ISSN 0012-5016, Doklady Physical Chemistry, 2017, Vol. 475, Part 1, pp. 129–133. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © S.M. Frolov, V.S. Aksenov, I.A. Sadykov, K.A. Avdeev, I.O. Shamshin, 2017, published in Doklady Akademii Nauk, 2017, Vol. 475, No. 3, pp. 281–285.

PHYSICAL CHEMISTRY

Hydrojet Engine with Pulse Detonation Combustion of Liquid-Fuel

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Presented by Academician A.A. Berlin February 27, 2017

Received February 27, 2017

Abstract—An experimental prototype of an engine of a new type for water transport—pulse detonation hydroramjet—was designed, built, and tested for the first time. Firing test of the prototype with a 2-L combustor was performed on a specially designed test stand with a thrust-measuring frame capable of producing an approach water stream in the form of a submerged jet with a velocity up to 10 m/s. The specific impulse was experimentally measured, ranging from 370 s at high operation frequency (20 Hz) to 1200 s at low operation frequency (1 Hz); i.e., the measured specific impulse of the pulse detonation hydroramjet exceeded that of the best modern liquid rocket engines.

DOI: 10.1134/S0012501617070053

An idea of a new type of engine for rapid water transport—pulse detonation hydroramjet (PDH)—was put forward for the first time in our previous works [1–3]. In PDH, the hydrojet thrust is produced by repetitively pulsed shock waves entering a direct-flow water duct from a combustor, in which there is cyclic pulse detonation combustion of fuel. Unlike other known engines, PDH directly converts the chemical energy of fuel into the kinetic energy of the directional motion of seawater; i.e., it has no intermediate moving parts such as screw propeller, impeller, etc. According to the results of calculations and experiments [4], the highest efficiency of the momentum transfer from the shock waves to seawater (highest specific impulse) is reached at a gas content of water in the water duct of 20–25%; i.e., the working body in the water duct is a compressible bubbly liquid. Such a gas content of water can be ensured by the gaseous products of the detonation in the previous cycle. The purpose of this work was to design and test the first experimental prototype (EP) of PDH.

Figure 1 shows a schematic of PDH EP. EP consists of a combustor (a 2-L steel tube 49 mm i.d.) with propellant component feed, ignition, detonation diagnostics, and control systems and of a direct-flow water duct (a steel tube 80 mm in diameter) with a conical water intake and an interchangeable nozzle.

Propellant components—a fuel (Nefras C2-80/120 petroleum solvent) and an oxidizer (gaseous oxygen)—are fed to the combustor separately. The fuel is injected into the combustor with a car injector, and the oxidizer is fed through two tubes 3 mm in diameter, equipped with check valves. The fuel is delivered from a fuel tank by pressurization. The excess pressure in the tank is maintained constant from 1.5 to 3 atm, which corresponds to an injector capacity of 1.70 to 2.35 g/s. Oxygen is supplied to the valves from a BKO-50-4 oxygen pressure regulator under an excess pressure of 7 atm. To prevent pre-ignition of a fresh portion of fuel in the combustor, before feeding the fuel mixture, the combustor is purged for a short time with a purging gas (nitrogen) under an excess pressure of 4.5 atm through one of the oxygen tubes.

The ignition system comprises a car electronic ignition module and two car spark plugs. The ignition energy does not exceed 0.2 J. The control system consists of a control unit based on an AtMega-328p microcontroller and actuators: solenoid valves for supplying oxygen and nitrogen, injector, and ignition module. The control unit software allows one to specify the time intervals of feeding the propellant components (petroleum solvent and oxygen) and the purging gas (nitrogen) and sending an ignition pulse, and also generates control signals in frequency mode.

The system of diagnostics of the fast process in the combustor includes four ionization probes and an analog-to-digital converter connected to a PC. The

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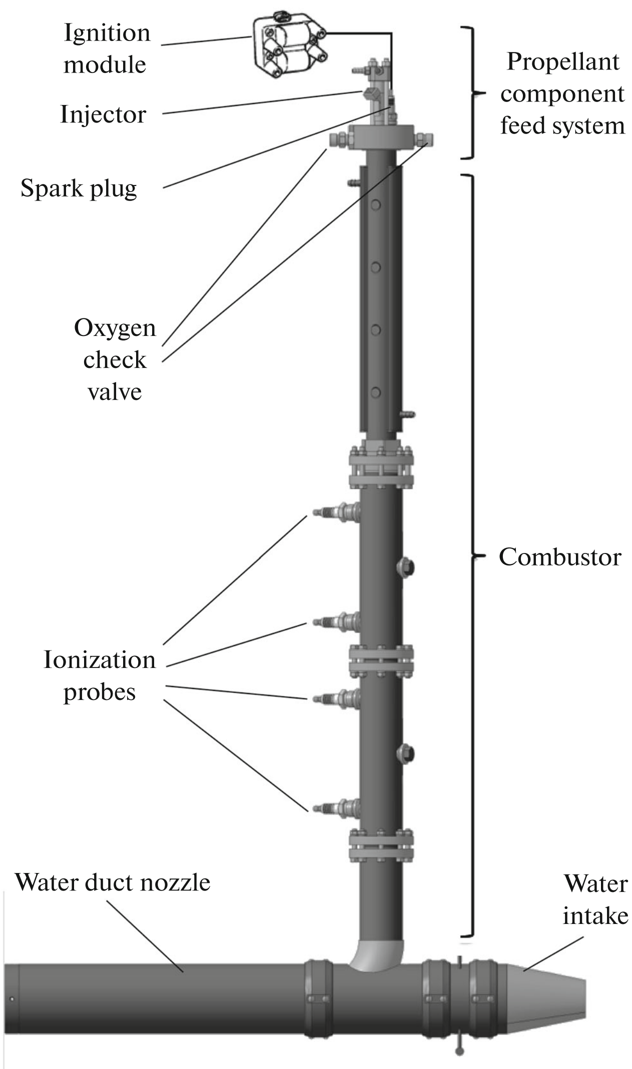

Fig. 1. Schematic of PDH EP.

registration of the fast processes of combustion and detonation with ionization probes was tested previously and showed high efficiency [5]. As ionization probes, car spark plugs were used.

To perform a rapid deflagration-to-detonation transition and generate a detonation wave (hereinafter referred to as the donor detonation wave), turbulence promoters of special shape were installed in the combustor [6]. The combustor is bent so that its exit cross section is coaxial with the water duct nozzle—for the donor detonation wave to enter the water duct nozzle coaxially with the water stream and, transforming to a shock wave (hereinafter referred to as the acceptor shock wave), to transfer the accumulated momentum to the water.

The operation cycle of PDH EP comprises four stages:

(1) the filling of the combustor and water duct (the filling of the combustor with the fuel mixture and of the water duct with the gas-containing aqueous medium),

(2) the formation of a donor detonation wave in the combustor (the ignition of the combustible mixture, the deflagration-to-detonation transition, and the propagation of the donor detonation wave in the combustor),

(3) the formation of a pulsed hydrojet (the outflow of the donor detonation wave from the combustor; the formation and propagation of an acceptor shock wave in the water duct nozzle, causing acceleration of the bubbly medium being compressed; and its efflux from the nozzle at elevated velocity), and

(4) the purging of the combustor for preparing the next operation cycle (the purging of the combustor with nitrogen).

Because stages (2) and (3) are completed within a relatively short time, the effective operation cycle time $\Delta\tau_c$ is the sum of the characteristic times $\Delta\tau_f$ and $\Delta\tau_p$ of stages (1) and (4), respectively, and also of the time interval $\Delta\tau_i$ between cycles: $\Delta\tau_c = \Delta\tau_f + \Delta\tau_p + \Delta\tau_i$. In this case, the EP operation frequency is $f \approx 1 / \Delta\tau_c$.

To make firing tests of PDH EP, we designed and built a test stand. Figure 2 presents a schematic of the test stand with a system for producing a free submerged water jet in a basin. The basin is a 1.26 × 1.05 × 2.54-m^3 tank made of 2.5-mm stainless steel sheets. The thrust force generated by PDH EP is measured with a thrust-measuring frame consisting of two parts: a fixed base and a suspension. To the fixed base mounted on a support beam, a stainless-steel diaphragm-type compression strain gage is attached. The maximum force that can be measured by the gage is 5 kN. PDH EP is fastened to the suspension, which transfers the force to the gage. The suspension is pulled to the fixed base by a spring pack. Such a preload of the gage allows one to record the longitudinal thrust in both directions. When the water jet flows past the EP without feeding the propellant components to the combustor, the force gage readings are taken to be zero, and when EO operates, the force gage measures the thrust.

The system for producing a free submerged water jet in the basin includes a 9-hp motor pump of a capacity of 1800 L/min, and also intake and supply water ducts, each 110 mm in diameter, which are introduced into the basin through seals ensuring watertightness and axial mobility. The supply water duct is equipped with a convergent conical nozzle. Water is sucked into the motor pump through the intake water duct and returned back to the basin as a submerged jet through the supply water duct. The water intake of EP is placed along the jet axis. The axis of the water duct of EP is at a depth of 35 cm. The outer diameter (49 mm) of the conical nozzle of the supply water duct virtually coincides with the inner diameter of the water intake, so that much of the water

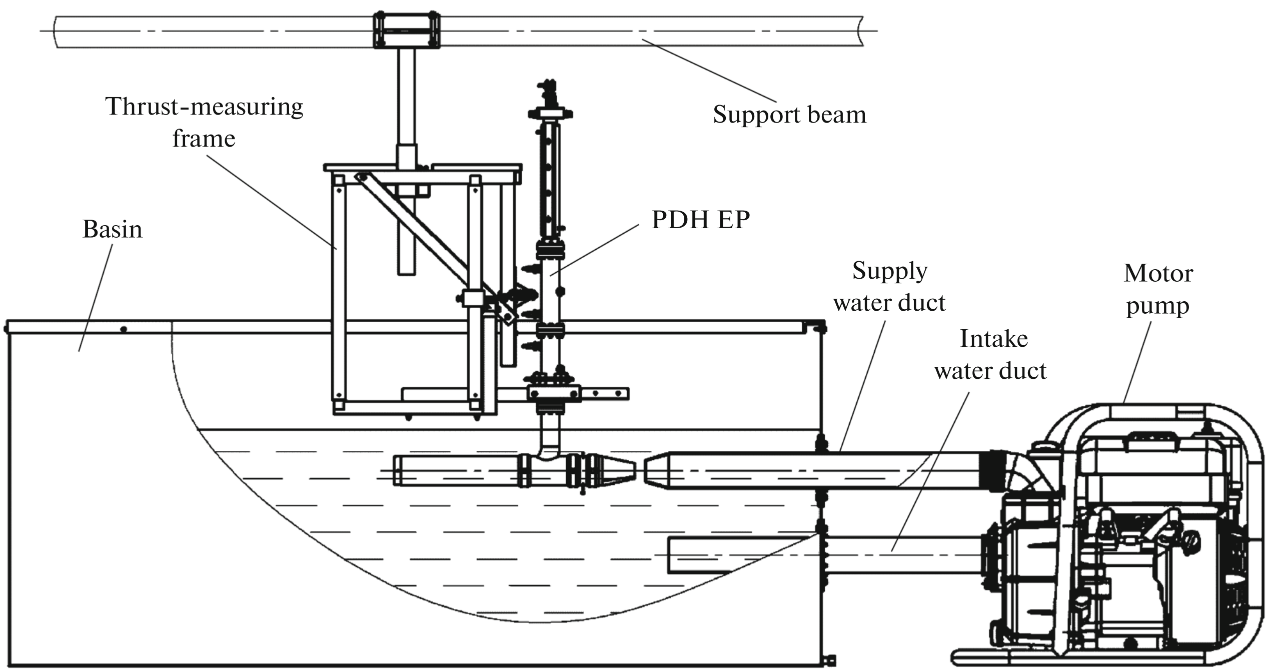

Fig. 2. Schematic of test stand.

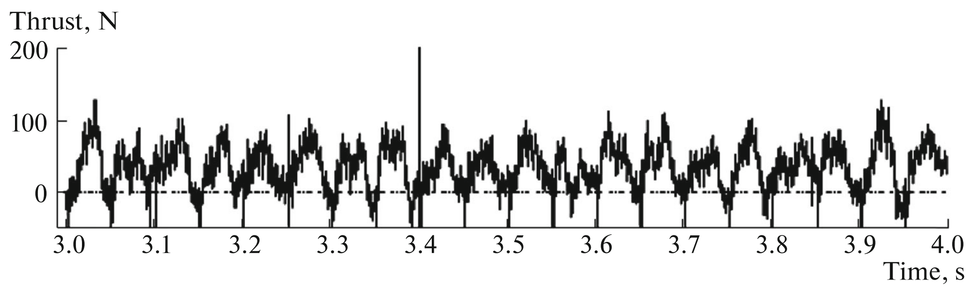

Fig. 3. Example of the oscillogram of the thrust force generated by PDH EP at an approach water stream velocity of 10 m/s and an operation frequency of 20 Hz.

stream passes through the water intake, and only a small remaining part of the water stream flows past EP on the outside. Thus, PDH EP is tested under conditions when the external drag can be neglected.

Figure 3 gives an example of the thrust force gage readings at an approach water stream velocity of 10 m/s and an operation frequency of 20 Hz. Note that first several operation cycles of EP typically differed significantly from the next ones, which is due to different initial conditions in the combustor and in the water duct before starting PDH EP. Beginning with the second or third cycle, the amplitude of the positive signal of the thrust was repeated from cycle to cycle. Therefore, in evaluating the EP thrust characteristics, first several working cycles were neglected.

The main engine thrust characteristics are average and specific impulse. They were determined as follows. Initially, in the thrust versus time curve, a series of N cycles was chosen, to which the time interval (t_1, t_2) corresponded, and the integral of the thrust $F(t)$,

$$P = \int_{t_1}^{t_2} F(t)\,dt,$$

and the average thrust

$$T = \frac{P}{\Delta\tau} = \frac{P}{t_2 - t_1}$$

were found.

Then the specific impulse

$$I_{sp} = \frac{P}{\Delta m g} = \frac{T}{Q_m g} \quad (1)$$

Measured values of average thrust, fuel mixture flow rate, and specific impulse at various values of PDH EP operation frequency and approach water stream velocity u

f, Hz	$u = 5$ m/s			$u = 10$ m/s		
	T, N	Q_m, g/s	I_{sp}, s	T, N	Q_m, g/s	I_{sp}, s
1	5.8	0.63	936	7.8	0.65	1224
2	7.9	1.18	683	5.0	1.18	433
3	12.4	1.64	771	8.1	1.64	506
5	10.2	3.10	337	10.9	3.10	359
7	21.0	4.10	521	13.7	4.10	340
10	15.6	6.20	257	24.6	6.20	404
14	17.4	7.00	250	21.0	7.00	306
17	18.7	8.10	235	25.8	8.10	325
20	20.2	9.20	224	34.2	9.50	367

was calculated, where $\Delta m = Q_m\Delta\tau$ is the mass of the fuel mixture fed to EP in N cycles, g is the gravitational acceleration, and $Q_m = (\dot{m}_g + \dot{m}_{ox})\Delta\tau_f f$ is the flow rate of the fuel mixture in EP operating in frequency mode as determined from the injector capacity $\dot{m}_g$ and the oxidizer mass flow rate $\dot{m}_{ox}$ at given values of fuel mixture feeding duration $\Delta\tau_f$ and operation frequency f.

In the calculations, as a rule, it was taken that $N = 10$. To check that EP operates under steady-state conditions, the thrust and the specific impulse were also calculated at $N = N_{max}$, where N_{max} is the total number of cycles in a single test. For example, under the conditions shown in Fig. 3, the average thrust and the specific impulse were found to be 26 N and 280 s, respectively.

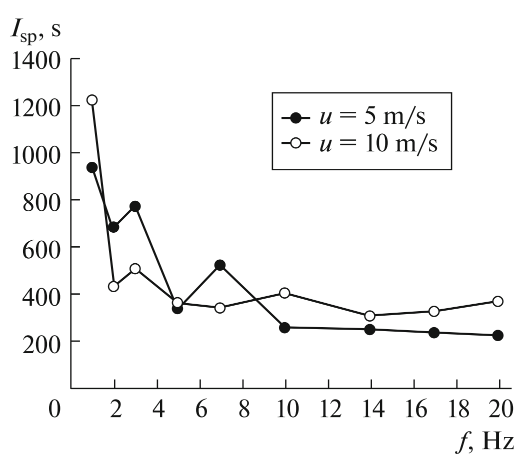

Fig. 4. Measured dependences of the specific impulse of PDH EP on the operation frequency at two values of the approach water stream velocity.

The table presents the measured values of the average thrust and specific impulse of PDH EP operating in pulse detonation mode at various frequencies at approach water stream velocities of 5 and 10 m/s. The table also gives the corresponding flow rates Q_m of the fuel mixture in EP operating in frequency mode. It was taken into account that the fuel mixture feeding duration in a single operation cycle was $\Delta\tau_f = 36$ ms. The time $\Delta\tau_p$ of purging the combustor with nitrogen was varied from 10 to 20 ms. The EP operation frequency was given by a single parameter—time interval $\Delta\tau_i$ between operation cycles. For example, at a frequency of $f = 1$ Hz, we have $\Delta\tau_i = 950$ ms, and at $f = 20$ Hz, we have $\Delta\tau_i = 0$. The approach water stream velocity was varied by varying the motor pump power.

Figure 4 illustrates the measured dependences of the specific impulse of EP on the operation frequency. The table and Fig. 4 show that, with increasing operation frequency, the specific impulse decreases, on the average, from 1000 s at $f = 1$ Hz to 220–370 s at $f = 20$ Hz. Some deviations from a monotonic dependence may be due to the unsteady-state operation of EP in detonation mode—to preignitions of the fuel mixture coming into contact with the combustion products remaining in the combustor after the previous cycle—and also due to resonance phenomena in the combustor–water duct system in some modes. One can also note that, at operation frequencies f above 10 Hz, the specific impulse increases with increasing approach water stream velocity. This is likely to be related to improvement of filling the water duct with water before the next operation cycle.

Remarkably, the average thrust and the specific impulse in the first operation cycle were much higher than those in the following cycles. In the tests, the average thrust in the first cycle varied from 300 to 480 N, and the specific impulse varied from 960 to 2690 s. This indicates that there is a potential of increasing the thrust characteristics of EP.

Thus, in this work, we designed, built, and tested for the first time the experimental prototype of an engine of a new type for rapid water transport—pulse detonation hydroramjet. The firing test of the prototype with the 2-L combustor was carried out on the specially designed test stand, which can produce an approach water stream in the form of a submerged jet with a velocity up to 10 m/s. The specific impulse was experimentally generated, ranging from 1200 s at low operation frequency (1 Hz) to 370 s at high operation frequency (20 Hz); i.e., the measured specific impulse of the pulse detonation hydroramjet turned out to be higher than that of the best modern liquid rocket engines. At the same time, the initial pressure of the propellant components in PDH EP before ignition was close to atmospheric pressure, whereas that in rocket engines reaches several hundred atmospheres. The following was shown:

(i) with increasing operation frequency, the specific impulse, on the average, decreases;

(ii) at a given operation frequency with increasing approach water stream velocity, the specific impulse increases;

(iii) the average thrust developed by PDH EP increases with increasing operation frequency from 8 N at a frequency of 1 Hz to 34 N at a frequency of 20 Hz;

(iv) the measured values of the average thrust and specific impulse in the first operation cycle are always significantly higher than those in the following cycles; in the tests, the average thrust in the first cycle varied from 300 to 480 N, and the specific impulse varied from 960 to 2690 s, which suggests that there is a potential of increasing the thrust characteristics of EP.

ACKNOWLEDGMENTS

This work was partially supported by the Ministry of Education and Science of the Russian Federation (State contract no. 14.609.21.0001, contract identifier RFMEFI60914X0001) and Russian Foundation for Basic Research (grant no. 16-29-01065 ofi-m).

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Translated by V. Glyanchenko