Deflagration-to-Detonation Transition in Kerosene – Air Mixtures

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1 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 at short distances by arranging combined approaches enhancing fuel detonability, obstacle-forced flame acceleration, and shock-to-detonation transition.

2 Experimental setup

Figure 1 shows the experimental setup, comprising kerosene injector *1*, detonation tube *2*, electrical 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 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.

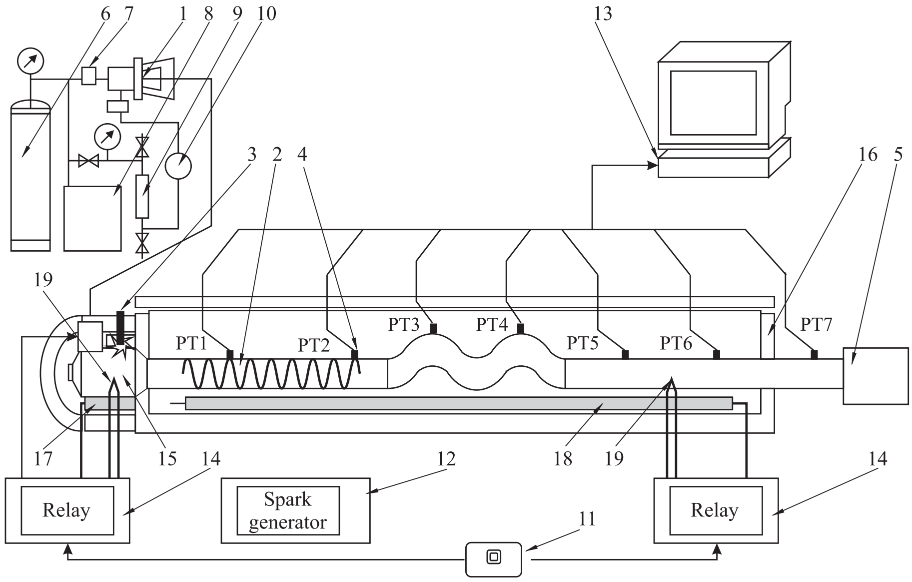

Fig. 1: Schematic of the experimental setup

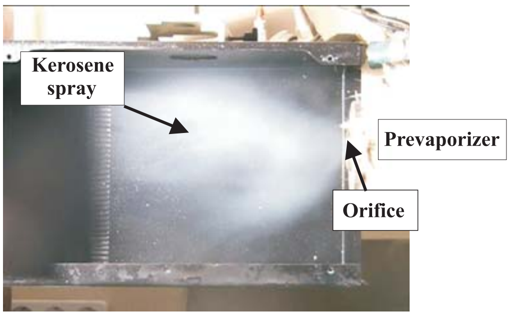

Fig. 2: Visualization of kerosene spray exhasting from the prevaporizer orifice (left) at prevaporizer wall temperature of 90 ^{o}C.

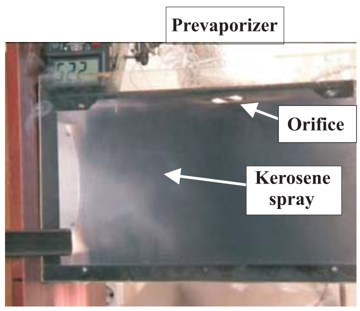

Fig. 3: Visualization of kerosene spray exhasting from the prevaporizer orifice (top) at prevaporizer wall temperature of 225 ^{o}C.

Fig. 4: The curved tube segment in the thermostat.

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 Schelkin spiral	Section with Schelkin spiral	Staright Tube	Staright Tube	Staright tube	Staright tube	Staright 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 Schelkin spiral	Section with Schelkin spiral	Curved tube segment	Curved tube segment	Staright tube	Staright tube	Staright Tube

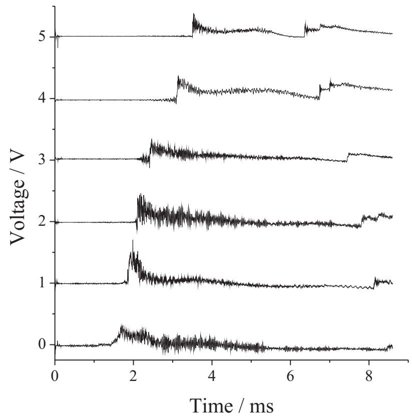

Fig. 5: Pressure records in the run with igniter energy of 225 J.

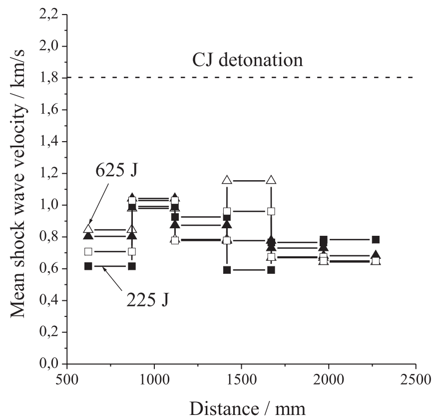

Fig. 6: Measured mean shock wave velocities as a function of distance from the igniter in 4 runs with the ignition energy varied from 225 to 625 J.

3 Experiments

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 segment with the Shchelkin spiral was 120–130 ^{o}C and the temperature of the tube segment up to pressure transducer PT6 was 110–120 ^{o}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).

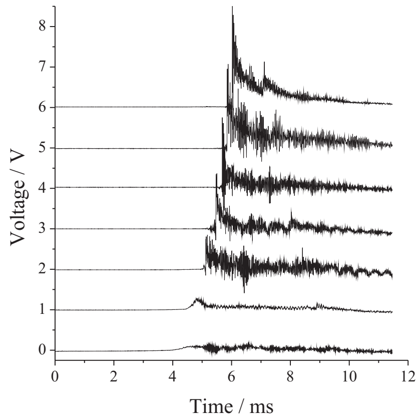

Fig. 7: Pressure records in the run with igniter energy of 5 J.

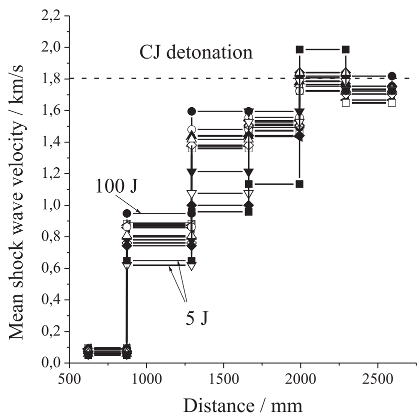

Fig. 8: Measured mean shock wave velocities as a function of distance from the igniter in 12 runs with the ignition energy varied from 5 to 130 J.

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 PT5 and PT6. 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 even at 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 might lead to gas-dynamic focusing of compression waves generated by the accelerating flame [3, 4].

Concluding remarks

The possibility of DDT in partly prevaporized kerosene TS-1 (Russian analog of JetA) – 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 2 m and run-up time of 5–6 ms at ignition energy as low as 5 J. 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.

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References

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