Multipulse Detonation Initiation by Spark Plugs and Flame Jets

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The possibility of single-pulse and multipulse DDT in partly prevaporized kerosene TS-1 (Russian analog of JetA) – air mixture at normal atmospheric pressure in a heated tube 52 mm in diameter was demonstrated experimentally. The DDT was repeatedly detected with a run-up distance of about 2 m and time of 7–8 ms at ignition energy as low as 100 mJ. The successful DDT became possible solely due to the application of the "Shchelkin spiral – tube coil" combination we proposed and tested previously.

Introduction

Low detonability of jet propulsion kerosene in air is the key barrier for the progress in the development of air-breathing pulse detonation engines (PDE) [1]. In view of it, various approaches are currently under consideration, which are aimed at decreasing the detonation initiation energy and predetonation distance and time of kerosene–air mixtures. Chemical sensitization, blending, emulsifying, bubbling, thermal and irradiation preconditioning, prevaporization, and premixing of kerosene and/or air are several approaches applied to achieve the goal. Despite some of these approaches appear promising there are still the issues of their feasibility for propulsion applications with low-weight, low-energy and safe-operation constraints. The other directions of PDE-oriented research concentrate on various physical methods to accelerate deflagration-to-detonation transition (DDT) in fuel–air mixtures, namely, flame and plasma jet ignition, obstacle-forced flame acceleration, shock reflections and focusing, resonant amplification of shocks by traveling ignition pulses, U-bend tubes and tube coils, and various techniques applying the combinations of the approaches listed.

The experimental research outlined in this paper was aimed at obtaining detonations of jet propulsion kerosene TS-1 (Russian analog of Jet-A) in a tube 52 mm in diameter at short distances by arranging combined approaches enhancing fuel detonability, obstacle-forced flame acceleration, and shock-to-detonation transition.

Experimental Setup

Figure 1 shows the experimental setup, comprising kerosene injector *1*, detonation tube *2*, igniter *3*, pressure transducers *4*, detonation arrester *5*, air bottle *6*, fuel valve *7*, air compressor *8*, kerosene tank *9*, fuel filter *10*, digital controller *11*, power supply *12*, PC *13*, control relay *14*, prevaporizer *15*, thermostat *16*, electrical heaters *17* and *18*, and thermocouples *19*. The fuel and air supply system provides the supply of fuel mixture components (liquid kerosene TS-1 and air) in constant proportion due to the same driving pressure. Mixing of fuel and air starts in the air-assist atomizer *1* and terminates in the detonation tube *2* of internal diameter 52 mm and 3 m long. The detonation tube is equipped with the igniter *3*, water-cooled high-frequency pressure transducers PT1 to PT7 and/or ionization probes. The air-assist atomizer provides very fine kerosene drops 5 to 10 μm in diameter. Drop size distribution was measured by a soot-sampling method [2]. The air is fed from the air bottle *6* connected to air compressor *8*. The two-phase fuel–air mixture is continuously injected to the prevaporizer section *15* of the detonation tube *2*. In this section, kerosene drops are partly vaporized and the hybrid drop – vapor – air mixture follows to the tube section with the Shchelkin spiral and shock-focusing elements with low hydraulic resistance. To the end of the detonation tube, a detonation arrester is attached, which is a piece of 80-mm tube filled with the roll of thin corrugated metal tape.

The heating system consists of the thermostat with the prevaporizer *15* and the thermostat *16* with the

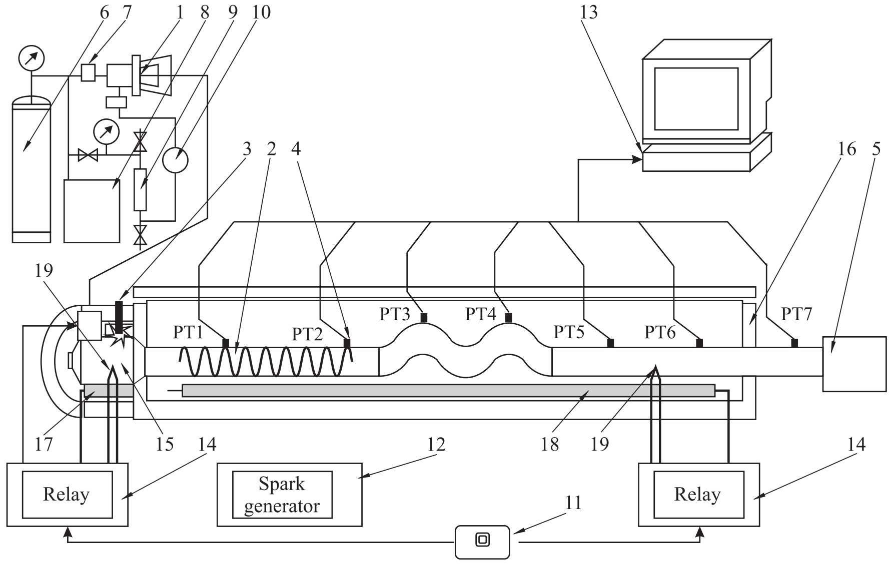

Figure 1: Schematic of the experimental setup

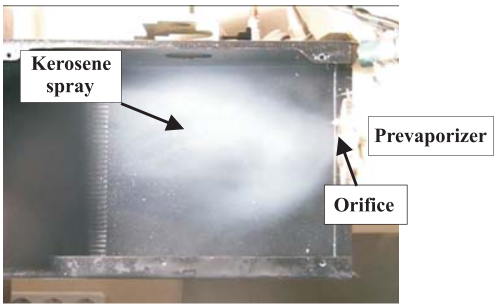

Figure 2: Visualization of kerosene spray exhasting from the prevaporizer orifice (right) at prevaporizer wall temperature 90 ^{o}C

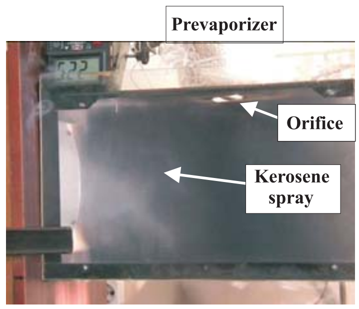

Figure 3: Visualization of kerosene spray exhasting from the prevaporizer orifice (top) at prevaporizer wall temperature of 225 ^{o}C

detonation tube. The thermostats are equipped with electrical heaters *17* (0.6 kW) and *18* (2.5 kW), as well as with thermocouples *19*. The thermostats are controlled by the control relays *14*. The data acquisition system is based on analog-to-digital converter and a PC *13*. The total number of registration channels is 16. The experimental stand is operated remotely.

Figures 2 and 3 show the photographs of the TS-1 sprays issuing from the prevaporizer into the laboratory hood. Figure 2 relates to the prevaporizer wall temperature of 90 ^{o}C and the coflow air with the velocity of 10 m/s (from right to left). Figure 3 relates to the prvaporizer wall temperature of 225 ^{o}C and crossflow air with the velocity of 0.4 m/s (from right to left). Under conditions of Fig. 3, there are no visible fuel drops at the prevaporizer nozzle exit. However, downstream from the nozzle there is a visible mist appearing due to kerosene vapor condensation. The mass flow rate of the fuel–air mixture through the prevaporizer was varied from 12 to 20 l/s.

Experiments with Discharge Ignition

Two sets of experiments have been made. In the first set, the detonation tube was straight, while in the second it contained a curved segment as shown in Fig. 4. Tables 1 and 2 show the locations of the pressure transducers PT1 to PT7 in the straight and curved detonation tubes, respectively. The length of the Shchelkin spiral in both detonation tubes was 800 mm. The spiral was mounted 70 mm downstream from the prevaporizer nozzle. In the experiments with both tubes, the prevaporizer wall temperature was 190±10 ^{o}C. The temperature of the tube

Figure 4: The curved tube segment in the thermostat

segment with the Shchelkin spiral was 120–130 °C and the temperature of the tube segment up to pressure transducer PT6 was 110–120 °C. The temperature of the tube segment downstream from pressure transducer PT6 was 20–30 °C. The fuel –air mixture was ignited in the prevaporizer either by the standard spark plug or by the three-electrode discharge [3].

In the experiments with the straight tube, the ignition energy was varied from 5 to 700 J. Figure 5 shows the example of pressure records by pressure transducers PT1 to PT6 at relatively high ignition energy (225 J). The maximum registered shock wave velocity at the measuring segment PT5–PT6 was about 800 m/s (Fig. 6). Symbols in Fig. 6 are used for distinguishing the data from different runs.

The second experimental series was performed with the curved tube of Fig. 4. The idea of using such a curved tube comes from [3, 4], where the combination of Shchelkin spiral followed by the tube coil was shown to be very efficient for shortening DDT distance and time. The curved tube segment consisted of two complete turns of the tube with the external diameter of 57 mm tightly around a rod 28 mm in diameter with the pitch of 255 mm (see Fig. 4).

Table 1 : Locations of pressure transducers in the straight detonation tube

Location of pressure transducer, mm	622	872	1118	1416	1670	1970	2270
Remark	Section with Shchelkin spiral	Section with Shchelkin spiral	Straight tube	Straight tube	Straight tube	Straight tube	Straight tube

Table 2 : Locations of pressure transducers in the detonation tube with the curved segment

Location of pressure transducer, mm	622	872	1292	1662	1992	2292	2592
Remark	Section with Shchelkin spiral	Section with Shchelkin spiral	Curved tube segment	Curved tube segment	Straight tube	Straight tube	Straight tube

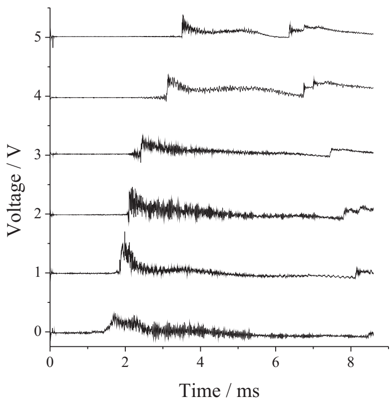

Figure 5: Pressure records in the run with igniter energy of 225 J

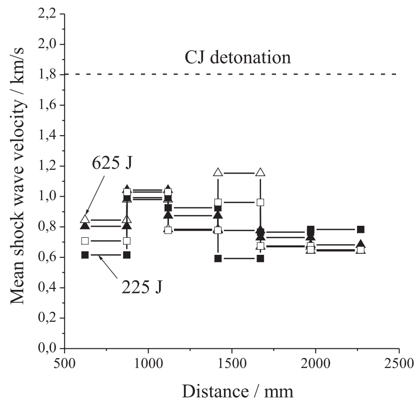

Figure 6: Measured mean shock wave velocities as a function of distance from the igniter in 4 runs with the ignition energy varied from 225 to 625 J

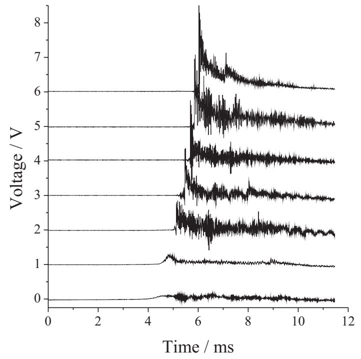

Figure 7: Pressure records in the run with igniter energy of 5 J

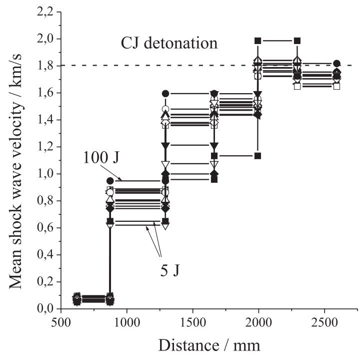

Figure 8: Measured mean shock wave velocities as a function of distance from the igniter in 12 runs with the ignition energy varied from 5 to 130 J

Table 3: Pulse-to-pulse shock wave velocities (in m/s) at different measuring segments at the setup operation frequency of 1.5 Hz

Pulse No.	PT1–PT2	PT2–PT3	PT3–PT4	PT4–PT5	PT5–PT6	PT6–PT7
1	912	952	1014	1182	1852	1734
2	912	987	1105	1633	1961	1852
3	794	1020	1139	1690	1852	1841
4	947	955	1073	1690	1841	1744
5	929	952	1105	1633	2113	1639
6	791	1064	1457	1752	1734	1852
7	822	1095	1138	1633	1841	1744
8	746	1017	1402	1678	1875	1734
9	850	1017	1402	1633	1974	1734
10	725	1141	1581	1690	1841	1744
11	725	1095	1588	1690	1841	1852
12	702	1141	1729	1633	1852	1840
13	631	1136	1588	1752	1734	1744
14	648	1186	1652	1752	1734	1744
15	746	1056	1588	1690	1734	1961
16	702	1020	1588	1627	1852	1840
17	587	987	1652	1633	1974	1734
18	723	926	1457	1690	1840	1852
19	912	896	1652	1690	1744	1840
20	725	822	1138	1627	1852	1852

The curved tube segment was mounted 100 mm downstream from the end of Shchelkin spiral. In the experiments with the curved tube segment the ignition energy was varied from 5 to 176 J. In these experiments, we have repeatedly registered detonation even at the lowest ignition energy used (5 J). Figure 7 shows the example of pressure records by pressure transducers PT1 to PT7 at the ignition energy of 5 J indicating the onset of detonation between PT4 and PT5 with its further propagation at 1600–1800 m/s. Figure 8 shows the measured mean shock wave velocities along the detonation tube in 12 runs with different ignition energy ranging from 5 to 130 J. Again, symbols in Fig. 8 are used for distinguishing the data from different runs. Clearly, DDT in kerosene – air mixture was repeatedly attained at a distance of about 2 m within 5–6 ms even at

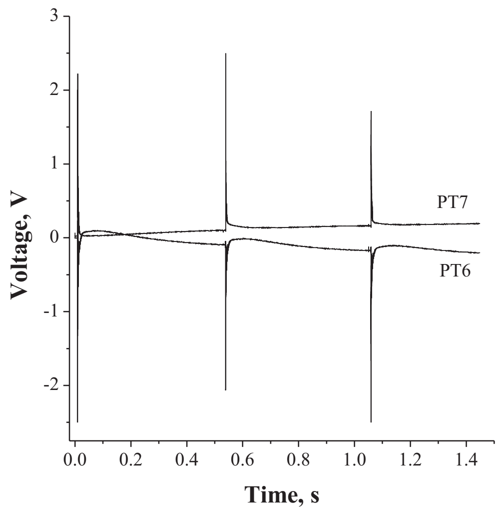

Figure 9: Records of pressure transducers PT6 and PT7 in three successive detonation pulses at the operation frequency of about 2 Hz

a very low ignition energy of 5 J. This effect is solely attributed to the use of the curved tube segment. The curvilinear reflecting surfaces in the curved tube lead to gas-dynamic focusing of compression waves generated by the accelerating flame [3, 4].

Experiments with Flame Jet Ignition

For further decreasing the ignition energy required for DDT while insuring reliable ignition at high flow velocities and short detonation run-up distance and time, we replaced the electrical igniter by a flame-jet generator of special design (a sort of prechamber). The flame-jet generator was equipped with two standard automobile spark plugs and was combined with the prevaporizer in such a way that the spark plugs could reliably ignite the fuel – air mixture producing energetic flame torch. For optimizing the design of the prevaporizer with the built-in prechamber, preliminary studies with coupled flow visualization (flame self-luminosity and Schlieren) and pressure measurements were conducted using a model device with transparent walls. The resultant modification of the ignition system made it possible to arrange multipulse detonation initiation of TS-1 – air mixture in the tube similar to that shown in Fig. 1. Table 3 shows the example of multipulse detonation initiation in the run with the ignition energy of 100 mJ at a low operation frequency of 1.5 Hz in 20 successive pulses. Detonation was initiated at the exit of the curved tube section (measuring segment PT4–PT5) in each pulse except for pulse #1. The detonation run-up time in this test was about 7–8 ms. The error of shock velocity measurements was estimated as 3%. Figure 9 shows the records of pressure transducers PT6 and PT7 in three successive detonation pulses at the operation frequency of about 2 Hz. The run-up time of DDT was shown to decrease when the ignition triggering time in the prechamber overlaped with the fuel-fill phase. The run-up time and distance were shown to depend on the design of the transition section between the prevaporizer and the tube. Note that similar experiments with the straight tube did not result in detonation initiation at all.

Concluding Remarks

The possibility of single-pulse and multipulse DDT in partly prevaporized kerosene TS-1 – air mixture at normal atmospheric pressure in a heated (110–130 ^{o}C) tube 52 mm in diameter was demonstrated experimentally. The DDT was repeatedly detected with a run-up distance of about 2 m and run-up time of 7–8 ms at ignition energy as low as 100 mJ. The successful DDT became possible solely due to the application of the "Shchelkin spiral – tube coil" combination proposed and tested in [3, 4]. The results obtained are important for advancing the research on pulse detonation propulsion.

References

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