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Deflagration-to-Detonation Transition in a Kerosene–Air Mixture

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The possibility of deflagration-to-detonation transition (DDT) has been demonstrated for the first time in a tube in a continuous flow of a prevaporized TS-1 jet kerosene–air mixture at atmospheric pressure. These results open up new possibilities for the design of air-breathing propulsion systems with fuel combustion in the detonation mode.

The low detonability of jet kerosene–air mixtures is the major obstacle to the development of an air-breathing pulse detonation engine (PDE) [1]. Currently, work is underway to considerably decrease the detonation initiation energy of hydrocarbon fuels, as well as to reduce the predetonation distance and time [2]. On the one hand, to achieve this aim, it is suggested to use active chemical additives to fuels, fuel blends, emulsified fuels, barbotage of fuel with an active gas, preliminary thermal and radiation treatment of fuel, fuel prevaporization, and premixing of fuel with oxygen or air. Notwithstanding the fact that some of these solutions are believed to be promising, their use in PDEs for flying vehicles is limited by severe safety requirements for their operation, weight restrictions, etc. On the other hand, physical methods aimed at reducing the DDT distance and time are currently being studied. It is suggested to use prechamber jet [3] and plasma jet [4] ignition, traveling igniters [5], regular obstacles [6, 7], tubes of near-limiting diameter [7], regular shaped reflectors of shock waves [8], or tube U bends [9] or tube coils [7, 10], as well as different combinations thereof [7, 10, 11].

This work deals with experimental studies aimed at obtaining detonation of a TS-1 jet kerosene–air mixture at the shortest distances and minimal ignition energies. A combination of methods and means was used, including the enhancement of fuel detonability, flame acceleration by means of regular obstacles, and multiple reflections of the generated shock wave in a special focusing device, a coil.

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Figure 1 shows the scheme of the experimental setup, consisting of continuous-flow air-assisted fuel atomizer *1*, heated detonation tube *2*, igniter *3*, pressure transducers *4*, flame arrester *5*, air cylinder *6*, fuel valve *7*, air compressor *8*, fuel tank *9*, fuel filter *10*, digital controller *11*, power supply unit *12*, personal computer *13* with a 16-channel analog-to-digital converter, relay *14*, fuel prevaporizer *15*, thermostat *16*, electrical heaters *17* and *18*, and thermocouples *19*. The fuel and air feed systems maintained a constant ratio between the mass flow rates of the mixture components—TS-1 liquid kerosene and air—in the fuel atomizer due to the same feed pressure (from 6 to 4.8 atm) of these components. Mixing of the fuel with air was started in the fuel atomizer and completed in the detonation tube 52 mm in diameter and 3 m in length. The air-assisted fuel atomizer ensured very fine atomization of kerosene into droplets 5–10 μm in diameter. The size distribution of droplets was measured by the soot sampling method [12]. Air was fed from cylinder *6* connected with air compressor *8*. The two-phase kerosene–air mixture was continuously fed into prevaporizer *15*. The prevaporizer was used for enhancing the detonability of the fuel–air mixture, according to the conclusions in [13]. Passing through the prevaporizer, kerosene was partially vaporized on the hot walls. Thus, the prevaporizer contained a heterogeneous mixture of air, kerosene vapor, kerosene droplets from the air-assisted fuel atomizer, and mist (a condensate of the vaporized kerosene, Fig. 1a); this mixture was fed through an outlet nozzle into the straight section of the detonation tube with a Shchelkin spiral (Fig. 1b) and then either into the straight smooth-walled tube section or into the smooth-walled tube coil (Fig. 1c). The end of the detonation tube was connected to the flame arrester, an open-to-atmosphere tube section 80 mm in diameter tightly packed with a corrugated metal tape. For diagnosing explosion processes, water-cooled high-frequency piezoelectric pressure transducers PT1–PT7 of the LKh type and ionization probes were mounted in the detonation tube.

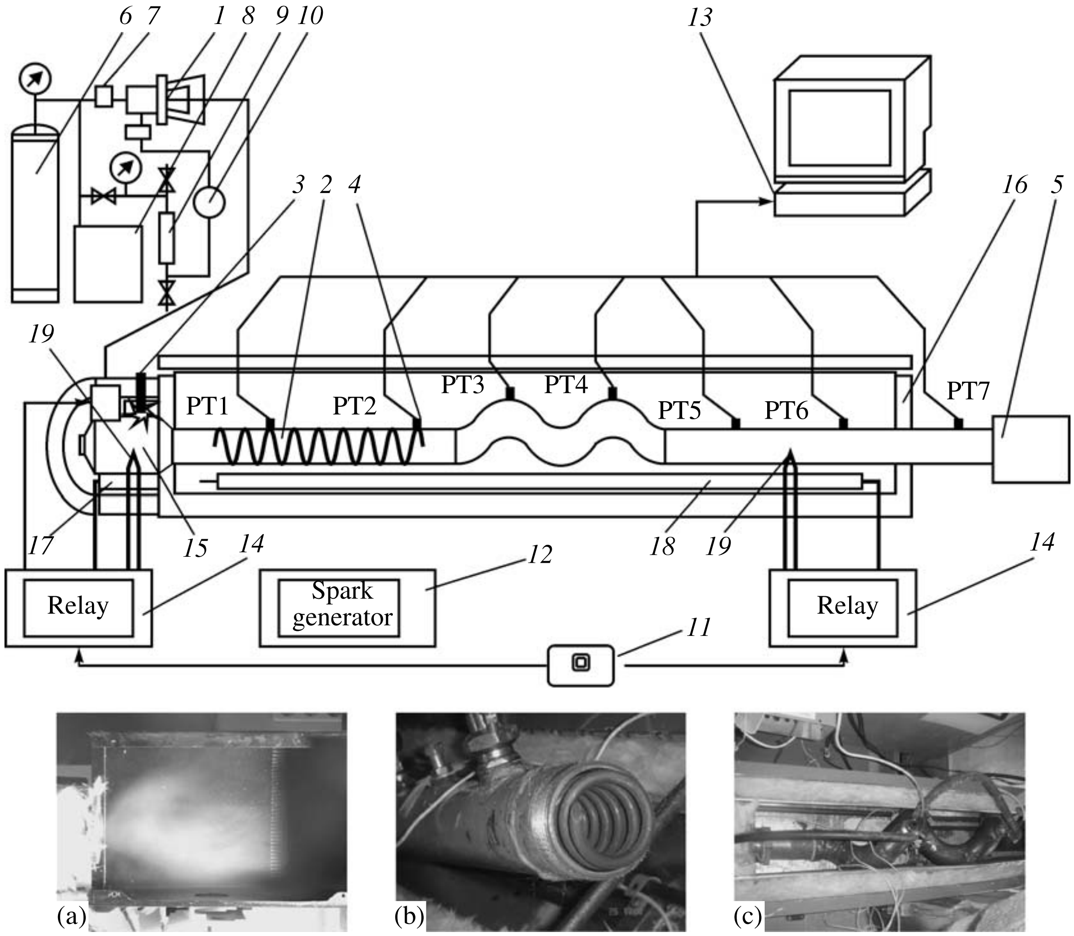

Fig. 1. Scheme of the experimental setup with (a) a kerosene prevaporizer, (b) a Shchelkin spiral, and (c) a tube coil.

The tube heating system comprised two thermostats: the thermostat of prevaporizer *15* and detonation tube thermostat *16*. The prevaporizer thermostat was equipped with 0.6-kW electrical heater *17*, and 2.5-kW three-section electrical heater *18* and thermocouples *19* were placed into the detonation tube thermostat. Thermostat operation was controlled by relay *14*. The typical duration of one run in the preheated tube was about 1 s.

The prevaporizer wall temperature in the runs was (190 ± 10)°C. The temperature of the straight tube section with the Shchelkin spiral was 120–130°C, and the temperature of the adjacent tube section to pressure transducer PT6 was 110–120°C. The tube section between PT6 and the flame arrester was not thermostated and had a temperature of 20–30°C.

Two series of runs were carried out. In the runs, the tube section with the Shchelkin spiral was connected either with the straight smooth-walled tube (the first series) or with the tube coil shown in Fig. 1c. The positions of the pressure transducers in the two series are presented in the table. The distance to the transducers was measured from the igniter.

The Shchelkin spiral was used for flame acceleration and generation of the shock wave propagating at a velocity of 800–900 m/s [7, 10, 11]. The spiral was wound from a steel wire 7 mm in diameter with a pitch of 22 mm. The spiral length in both series was 800 mm. The spiral was placed at a distance of 70 mm from the outlet nozzle of the prevaporizer. The fuel–air mixture was ignited in the prevaporizer either by an modified automobile spark plug or by a three-electrode electric discharger [14].

In the runs of the first series, the ignition energy was varied within the range 5–700 J. The ignition energy was calculated from the capacity of the discharge capacitor and voltage. Figure 2 shows the results of measuring the pressure wave velocity along the detonation tube in four typical runs of the first series. The symbols on the curves were used for identifying the data of each run. As is seen, in the straight tube, DDT did not occur even at high ignition energy: the pressure wave velocity at the exit from the section with the Shchelkin spiral was no more than 1200 m/s.

In the runs of the second series, the tube coil was placed downstream of the section with the Shchelkin

Location of pressure transducers in two series of runs

Series	PT1	PT2	PT3	PT4	PT5	PT6	PT7
1. Straight tube	622 mm, section with a Shchelkin spiral	872 mm, section with a Shchelkin spiral	1118 mm, straight tube	1416 mm, straight tube	1670 mm, straight tube	1970 mm, straight tube	2270 mm, straight tube
2. Tube with a coil	622 mm, section with a Shchelkin spiral	872 mm, section with a Shchelkin spiral	1292 mm, coil	1662 mm, coil	1992 mm, straight tube	2292 mm, straight tube	2592 mm, straight tube

spiral. The idea of coupling a Schelkin spiral with a tube coil is based on the experimental results in [10, 11], where the effect of tube coils on DDT in a flow of two-phase *n*-hexane–air and *n*-heptane–air mixtures was demonstrated for the first time. The coil consisted of two turns of a tube with an outer diameter of 60 mm (the inner diameter was 52 mm) wound with a pitch of 255 mm around a straight rod 28 mm in diameter. The ignition energy in the second series of runs was varied within the range 5–180 J.

As distinct from the first series, DDT was repeatedly detected in the flow of a TS-1 kerosene–air mixture in the runs of the second series. Figure 3 shows the results of measuring the pressure wave velocity along the detonation tube in 12 runs of the second series with the ignition energy from 5 to 100 J. As in Fig. 2, the symbols on the curves were used only for identifying the data of each run. It is seen that, in the tube with the coil, DDT occurred even at the ignition energy 5 J: the pressure wave velocity at the exit from the coil (at a distance of about 2 m from the igniter) was 1600–1800 m/s, i.e., was at the level of the Chapman–Jouguet (C–J) detonation velocity for hydrocarbon–air mixtures. The detonation wave generated in the coil propagated at a constant velocity along the last two measuring segments between transducers PT5 and PT6 and between PT6 and PT7. Current pulses detected by the ionization probes in the sections where transducers PT5, PT6, and PT7 were located coincided with the moments of arrival of the shock wave at the corresponding section, which confirmed the existence of detonation.

Figure 4 shows, as an example, the records of pressure transducers PT1–PT7 in the run with the ignition energy 5 J. In this run, detonation was initiated at the tube segment between transducers PT5 and PT6 about 6 ms after ignition. It is evident that the DDT in the second series of runs is completely due to the use of the coil, in which multiple reflections of shock waves and pressure waves generated by the accelerated flame took place [7, 10, 11].

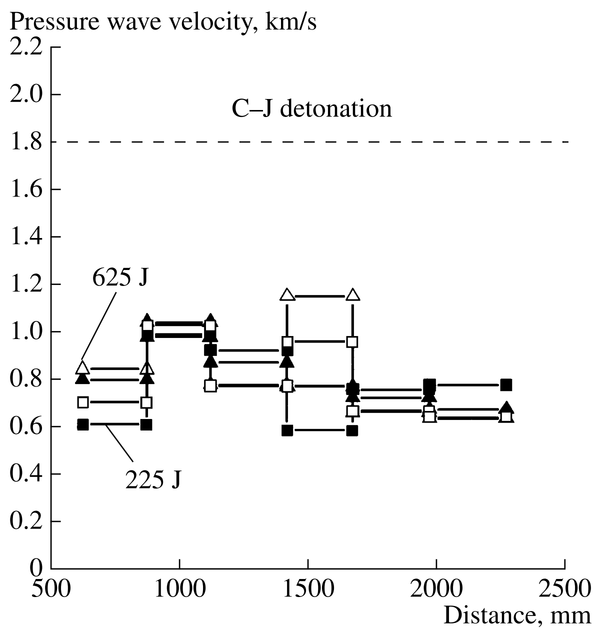

Fig. 2. Change in the pressure wave velocity in a kerosene–air flow in four runs in the straight detonation tube at an ignition energy from 225 to 625 J.

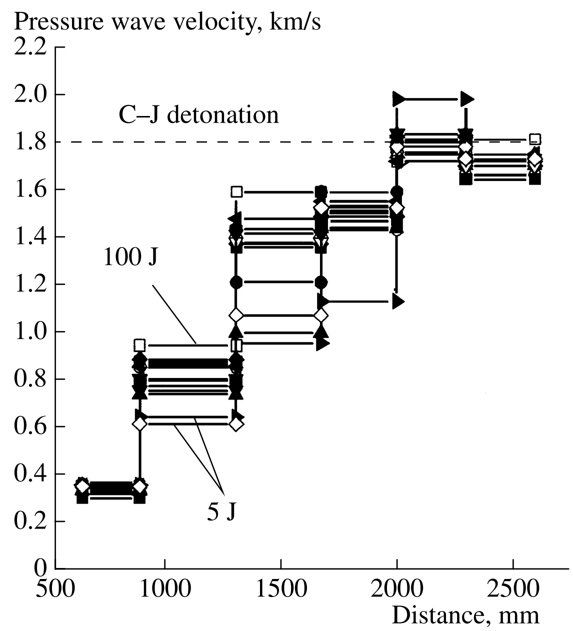

Fig. 3. Change in the pressure wave velocity in a kerosene–air flow in 12 runs in the detonation tube with the Shchelkin spiral and the coil at an ignition energy from 5 to 100 J.

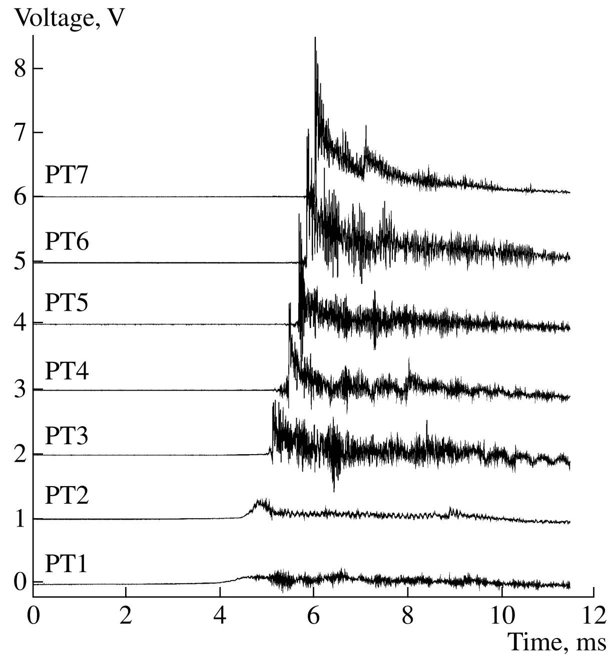

Fig. 4. Records of pressure transducers PT1–PT7 for the DDT in the run with the ignition energy 5 J.

Thus, we have demonstrated, for the first time, the possibility of DDT in a continuous flow of a mixture of partially prevaporized TS-1 jet kerosene with air at atmospheric pressure and a tube wall temperature of 110–130°C. In the thermostated tube 52 mm in diameter consisting of a kerosene prevaporizer, a straight section with a Shchelkin spiral, and a smooth-walled coil, DDT occurred at a distance of about 2 m in 5–6 ms at a low ignition energy of 5 J. These results open up new possibilities for the design of air-breathing propulsion systems with fuel combustion in the detonation mode, PDEs.

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