ISSN 1990-7931, Russian Journal of Physical Chemistry B, 2011, Vol. 5, No. 4, pp. 664–667. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © S.M. Frolov, V.S. Aksenov, V.S. Ivanov , 2011, published in Khimicheskaya Fizika, 2011, Vol. 30, No. 8, pp. 58–61.

Experimental Demonstration of the Operation Process of a Pulse-Detonation Liquid Rocket Engine

S. M. Frolov, V. S. Aksenov, and V. S. Ivanov

Semenov Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

e-mail: smfrol@center.chph.ras.ru

Received March 18, 2011

Abstract—A low-frequency demonstrator of the operation process of a pulse-detonation liquid-fuel rocket engine, intended for shaping the future design of a new type of rocket engines for spacecraft control, is for the first time developed and tested. As a result, the conditions are determined under which the demonstrator provides reliable deflagration-to-detonation transition (DDT) in a single-pulse or repetition mode. Because DDT occurs within a very short distance (less than 10 bores of the detonation tube), the operating frequency of the demonstrator can be substantially increased.

Keywords: pulse detonation liquid-fuel rocket engine, deflagration-to-detonation transition, repetition mode, experimental studies.

DOI: 10.1134/S1990793111040178

At present, the possibilities of improving the existing types of liquid rocket engines (LRE) for space transportation systems are almost completely exhausted. At present, hopes for a qualitative leap in the development of outer space engines are pinned on the development and introduction of fundamentally new rocket engines based on pulse-detonation combustion [1]. In such pulse-detonation rocket engines (PDREs), the fuel components, periodically injected into the combustion chamber, chemically react in periodically initiated detonation waves. Due to a strong shock compression, the chemical reaction in the detonation wave proceeds in the mode of ignition at high excess pressures and temperatures. Therefore, to efficiently convert the chemical energy of fuel into the work of expansion in such engines, it is not necessary to maintain a very high pressure in the combustion chamber and to use high-pressure turbo pump assemblies.

The literature contains dozens of publications on experimental studies of the operation process in PDREs intended for use as the main spacecraft propulsion system, see, e.g., [1]. Another promising application for PDREs, more specifically, micro-PDREs, is to correct the position and to execute orbital maneuvering of satellites. It is expected that, due to a high thermodynamic efficiency of detonation combustion cycle [2] and a high repetition frequency of detonation pulses, such micro-PDREs will surpass the existing analogues not only in design (manufacturability, ease of construction, etc.) and performance (reliability, cyclic stability, etc.), but also in terms of specific propulsion characteristics (specific impulse, specific gravity, etc.). While the future constructions of cruising PDREs are actively discussed in the literature, the design of micro-PDREs has not yet been determined.

The aim of this work is to try to shape the future design of micro-PDREs for spacecraft control systems on the basis of a laboratory realization of a low-frequency pulse detonation cycle in liquid hydrocarbon fuel—gaseous oxygen sprays in short tubes of small diameter.

In the course of the work, we assembled an experimental setup with systems of fuel and oxidizer supply, ignition, power supply, diagnostics, monitoring of combustible gases, emergency security, and digital control. In addition, we developed and tested a pulse ignition unit (PIU) operating in a single-pulse mode and a repetition mode with variable pulse frequency and constructed and tested a low-frequency demonstrator of the operation process of micro-PDREs (Fig. 1).

The demonstrator consisted of a PIU and a detonation tube attached to it. The housing of the PIU was made of brass. Gaseous oxygen was supplied into a cooling jacket with internal ribs. The channels of the heat exchanger were arranged in such a way as to make the high-speed oxygen flow cross the jet of liquid fuel (n-hexane, supplied by a fuel injector from the VAZ

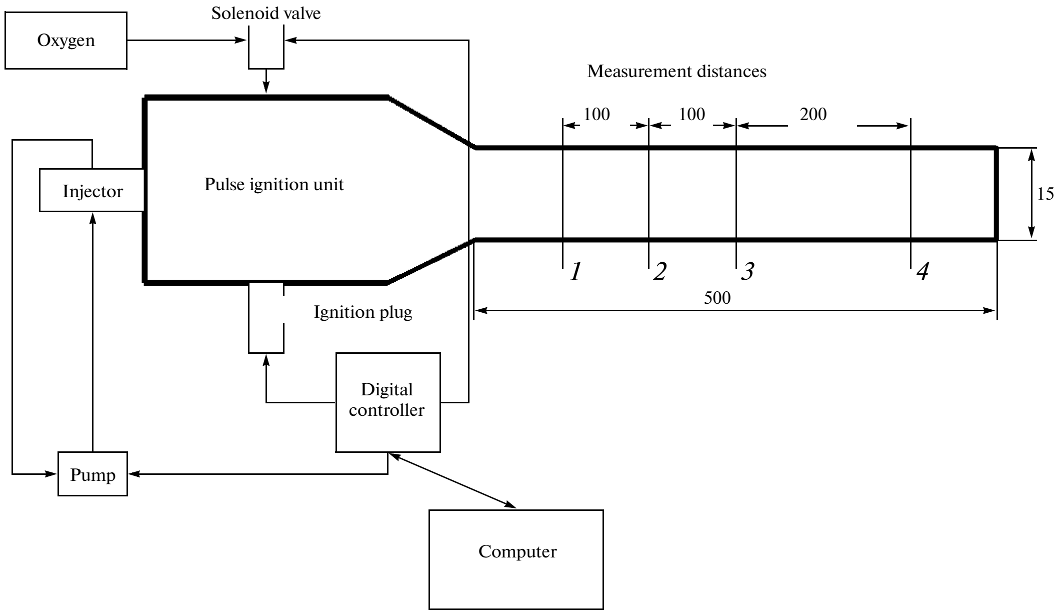

Fig. 1. Schematic of the demonstrator of the operation process in micro-PDRE: (*1–4*) ionization probes. The sizes are given in millimeters.

2110 car engine) and direct the fuel into the nozzle hole that connects the feed system with the combustion chamber of the PIU. The PIU combustion chamber had a complex shape, with divergent and convergent areas. The combustion chamber had holes in the walls for standard automotive spark plugs or screw caps. The steel detonation tube, 15 mm in diameter and 500 mm in length, was joined to the combustion chamber of the PIU via a threaded connection.

Along the detonation tube, screw holes for accommodating ionization probes were made 100 mm apart. In the firing tests, we used four ionization probes, denoted in Fig. 1 as *1–4*. The probe was an isolated steel rod fastened in a threaded bushing. During measurements, the rod was deepened into the tube by at least a third of its inner diameter. A dc voltage, from +100 to +200 V was applied to the rod. In the presence of negative charges in medium, an electric signal appeared in the circuit of the probe, which was fed into an USB-300 analog-to-digital converter (with an acquisition time of 0.3 μs) and then into a personal computer. The time constant of the probe was essentially dependant on the conductivity of the medium, typically < 3 μs and ~1 ms, for detonation and deflagration, respectively.

The operation of all systems of the micro-PDRE demonstrator, including the emergency cutoff of the combustible mixture components, was managed by a digital controller. During the firing tests, the fuel pump ran continuously. At some predetermined time t_1, the digital controller actuated the solenoid valve of the injector, and the fuel started flowing into the combustion chamber of the PIU. Later, at time t_2, the digital controller actuated the ignition coil circuit and, then, at time t_3, produced a fuel cutoff signal. At time t_4, the power supply of the plugs was switched off. The supply of fuel through the injector was renewed at time t_5. Oxygen was fed into the combustion PIU continuously. The main settings of the PIU were the fuel supply duration ($\Delta t_{1-3} = t_3 - t_1$), ignition advance ($\Delta t_{2-3} = t_3 - t_2$), spark discharge duration ($\Delta t_{2-4} = t_4 - t_2$), duration of blow-through of the PIU with oxygen ($\Delta t_{4-5} = t_5 - t_4$), and the pressure of oxygen supply.

The schedule of firing tests of the micro-PDRE demonstrator included tests in single-pulse and repetition modes. In the course of tests, the settings of the PIU were varied, exhaust plume was filmed, and signals from the ionization probes were recorded. As a result, we determined the conditions (the pressure of oxygen supply and durations of the different stages of the operation process) under which deflagration-to-detonation transition (DDT) occurred in the micro-PDRE demonstrator in both single-pulse and repletion modes.

As an example, the table shows the values of key parameters of the cyclogram of operation of the demonstrator in the DDT mode at a repetition frequency of 10 Hz and an oxygen pressure of 5.5 atm. In this case, the fuel in the PIU and detonation tube was sup-

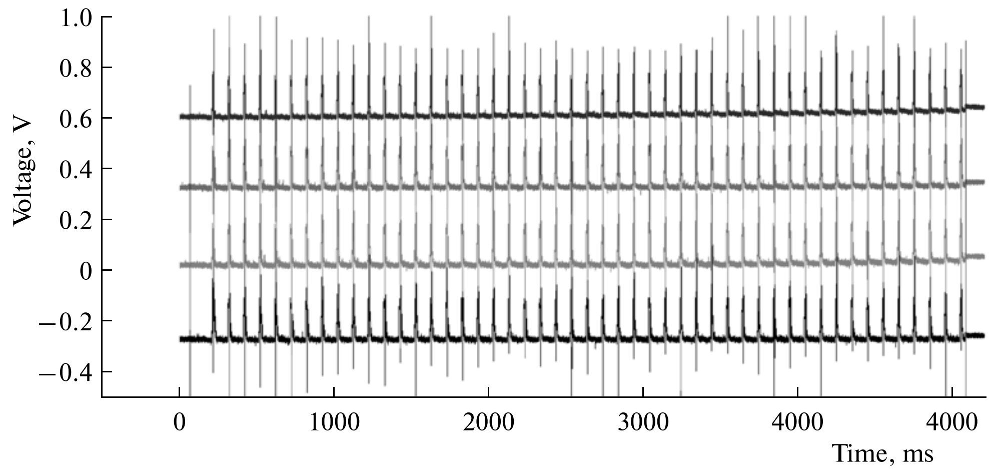

Fig. 2. Voltage signals from ionization probes *1–4* (from bottom to top) recorded for 5 s of operation of the micro-PDRE demonstrator (50 pulses at a repetition frequency of 10 Hz).

plied for 50 ms, which constitutes exactly half the operation cycle of the demonstrator.

Figure 2 shows the voltage signals from ionization probes *1–4* (Fig. 1) recorded for 5 s of operation of the demonstrator (50 pulses at a frequency of 10 Hz). Upon increasing the temporal resolution of the records in Fig. 2, it is possible to calculate the combustion wave velocities over the measurement distances between the probes by the formula $D = \Delta X/\Delta t$, where ΔX is the distance between adjacent probes and Δt is the time interval between the arrivals of the combustion wave to the locations of two adjacent probes. An analysis showed that, in all 50 cycles, the combustion wave velocity over the measurement distances was nearly constant, $D \approx (2060 \pm 100)$ m/s. This value corresponds to the thermodynamic detonation velocity of a *n*-hexane–oxygen mixture with an oxygen-to-fuel equivalence ratio of 2.0. In all cycles, the visible flame length was ~300 mm, i.e., ~20 detonation tube diameters. The flame pattern was well repeated from pulse to pulse. Thus, the demonstrator provides good repeatability of the shape and duration of pulses, a behavior indicative of reliable periodic DDT in the detonation tube.

Note that the developed PIU provides a very fast DDT: detonation is recorded already within the first measurement distance, i.e., less than 150 mm from the exit section of the PIU. We would like to emphasize that the design of the demonstrator does not make use a Shchelkin spiral or a set of annular inserts. The result obtained will be used in the future to increase the operation repetition frequency of the demonstrator.

Thus, we developed and tested a low-frequency demonstrator of the operation process of micro-PDREs operating on liquid fuel to try to shape the future design of a new type of rocket engines for space-

Cyclogram of operation of the demonstrator at repetition frequency of 10 Hz

Parameter	Value, ms	Description
t_1	0	Cycle commencement, beginning of fuel supply
t_2	41	Application of voltage to the coil
t_3	50	End of fuel injection
t_4	51	Ignition plug power supply is switched off
t_5	100	End of the cycle, beginning of a new one

craft control systems. The tests made it possible to determine the conditions under which reliable DDT in both single-pulse and repletion modes took place in the demonstrator. Because DDT occurred at very short distances from the igniter (less than 10 detonation tube diameters), the operating repetition frequency of the demonstrator can be substantially increased.

This work was performed within the framework of the scientific and technical program of the Union State "Development of Technologies for Production of Materials, Devices, and Systems for Space Engineering and Its Adaptation to Other Industries and Mass Manufacturing" ("US Nanotechnology") for 2009–2012 under state contract no. 019-600.2009: "Development of Technologies for Manufacturing Micro Pulse Detonation Jet Engines Operating on Liquid Fuel with Energetic Material Nanoparticle Additives for Universal Spacecraft Control Systems", state contracts P502 and P1085.

REFERENCES

1. *Pulse Detonation Engines*, Ed. by S. M. Frolov (Torus Press, Moscow, 2006) [in Russian].
2. Ya. B. Zel'dovich, Zh. Tekh. Fiz. **10** (17), 1453 (1940).