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Liquid-Fueled, Air-Breathing Pulse Detonation Engine Demonstrator: Operation Principles and Performance

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A demonstrator of the liquid-fueled air-breathing pulse detonation engine with relatively low energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of onboard oxygen, and reasonable geometrical dimensions has been designed and tested. The design of the demonstrator combined several new principles and technologies. One of the most important design principles is the use of the "detonation peninsular" in the tube comprising the Shchelkin spiral followed by the tube coil. For the cold startup of the demonstrator, a new method for detonation initiation by successive triggering of two igniters was applied. The demonstrator design was optimized for attaining stable operation in the detonation mode. The thrust was measured by the ballistic pendulum technique during the operation of the demonstrator at frequencies of 2.2, 3.1, and 3.9 Hz. The maximal measured thrust was about 30 N. Because of acceptable weight and size characteristics of the pulse detonation engine demonstrator, the proposed process design can be regarded as promising for practical applications.

Nomenclature

C_1, C_2	=	capacitances of the main discharge of the dischargers D_1 and D_2
C_1, C_2	=	capacitors of the igniters ED1 and ED2
E	=	discharge energy
ED1, ED2	=	igniters
PT1 to PT6	=	pressure transducers
U	=	discharge voltage
V	=	mean shock wave velocity
X	=	measuring segment length
ΔE	=	uncertainty in the discharge energy
Δt	=	uncertainty in measuring the time interval
ΔU	=	uncertainty in the discharge voltage
$\Delta \tau$	=	time delay

I. Introduction

DURING the last several decades there has been a growing interest in the development of a new type of jet propulsion engine, the pulse detonation engine (PDE) [1]. Such 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 [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 expensive compressors and turbopump machinery. Moreover, PDE is potentially robust because it contains no moving parts and is 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 recently in [1]. Most of the concepts imply fuel preconditioning (prevaporizing, preheating, partial decomposition, blending, etc.) before injection to a detonation chamber of a PDE, and the use of additional oxygen to facilitate detonation initiation. The reason for this kind of

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preconditioning is very low detonability of liquid fuel sprays in air and therefore extremely high energy requirement for direct detonation initiation [1,3–6]. As for the run-up distances for deflagration-to-detonation transition (DDT), for gaseous hydrocarbons like propane they are known to be very long [7–9]. In oxygen suspensions of liquid hydrocarbons, 20–100 tube diameters were required for the DDT [10]. 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 [11].

The operational and safety considerations imply that the following requirements to practical PDEs should be met: 1) propellants should enter the combustion chamber in the form of liquid sprays, e.g., similar to conventional air-breathing liquid-fueled ramjets; 2) prevaporization devices should be preferably avoided; 3) devices for fuel premixing with air should be avoided; 4) the use of onboard oxygen should be avoided; 5) low-pressure fuel atomizers should be used; 6) electrical igniters with low ignition energy should be used; and 7) compact geometrical dimensions should be attained (e.g., less than 2–3 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 relatively low energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of additional oxygen, and reasonable geometrical dimensions. The design and operation principle of the PDE demonstrator is based on the extensive experimental studies reported elsewhere [11–21].

Section II of the paper provides a general description of the PDE demonstrator. Sections III and IV describe the single-pulse and multipulse performance of the predetonator. Section V describes the operational principle and performance of the PDE demonstrator.

II. PDE Demonstrator: General Description

The schematic of the PDE demonstrator is shown in Fig. 1. Its main parts are the predetonator and the main tube. In the following we use the term "predetonator" implying its functional objective to provide a detonation wave with as low ignition energy as possible for further transitioning of the wave to the main tube.

The predetonator was a combination of two tubes 28 and 41 mm in diameter connected by a transition cone. At one end of the 28-mm tube an air-assist liquid fuel atomizer was attached. The design and performance of the atomizer have been reported elsewhere [12,14,18,21]. Note that the atomizer provided 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 was used. The design and performance of the igniter have been also reported earlier [18,21]. The discharge current duration through the igniter was 50 ± 5 μs. The igniter electrodes were 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 400 mm long was inserted in the straight portion of the 28-mm tube. The spiral was wound from a steel wire 4 mm in diameter at a pitch of 18 mm. Downstream of the spiral section, a single 28-mm tube coil of a length of 365 mm (measured along the axis) was attached. The coil favored the gas-dynamic focusing of the shock wave generated by the accelerating flame [11,17,20,21]. The coil was followed by the second igniter, which ignited the reactive mixture at the moment the shock wave arrived at its electrodes. Thereby, the second igniter was used to facilitate detonation initiation in each pulse according to a recently described mechanism [12–18,21]. The design and performance of the second and first igniters were similar. The synchronization of the triggering of the second igniter with the arrival of the shock wave was performed with a special activation probe. The design and performance of the probe have been described in [18]. Note that the second igniter was used only in the course of cold engine startup. The conical transition section was used to reliably transition the detonation wave to the 41-mm tube. The latter was inserted coaxially into the main 51-mm tube 540 mm long. The annular gap between the main tube and the predetonator was used for introducing the main stream of the fuel–air mixture. The other end of the main tube was open to the atmosphere. The total length of the PDE demonstrator with the predetonator and the main tube was 2.2 m.

The predetonator and main tube had 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 allowed for implementing both the single-fuel and dual-fuel concepts of the liquid-fueled, air-breathing PDE [22,23] or apply oxygen-enriched air in the predetonator. However, the fuels used in all the experiments reported herein were liquid *n*-hexane or liquid *n*-heptane and atmospheric air was used as an oxidizer gas.

Air for the predetonator was fed to the atomizer from the 40-liter receiver connected with a compressor. Liquid fuel for the predetonator was fed to the atomizer from a pressurized fuel tank I. The fuel tank was continuously pressurized with air from the receiver. The initial pressure in the receiver and in the fuel tank was 6 atm. During an experimental run, the pressure in the receiver and in the fuel tank gradually decreased but did not drop below 4.8 atm. Because of such arrangement of air and fuel supply, the fuel–air ratio in the atomizer spray was kept approximately constant. There was a possibility to adjust fuel supply by a mechanical adjusting screw.

Air for the main tube was supplied with the low-head centrifugal compressor. Liquid fuel for the main tube was fed with a standard low-pressure (3 atm) automobile fuel injector. The mean diameter of

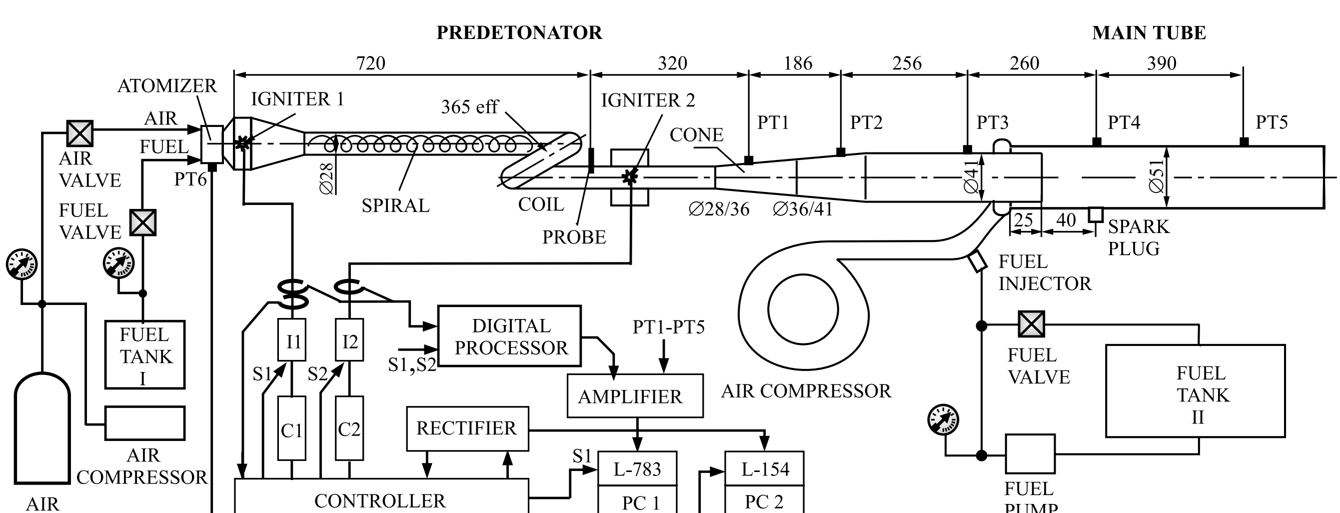


Fig. 1 Schematic of the PDE demonstrator. Dimensions are in millimeters.

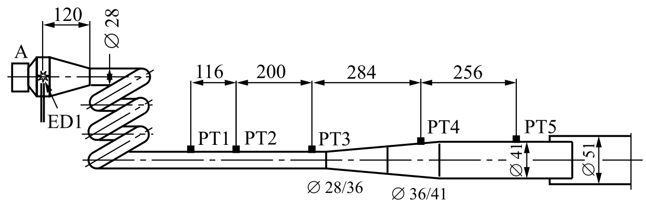


Fig. 2 Schematic of the predetonator with a three-coil section. Dimensions are in millimeters.

n-hexane and *n*-heptane drops measured by the slide sampling method [24] was 70–80 μm. The fuel supply system comprised a fuel tank II, as well as a fuel pump and valve.

The air and fuel supply, once activated by electromagnetic valves, was continuous both in the predetonator and in the main tube. The opening time of the electromagnetic valves in the air and fuel manifolds was 100 and 20 ms, respectively. The initial temperature of air and liquid fuel was 293 ± 4 K.

To feed the igniter circuits, a high-voltage rectifier was used [18]. The rectifier provided the operational voltage to charge the capacitors C_1 and C_2 via a digital controller. The controller, based on the preset program, activated the units I1 and I2, which, in their turn, activated the igniters.

The demonstrator was suspended by steel ropes from the ceiling of an explosion chamber for measuring the jet thrust by the ballistic pendulum method [19].

Both the predetonator and main tube were equipped with piezoelectric pressure transducers (PT1 to PT6). In some experiments, ionization probes were installed along the tube in the same measuring sections to identify detonations by observing simultaneous jumps at pressure and ionization current signals. The data acquisition system was 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 with a sampling rate of 200 Hz registered the voltage at the capacitors and the air pressure in the atomizer (with the pressure transducer PT6). The second converter with a sampling rate of 1 MHz registered the signals of pressure transducers PT1 to PT5, as well as the 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 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 at which electrical energy E was deposited into the working fluid was about 15–20% [19–21].

III. Predetonator Performance: Single-Pulse Experiments

The final design of the predetonator shown in Fig. 1 was based on the important preliminary findings described in this section. The tube diameter of the predetonator (28 mm) has been chosen based on the previous findings indicating that energy requirements for the direct initiation of the two-phase *n*-hexane–air and *n*-heptane–air detonations were minimal when the tube diameter approached the limiting value of 28 mm [18,21].

A. Effect of Tube Coils

Figure 2 shows a schematic of the smooth-walled predetonator tube 28 mm in diameter with an atomizer A, igniter ED1, and a three-coil section attached to the conical discharge chamber. The diameter of the coils was 140 mm (along the tube axis). This predetonator was mounted in the setup of Fig. 1 to check its performance in single-pulse experiments with the liquid *n*-hexane–air mixture.

Figure 3a shows the measured dependencies of the shock wave velocity V at different measuring segments on the electrical energy E deposited by the igniter. Notations ED1–PT1, PT1–PT2, etc., stand for the measuring segment between the igniter and pressure transducer PT1, pressure transducers PT1 and PT2, etc. At E ranging from 95 to 510 J, the shock wave velocity increases at all measuring segments of the predetonator. At the exit from the coil section (see PT1 record in Fig. 3b), the pressure profiles in the shock wave exhibit a stepwise shape. At a straight tube section after the coil (see PT2 and PT3 records in Fig. 3b) the pressure profile in the shock wave transforms to the triangular-shape signal. At ignition energies exceeding 470 J the detonation wave was detected in the experiments (see Figs. 3a and 3c). The measured propagation velocity of the detonation wave in Fig. 3c was 1675 ± 45 m/s.

This series of experiments indicates that the two-phase *n*-hexane–air detonation can be initiated in a smooth-walled tube 28 mm in diameter with three coils of the total length exceeding $\sim$1.4 m by using the igniter with $E > 470$ J. Note that similar experiments in a straight 28-mm tube required at least $E = 920$ J for the direct detonation initiation [18,21]. Thus, the use of tube coils allowed for a two-fold decrease of the critical initiation energy. This effect can be attributed to multiple reflections of the shock wave from the compressive surfaces inside the coils, which facilitate detonation initiation [11,17,20,21]. Note that the use of the tube coil sections with one or two coils required higher ignition energies than the use of the three-coil configuration.

The other important finding coming from Fig. 3a is that detonation arises when the mean shock wave velocity in the coils is about 700–800 m/s (see the symbols relevant to ED1–PT1 measuring segment). This finding implies that instead of using a powerful electrical igniter for detonation initiation one could look for a shock wave generator, which provides a shock wave of the same velocity at much lower electrical energy requirements. Such a generator can be based on the well-known Shchelkin spiral technique [25].

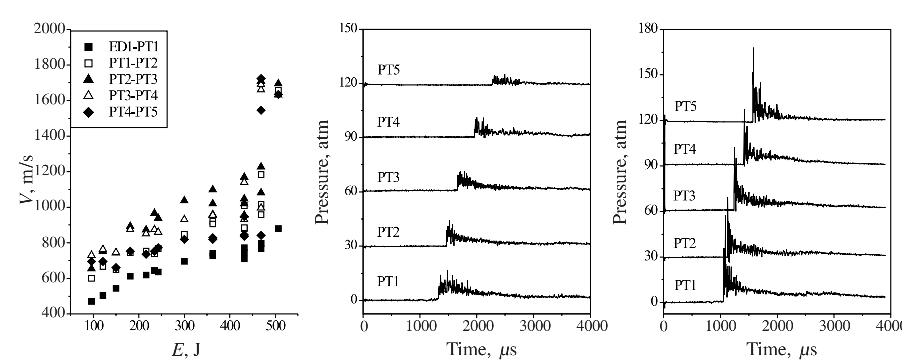


Fig. 3 a) Mean shock wave velocity at different measuring segments as a function of the ignition energy for the predetonator shown in Fig. 2, b) pressure records at $E = 300$ J, and c) pressure records at $E = 507$ J.

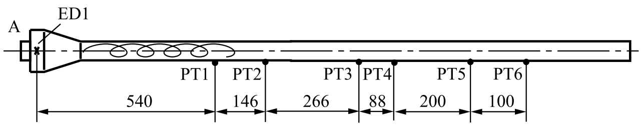


Fig. 4 Schematic of the predetonator with a Shchelkin spiral. Dimensions are in millimeters.

B. Effect of Shchelkin Spiral

Figure 4 shows a schematic of the predetonator tube 28 mm in diameter with an atomizer A, igniter ED1, and Shchelkin spiral 400 mm long wound from a steel wire 4 mm in diameter at a pitch of 18 mm. Similar to the tube with coils, this predetonator was mounted in the setup of Fig. 1 to check its performance in single-pulse experiments with the liquid n-hexane–air mixture.

Figure 5a shows the measured dependencies of the shock wave velocity V at different measuring segments on the electrical energy E deposited by the igniter. Notations in Fig. 5a are similar to those used in Fig. 3a. The maximal shock wave velocity measured in the tube was at the level of 800 ± 50 m/s within a wide range of the ignition energy from 24 to 130 J. After leaving the Shchelkin spiral, the shock wave propagated at a nearly constant velocity of 800 ± 50 m/s along a distance of 0.7–0.8 m. Figures 5b and 5c show the pressure profiles registered by pressure transducers PT1 to PT5 in two runs with $E = 24$ (Fig. 5b) and 60 J (Fig. 5c). Despite a large difference between the ignition energies, no considerable difference in the pressure records is observed. In a straight 28-mm tube with the Shchelkin spiral the detonation was not observed with spirals of different lengths (up to 750 mm) and wire diameter (up to 7 mm).

Nevertheless, this series of experiments indicates that the straight tube with the Shchelkin spiral can be readily used for generating shock waves propagating in the two-phase n-hexane–air mixture at the velocities of 800 ± 50 m/s. The minimal ignition energy attained in the setup of Fig. 4 was 24 J. At ignition energies below 24 J, ignition of the two-phase mixture failed due to flame blowoff from the igniter electrodes and reaction quenching. Special ignition arrangements should be used to further decrease this limit.

C. Shchelkin Spiral–Tube Coil Combination

The straight tube with the atomizer A, igniter ED1, and the Shchelkin spiral followed by the section with one tube coil 365 mm long appeared to be a very promising design for the practical predetonator shown in Fig. 6. Its geometry is similar to the predetonator of Fig. 1, except for the absence of the second igniter and different locations of pressure transducers. This predetonator was also mounted in the setup of Fig. 1 to check its performance in single-pulse experiments with the liquid n-hexane–air mixture.

Figure 7a shows the measured dependencies of the shock wave velocity V at different measuring segments on the electrical energy E deposited by the igniter. The notations in Fig. 7a are similar to those used in Figs. 3a and 5a and are self-explaining. The probe shown in Fig. 6 was the same as that used in the PDE demonstrator (see Fig. 1). At E ranging from 30 to 50 J, the detonation wave was registered at

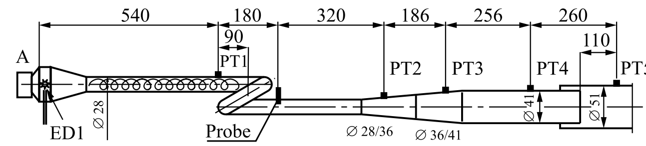


Fig. 6 Schematic of the predetonator with a combination of Shchelkin spiral and tube coil.

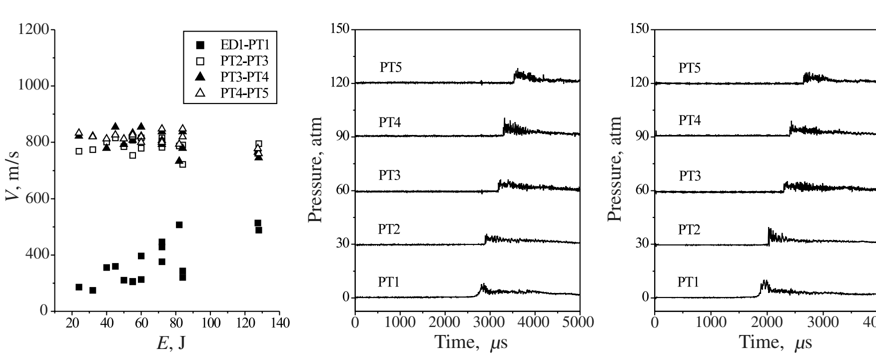
the measuring segments Probe–PT2, PT2–PT3, PT3–PT4, and PT4–PT5. The detonation wave arose at a distance of about 1 m from the igniter (about 36 tube diameters), transitioned to the 41-mm tube and then to the main 51-mm tube. The mean detonation velocity was 1600 ± 100 m/s. The pressure in the detonation wave attained the value of 15–20 atm (when omitting noise). Figures 7b and 7c show the pressure records at different measuring stations at $E = 30$ and 100 J, respectively. Curves "CC" correspond to the control channel record of the discharge current (near the origin of the curve) and of the probe signal (a pronounced spike).

The most intriguing finding in this experimental series is the existence of the "detonation peninsular" very similar to that discovered earlier [12,18,21]. At ignition energies ranging from 30 to 50 J the detonation initiation at the coil exit was highly reproducible and the detonation wave always transitioned to the main tube (see Fig. 7b). At ignition energies ranging from 50 to 130 J the detonation wave not always transitioned to the main tube (see Fig. 7c). 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 the 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 shock wave" (according to Shchelkin terminology [25]) inside the tube coil. Further reflections in the coil resulted in detonation initiation. At large ignition energies, the cumulating shock wave formed outside the coil and decayed due to the lack of reflections.

For better understanding of the accompanying phenomena, detailed computational and experimental studies are currently underway [26]. For example, Fig. 8 shows the establishment of the marginal detonation in the stoichiometric propane–air mixture after an incident shock wave with the propagation velocity of 1300 m/s passes through the U-bend of a planar channel 51 mm wide. Because of shock interaction with the walls of the U-bend, a transverse wave develops in the channel, which transforms to a single-head detonation. The details of the computational approach are reported in [26].

D. Shchelkin Spiral–Tube Coil–Second Igniter Combination

To improve the performance of the predetonator shown in Fig. 6, the second igniter ED2 was installed 90 mm downstream of the activation probe (Fig. 9). The idea of using the second igniter was discussed in detail elsewhere [12,18,21]. The second igniter when



a) b) c)

Fig. 5 a) Mean shock wave velocity at different measuring segments as a function of the ignition energy for the predetonator shown in Fig. 4, b) pressure records at $E = 24$ J, and c) pressure records at $E = 60$ J.

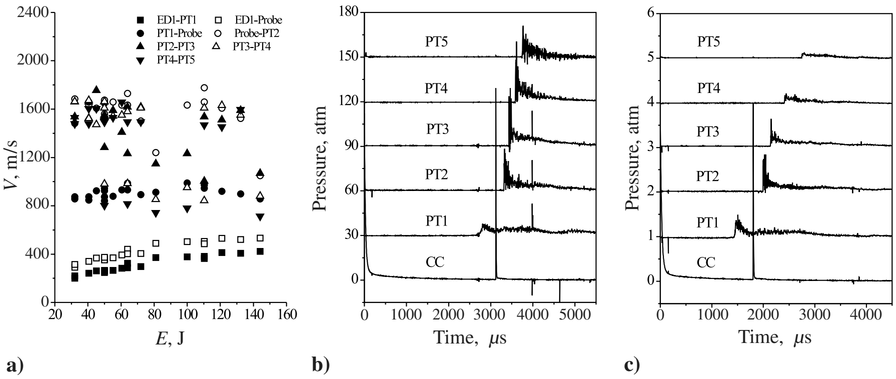


Fig. 7 a) Mean shock wave velocity at different measuring segments as a function of the ignition energy for the predetonator shown in Fig. 6, b) pressure records at $E = 30$ J, and c) pressure records at $E = 100$ J.

triggered in phase with the shock wave arrival at its position widened the detonation peninsular considerably. This property appeared to be very important for detonation initiation control at cold engine startup.

In the single-pulse experiments with this predetonator using liquid *n*-hexane–air mixture, the first igniter ED1 was used to ignite the mixture. The second igniter ED2 was used to accelerate the shock wave exiting from the tube coil to the detonation intensity when the detonation initiation in the Schelkin spiral–tube coil combination fails. The second igniter did not affect the detonation initiation process if the detonation wave formed in the tube coil and propagated downstream. The activation probe was used to provide precise synchronization of the second igniter triggering time with the shock wave arrival at its position. The probe activated the time-delay circuit in the digital controller, which, in its turn, triggered the second igniter (see Fig. 1). The time delay $\Delta\tau$ of the second-igniter triggering relative to the probe activation was preset in the controller. Figure 10 shows the example of pressure records relevant to this experimental series at the total ignition energy of two igniters of $E = E_1 + E_2 = 135$ J ($E_1 = 90$ J, $E_2 = 45$ J) and $\Delta\tau = 80$ μs. In addition to the record of the control channel (CC) and five records of pressure transducers PT1 to PT5, the voltage curve $U2$ for the second igniter is plotted to identify the timing of igniter triggering after the signal generated by the probe (a pronounced spike at the CC record). The drop of the voltage coincides with the second spike at the CC record.

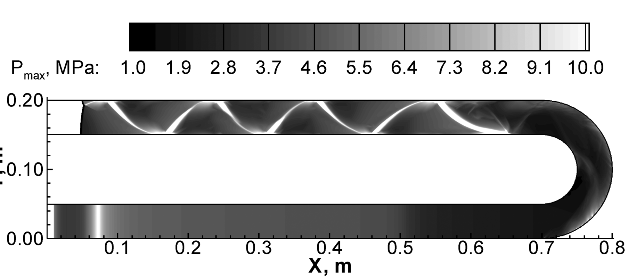


Fig. 8 Predicted maximum pressure traces at shock wave transition through the U-bend of a planar 51-mm wide channel filled with the stoichiometric propane–air mixture at normal initial conditions. The incident shock wave approaches the U-bend at 1300 m/s from the lower arm of the U-bend.

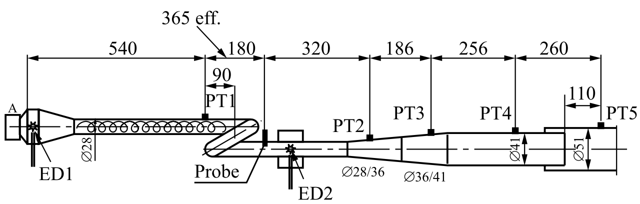


Fig. 9 Schematic of the predetonator with a combination of the Shchelkin spiral, tube coil, and second igniter.

The time interval between the spikes corresponds to the triggering delay time $\Delta\tau$ preset in the controller.

IV. Predetonator Performance: Multipulse Experiments

Figure 11a shows the mean velocities at different measuring segments of the predetonator of Fig. 9 in the multipulse operation mode with two igniters (i.e., during cold engine startup) at a frequency of 2.2 Hz as a function of the pulse number. The principle of pulse operation of the setup was the same as reported in [12,18]. In the run of Fig. 11a, a total detonation initiation energy of two igniters was 132 J ($U = 2300$ V, $C_1 = C_2 = 25$ μF) and $\Delta\tau = 80$ μs.

The mean velocity at the measuring segments PT2–PT3, PT3–PT4, and PT4–PT5 ranged from 1500 to 1800 m/s. The second igniter triggered at a properly chosen time served as an efficient means for detonation initiation control, in particular during the cold startup of the predetonator. Usually, after 7–8 detonation pulses the second igniter could be switched off and the predetonator operated in a stable detonation mode with a single (first) igniter.

Decrease in the total initiation energy to 110 J during cold engine startup 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 predetonator (Fig. 11b). This mode was characterized with a sort of regular detonation "go"–"no go" pulses. The propagation velocity of the shock waves in this run oscillated in the range from 800 to 1700 m/s.

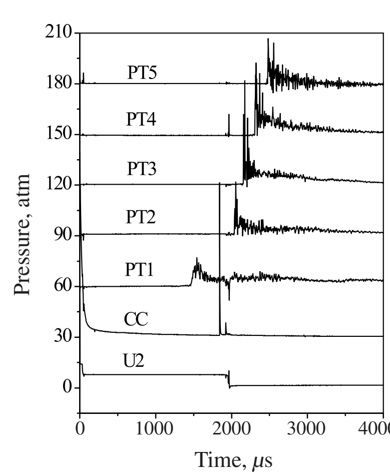
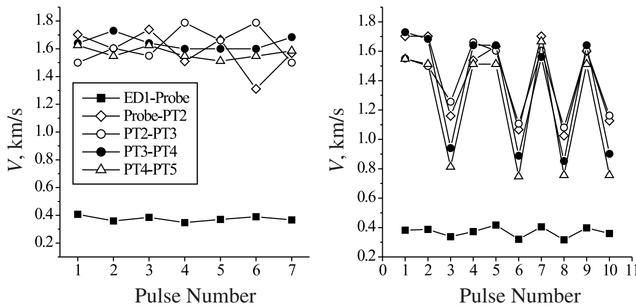
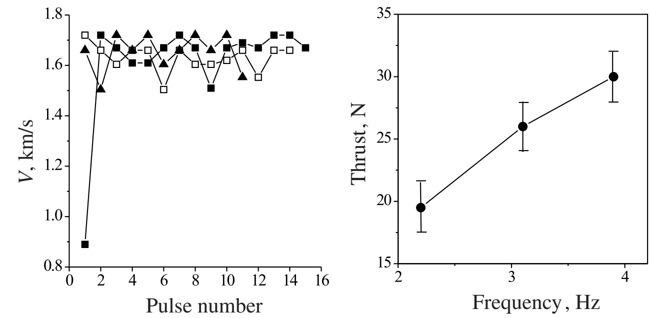


Fig. 10 Pressure records relevant to the single-pulse operation of the predetonator of Fig. 9 with two successively triggered igniters ED1 and ED2 at a total ignition energy of $E = 135$ J ($C_1 = 50$ μF, $C_2 = 25$ μF, $U = 1900$ V, and $\Delta\tau = 80$ μs). CC and U2 curves stand for the control channel record and voltage record at the igniter ED2.



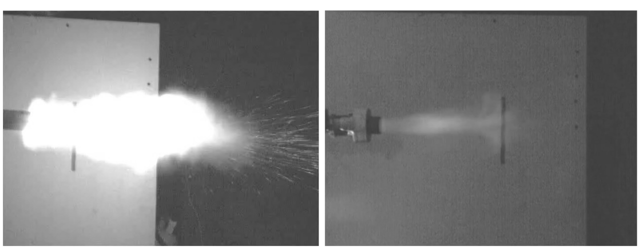
a) b)

Fig. 11 Multipulse operation of the predetonator of Fig. 9 with two igniters at cold startup. Symbols show pulse-to-pulse variation of the mean velocity of the pressure wave at different measuring segments. Operation frequency is 2.2 Hz. Total ignition energy per pulse is a) 132 and b) 110 J.



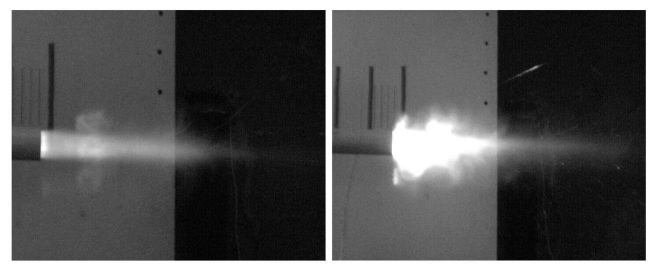
a) b)

Fig. 15 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 in three independent runs. b) Measured thrust vs frequency.



a) b)

Fig. 12 Photographs of the predetonator nozzle plume at a) detonation failure and b) successful detonation initiation.



a) b)

Fig. 16 PDE nozzle plume produced by a) detonation and b) deflagration.

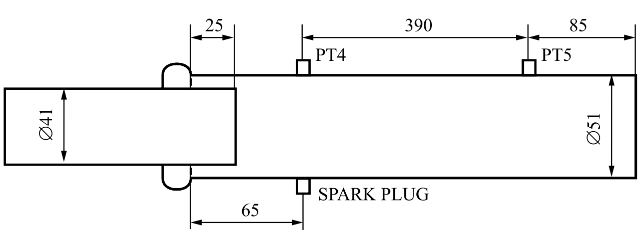
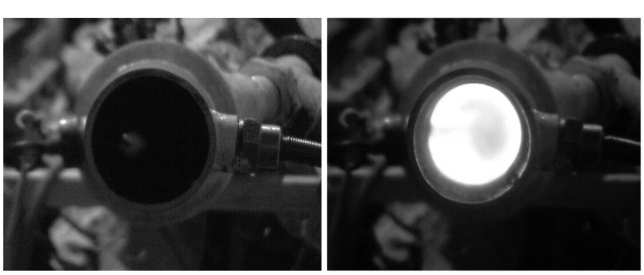


Fig. 13 Measuring segment in the main tube.



a) b)

Fig. 14 Preheating the main tube during the starting procedure: a) startup spark plug luminosity and b) onset of a two-phase spray flame.

To attain a stable detonation mode allowing for deactivating the second igniter, more than 12–15 pulses were required.

The maximal frequency attained in the predetonator was 8 Hz. The frequency limitation is caused by the air supply system used. The mass flow rates of fuel and air at predetonator operation in the stable detonation mode were 0.4 ± 0.1 and 6.7 ± 0.5 g/s, respectively.

Figures 12a and 12b show the photographs of plumes generated by the predetonator at "no go" and "go" detonation conditions (pulses No. 6 in Fig. 11b and No. 5 in Fig. 11a, respectively).

V. PDE Demonstrator: 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 demonstrator at different operation frequencies. Figure 13 shows the schematic of the main tube with two pressure transducers PT4 and PT5 and a startup spark plug.

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 startup spark plug. 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 14a and 14b show the photographs of the startup spark plug activation (Fig. 14a) and spray flame (Fig. 14b) luminosity in the main tube during the heating stage.

When the wall temperature reached 50°C, the air and fuel valves automatically opened for supplying air and fuel to the predetonator, and the first and second igniters were activated at a given frequency and time delay, while the startup spark plug was deactivated. As a result, 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. 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 as well as the discharge current in igniters ED1 and ED2 were monitored. The air pressure in the air-assist atomizer and the dynamics of wave processes were recorded using piezoelectric pressure transducers PT1 to PT6 (Fig. 1).

The minimal mean fuel–air ratio in the predetonator required for the cold startup 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 approached the stoichiometric value. This observation is based on the measurements of fuel consumption rate in experiments with the initially hot tube. Air and fuel flow rates in the detonation mode measured in the predetonator were 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. Because of the existence of two fueling zones there could be some overlap between them downstream from the entrance to the main tube. However, as the mass flow rates of fuel in the predetonator are about the order of magnitude less than in the main tube, this issue was not addressed in this study. The minimal energy of detonation initiation in the demonstrator 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 15a presents the shock wave velocities at the measuring segment PT4–PT5 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 15b presents the measured thrust vs frequency. The thrust of the PDE demonstrator is seen to increase linearly with frequency. The maximal measured thrust was 30 ± 2 N. The error in thrust measurements includes the effect of tare forces from the air and fuel delivery systems and run-to-run variability. The maximal achieved demonstrator operation frequency was 8 Hz.

It is seen from Fig. 15a 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 16 shows the typical photographic images of the plume produced by a detonation (Fig. 16a) and deflagration (Fig. 16b) at the demonstartor nozzle exit. In case of deflagration, the afterburning of fuel is observed in the plume.

VI. Concluding Remarks

Thus, the liquid-fueled, air-breathing PDE demonstrator was designed and tested. Unlike the existing designs of PDE demonstrators (see [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 additional oxygen. The design of the demonstrator combined several new principles and technologies.

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 diameters, and the total predetonation distance until the main tube 51 mm in diameter was less than 1.8 m. For comparison, we note that a DDT in a gaseous propane–air mixture required no less than 260 tube diameters for a straight smooth tube [7] and more than 60 tube diameters for a straight tube with turbulence promoters in the form of regular obstacles [8,9].

The DDT is solely attributable to the use of the new element–tube coil [11,17,20,21]. 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 [27]. Even the use of smooth-walled tubes with coils allows one to decrease the critical energy of direct detonation initiation at least by a factor of 2, as shown in Sec. III.A.

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 [11,17,20,21]. 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 [12–18,21]. 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 [12,18,21] 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 2 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 more efficient electrical igniters will further allow one to decrease the initiation energy. Special flow arrangements (e.g., recirculation zones) to facilitate ignition in the high-speed two-phase flow near the atomizer nozzle can also help decrease the initiation energy down to several joules per pulse.

The PDE demonstrator design was optimized for attaining 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 half of the specific impulse relevant to hydrocarbon-fueled ramjets at Mach 2 flight conditions. The obtained value of the specific impulse is mainly explained by incomplete fuel combustion caused by low operation frequency and short main tube. However, owing to acceptable weight and size characteristics of the demonstrator, the proposed process design can be regarded as promising for practical applications. The main problems to be solved are 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) and to increase the delivered specific impulse by optimizing the length of the main tube and the operation frequency.

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References

[1] Roy, G. D., Frolov, S. M., Borisov, A. A., and Netzer, D. W., "Pulse Detonation Propulsion: Challenges, Current Status, and Future Perspective," *Progress in Energy and Combustion Science*, Vol. 30, No. 6, 2004, pp. 545–672.

[2] Zel'dovich, Ya. B., "On the Power Engineering Use of Detonation Combustion," *Journal of Technical Physics*, Vol. 10, No. 17, 1940, pp. 1453–1461.

[3] Borisov, A. A., and Gelfand, B. E., "Review of Papers on Detonation of Two-Phase Systems," *Archivum Thermodynamiki Spalania*, Vol. 7, No. 2, 1976, pp. 273–287.

[4] Samirant, M., Smeets, G., Baras, Ch., Royer, H., and Oudin, L. R., "Dynamic Measurements in Combustible and Detonable Aerosols," *Propellants, Explosives, Pyrotechnics*, Vol. 14, No. 1, 1989, pp. 47–56.

[5] Benedick, W. B., Tieszen, S. R., Knystautas, R., and Lee, J. H. S., "Detonation of Unconfined Large-Scale Fuel Spray—Air Clouds," *Dynamics of Detonations and Explosions: Detonations*, edited by A. L. Kuhl, J.-C. Leyer, A. A. Borisov, and W. A. Sirignano, Vol. 133, Progress in Astronautics and Aeronautics, AIAA, New York, 1991, pp. 297–310.

[6] Dabora, E. K., "Lean Detonation Limit of Sensitized Kerosene Sprays in Air," *Dynamics of Detonations and Explosions: Detonations*, edited by A. L. Kuhl, J.-C. Leyer, A. A. Borisov, and W. A. Sirignano,

Vol. 133, Progress in Astronautics and Aeronautics, AIAA, New York, 1991, pp. 311–324.

[7] Veyssiere, B., Kerampran, S., Proust, C., and Gilles, S. "Effect of Tube Length on Flame Acceleration and DDT in Tubes of Constant Cross Section," *Proceedings of the 19th International Colloquium on Dynamics of Explosions and Reactive Systems*, Paper 154, Hakone, Kamagawa, Japan, 2003.

[8] Santoro, R. J., Lee, S.-Y., Conrad, C., Brumberg, J., Saretto, S., Lecat, P., Pal, S., and Woodward, R. D., "Deflagration-to-Detonation Transition Studies for Multicycle PDE Applications," *Advances in Confined Detonations*, edited by G. Roy, S. Frolov, R. Santoro, and S. Tsyganov, Torus Press, Moscow, 2002, pp. 243–249.

[9] Lee, S.-Y., Watts, J., Saretto, S., Pal, S., Conrad, C., Woodward, R. D., and Santoro, R. J., *Journal of Propulsion and Power*, Vol. 20, No. 6, 2004, pp. 1026–1036.

[10] Pierce, T. N., and Nicholls, J. A., "Two-Phase Detonations with Bimodal Drop Distributions," *Acta Astronautica*, Vol. 17, No.4–5, 1972, p. 703.

[11] Frolov, S. M., Basevich, V. Ya., and Aksenov, V. S., "Decreasing the Predetonation Distance in a Drop Explosive Mixture by Combined Means," *Doklady Physical Chemistry (Translation of the physical chemistry section of Doklady Akademii Nauk)*, Vol. 401, Pt. 1, 2005, pp. 28–31.

[12] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Initiation of Spray Detonation by Successive Triggering of Electric Discharges," *Advances in Confined Detonations*, edited by G. Roy, S. Frolov, R. Santoro, and S. Tsyganov, Torus Press, Moscow, 2002, pp. 150–157.

[13] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Detonation Initiation by Controlled Triggering of Electric Discharges," *Journal of Propulsion and Power*, Vol. 19, No. 4, 2003, pp. 573–580.

[14] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Initiation of Confined Spray Detonation by Electric Discharges," *Confined Detonations and Pulse Detonation Engines*, edited by G. Roy, S. Frolov, R. Santoro, and S. Tsyganov, Torus Press, Moscow, 2003, pp. 157–174.

[15] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Initiation of Gaseous Detonation by a Traveling Forced Ignition Pulse," *Doklady Physical Chemistry (Translation of the physical chemistry section of Doklady Akademii Nauk)*, Vol. 394, Pt. 1, 2004, pp. 16–18.

[16] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Detonation Initiation in Liquid Fuel Sprays by Successive Electric Discharges," *Doklady Physical Chemistry (Translation of the physical chemistry section of Doklady Akademii Nauk)*, Vol. 394, Pt. 2, 2004, pp. 39–41.

[17] Frolov, S. M., Basevich, V. Ya., and Aksenov, V. S. "Combustion Chamber with Intermittent Generation and Amplification of Propagating Reactive Shocks," *Application of Detonation to Propulsion*, edited by G. Roy, S. Frolov, and J. Shepherd, Torus Press, Moscow, 2004, pp. 240–249.

[18] Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov, S. A., "Spray Detonation Initiation by Controlled Triggering of Electric Dischargers," *Journal of Propulsion and Power*, Vol. 21, No. 1, 2005, pp. 54–64.

[19] Frolov, S. M., Basevich, V. Ya., and Aksenov, V. S., "Air-Breathing Liquid-Fueled Pulse Detonation Engine Demonstrator," *Doklady Physical Chemistry (Translation of the physical chemistry section of Doklady Akademii Nauk)*, Vol. 401, Pt. 2, 2005, pp. 29–31.

[20] Frolov, S. M., Aksenov, V. S., and Basevich, V. Ya., "Initiation of Detonation in Sprays of Liquid Fuel," *Advances in Chemical Physics*, Vol. 24, No. 7, 2005, pp. 71–79.

[21] Frolov, S. M., Basevich, V. Ya., and Aksenov, V. S., "Optimization Study of Spray Detonation Initiation by Electric Discharges," *Shock Waves*, Vol. 14, No. 3, 2005, pp. 175–186.

[22] Frolov, S. M., and Basevich, V. Ya., "Application of Fuel Blends for Active Detonation Control in a Pulsed Detonation Engine," International Symposium on Air Breathing Engines (ISABE) Paper 99-135, Sept. 1999.

[23] Frolov, S. M., Basevich, V. Ya., and Vasil'ev, A. A., "Dual-Fuel Concept for Advanced Propulsion," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. Roy, S. Frolov, D. Netzer, and A. Borisov, Elex-KM Publishers, Moscow, 2001, pp. 315–332.

[24] Elkotb, M. M., "Fuel Atomization for Spray Modelling," *Progress in Energy and Combustion Science*, Vol. 8, No. 1, 1982, pp. 61–91.

[25] Shchelkin, K. I., *Fast Combustion and Spinning Detonation of Gases*, Voenizdat, Moscow, 1949, pp. 44–73.

[26] Frolov, S. M., Aksenov, V. S., and Shamshin, I. O., "Detonation Propagation Through U-bends," *Nonequilibrium Processes: Combustion and Detonation*, edited by G. D. Roy, S. M. Frolov, A. M. Starik, Torus Press, Moscow, 2005, pp. 348–364.

[27] Sturtevant, B., and Kulkarny, V. A., "The Focusing of Weak Shock Waves," *Journal of Fluid Mechanics*, Vol. 73, No. 4, 1976, pp. 651–671.

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