generated by the accelerating flame [6–8].

The coil is followed by the second igniter *ED2*, which ignites the reactive mixture at the moment the shock wave arrives at its electrodes. Thereby, the second igniter is used to facilitate detonation initiation in each pulse according to a recently described mechanism [3–6]. 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 shock wave is performed with a special activation probe *4*. The design and performance of the probe have been described in [9]. Note that the second igniter is used only in the course of engine start-up.

The conical transition section *5* is used to reliably transition the detonation wave to the 41-millimeter tube. The latter is inserted coaxially into the main *6* 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 2.2 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. 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. The initial pressure in the receiver and fuel tank is 6 atm. During the experimental run, the pressure did not drop below 4.8 atm.

Air for the main tube is supplied with the low-head centrifugal compressor *11*. Liquid fuel for the main tube is fed with a standard low-pressure (3 atm) automobile fuel injector *10*. The mean diameter of *n*-hexane and *n*-heptane drops measured by the slide sampling method is 70–80 μm. The fuel supply system comprises a fuel tank *7*, as well as a fuel pump *8*, and valve *9*.

The air and fuel supply is continuous both in the predetonator and in the main tube. The initial temperature of air and liquid fuel was 293 ± 4 K.

To feed the igniter circuits, a high-voltage rectifier is used. The rectifier provides the operational voltage to charge the capacitors via a digital controller. The controller, based on the preset program, activates the igniters.

The demonstartor is suspended by steel ropes from the ceiling of an explosion chamber for measuring the jet thrust by the ballistic pendulum method.

Both the predetonator and main tube are equipped with piezoelectric pressure transducers. The data acquisition system is composed of analog-to-digital converters and two personal computers.

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 the activation probe. 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 of conversion of electrical energy E into the energy of the reactive medium was about 15%–20%..

PDE start-up and operation

The PDE demonstrator of Fig. 1 was tested in a series of experimental runs. The objective of the tests is to obtain stable operation of the demonstrator 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 a special spark plug installed in the main tube. Then, air and fuel were fed to the main tube. After the fuel–air mixture was ignited, there was steady-state diffusion combustion in the main tube, which caused heating of the tube wall. Figures 2*a* and 2*b* show the photographs of the spark plug (*a*) and flame (*b*) luminosity in the main tube during the heating stage.

When the wall temperature reached 50 ^{o}C, air and fuel were automatically supplied to the predetonator, spark plug was switched off, and by activating the first and second igniters at the given frequency and time delay, the operation mode of periodic combustion of the fuel–air mixture in the traveling detonation wave was attained (after 7–8 pulses). Thereafter the second igniter was deactivated and the demonstrator operated in the stable detonation mode with one (first) igniter.

(*a*)

(*b*)

Fig. 2

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 air and fuel flow rates in the predetonator and in the main tube, the discharge current in igniters ED1 and ED2, air pressure in the air-assist atomizer, and the dynamics of wave processes were recorded using piezoelectric pressure transducers.

The minimal mean fuel–air ratio in the predetonator required for the cold start of the demonstrator was 1.3 ± 0.1. The need in the fuel-rich mixture is attributed to the partial deposition of the injected fuel on the cold inner wall of the tube. After the transient initial period of operation, the optimal fuel–air ratio in both the predetonator and the main tube approaches the stoichiometric value. Air and fuel flow rates in the detonation mode measured in the predetonator are 6.7 ± 0.5 and 0.4 ± 0.1 g/s, respectively; and in the main tube, 60 ± 7 and 3.8 ± 0.1 g/s, respectively. The minimal energy of detonation initiation in the demonstrator

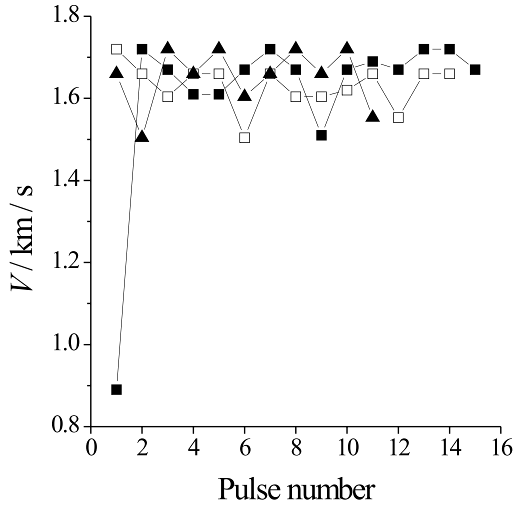


Fig. 3

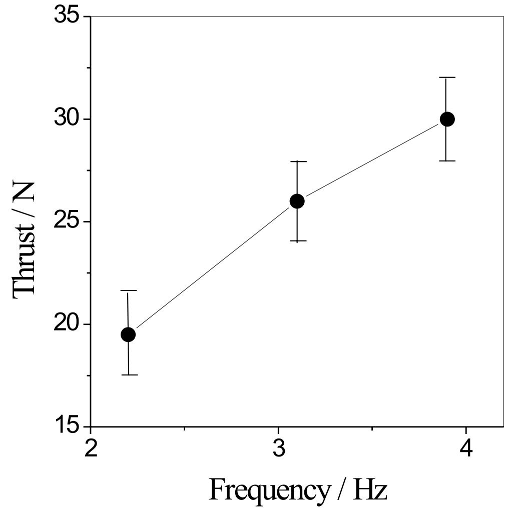


Fig. 4

was about 24 J per pulse. During the cold start, when two igniters were used, the minimal total initiation energy was about 130 J.

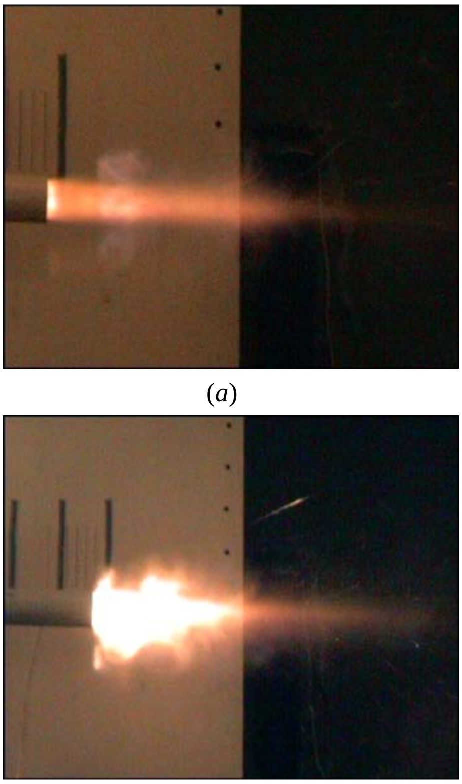
Figure 3 presents the shock wave velocities in the main tube during the operation of the PDE demonstrator of Fig. 1 in the detonation mode in three independent runs at a pulse repetition frequency of 3.9 Hz. The jet thrust was measured during the operation of the demonstrator at frequencies of 2.2, 3.1, and 3.9 Hz. Figure 4 presents the measured thrust versus frequency. The thrust of the PDE demonstrator is seen to increase linearly with frequency. The maximal measured thrust was 30 ± 2 N. The maximal achieved demonstrator operation frequency was 8 Hz.

It is seen from Fig. 3 that, in all the pulses, except for the first pulse in one of the three runs, detonation in the main tube propagated at an average velocity of 1600–1700 m/s. Note that, in case of detonation failure, the shock wave velocity at the measuring segment PT4–PT5 decreased to 900–1000 m/s. Figure 5 shows the typical photographic images of the plume produced by a detonation (Fig. 5*a*) and deflagration (Fig. 5*b*) at the demonstartor nozzle exit. In case of deflagration, the afterburning of fuel is observed in the plume.

Concluding remarks

Thus, the liquid-fueled air-breathing PDE demonstrator was designed and tested. Unlike the existing design of PDE demonstrators [1], in which a detonation wave in the predetonator is initiated using a fuel–oxygen mixture, the present demonstrator exhibits stable operation with periodic detonation of liquid fuel without using oxygen. The design of the demonstrator is based on several new findings.

In the experiments with the predetonator comprising the Shchelkin spiral followed by the tube coil, an electric igniter was used as a source of ignition of a two-phase mixture, rather than a source of a strong initiating shock wave. Consequently, DDT in the two-phase mixtures of hydrocarbon fuel with air was detected apparently for the first time. The predetonation distance in the tube 28 mm in diameter turned out to be close to 1 m, i.e., to 36 tube calibers, and the total predetonation distance until the main tube 51 mm in diameter is less than 1.8 m. For comparison, we note that a deflagration-to-detonation transition in a gaseous propane–air mixture requires no less than 260 calibers for a straight smooth tube [10] and more than 60 calibers for a straight tube with



(*a*)

(*b*)

Fig. 5

turbulence promoters in the form of regular obstacles [11]. The DDT is solely attributable to the use of the new element – tube coil [7,9]. The focusing effect of tube coils in reactive media has not hitherto been studied, although the phenomenon of focusing of shock waves in straight tubes after reflection from a nonflat end wall has long been known.

One of the most intriguing findings is the existence of the 'detonation peninsular' in the predetonator comprising the Shchelkin spiral followed by the tube coil [7,9]. The curvilinear reflecting surfaces in the coil might lead to gas-dynamic focusing of compression waves generated by the accelerating flame, their interaction with a lead shock wave and to detonation. However these effects appeared to be most pronounced at low ignition energies and vanish with increasing the ignition energy.

A new method for detonation initiation in sprays of the liquid fuel in air by successive triggering of two igniters was applied. The method was experimentally demonstrated in [3–6]. It complements the known methods – direct detonation initiation and DDT – and is based on forced ignition of a combustible mixture by an electric igniter in the vicinity of the front of a relatively weak primary shock wave. The second igniter provides rapid combustion of the mixture and transformation of the primary shock wave into a detonation. Detonation arises at short distances, the initiation energy being considerably lower than in the case of direct initiation by a single discharge. The use of a tube with a nearly limiting diameter and the Shchelkin spiral enhances the efficiency of the method by decreasing the energies required and extending the detonation initiation limits.

Thus, the replacement of the straight explosion tube 51 mm in diameter [9] by the combined predetonator shown in Fig. 1 decreased the initiation energy of detonation of two-phase *n*-hexane–air and *n*–heptane–air mixtures by two orders of magnitude: from 3300 to 24 J. Taking into account that the efficiency of the electric dischargers used was 15%–20%, one can expect that the use of other, more efficient, igniters will further allow one to decrease the initiation energy down to several joules per pulse.

The PDE demonstrator design was optimized for attaining a stable operation in the detonation mode rather than for obtaining high thrust performance. Nevertheless, a specific impulse of 700–800 s was gained at static conditions, which is roughly a half of the specific impulse relevant to hydrocarbon-fueled ramjets at Mach 2 flight conditions. 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).

Acknowledgements

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