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PHYSICAL CHEMISTRY

Rocket Engine with Continuous Detonation Combustion of the Natural Gas–Oxygen Propellant System

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Abstract—In a demonstrator of a detonation rocket engine (DRE) using the natural gas–oxygen propellant system, a high (270 s) specific impulse at sea level at a low (32 atm) mean combustor pressure was experimentally obtained for the first time. Comparison of these characteristics with the respective ones (263 s and 61 atm) of the well-known Russian RD 170-A liquid-propellant rocket engine using deflagration combustion of the kerosene–oxygen propellant system showed that the specific impulse at sea level in the DRE is close to that in the deflagration-combustion engine but is produced at half as high a mean combustor pressure. This indicates that the energy efficiency of detonation combustion exceeds that of deflagration combustion, and that there is room to improve the weight–size characteristics of the turbopump unit in the DRE.

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Currently, in space propulsion technology, there are a number of promising trends of development of liquid-propellant rocket engines. One of such trends is to replace the kerosene–oxygen propellant system by the liquefied natural gas–oxygen propellant system. The advantages of this replacement are explained by a higher (by 3–4%) specific impulse, higher availability and lower price of liquefied natural gas, and also better environmental performance of liquefied natural gas combustion in comparison with kerosene combustion [1]. Another trend is to replace deflagration (subsonic) combustion by continuous detonation (supersonic) combustion of the propellant mixture in the rocket engine combustor. The transition to continuous detonation combustion is advisable because the thermodynamic cycle efficiency of the detonation combustion engine is higher than that of the conventional deflagration combustion engine [2, 3] (theoretically, by 13–15% [4]). Moreover, in the detonation rocket engine (DRE), the combustor and the nozzle are more compact, and the detonation combustion is characterized by high completeness and by low emissions of hazardous pollutants. The energy efficiency of using detonation combustion in a rocket engine was experimentally proven in our previous studies [5–7], where we reported that the specific impulse increases by 7–8% in the deflagration-to-detonation combustion transition.

The first experiments with continuous detonation combustion of a methane–oxygen gas mixture in an annular combustor were carried out by Bykovskii and Zhdan [8]. Similar experiments were also conducted by Kindracki et al. [9]. We continued experimental investigation of this technology [10, 11]. In a demonstrator of a DRE using the methane–oxygen propellant system, the thrust was experimentally measured at low (to 3 atm) pressures in the annular combustor [10]. The maximum measured specific impulse at sea level was 107 s [10]. These experimental results were developed further [11]: owing to an increase in the mean combustor pressure to 9–10 atm and a change in the DRE design, the maximum measured specific impulse at sea level using the natural gas–oxygen propellant system reached 160 s. Various DRE designs were preliminarily studied by multidimensional numerical calculations of the operation process [12]. The purpose of this work was to experimentally obtain a high (to 270 s) specific impulse at sea level by in-depth modernization of the DRE design [11] using

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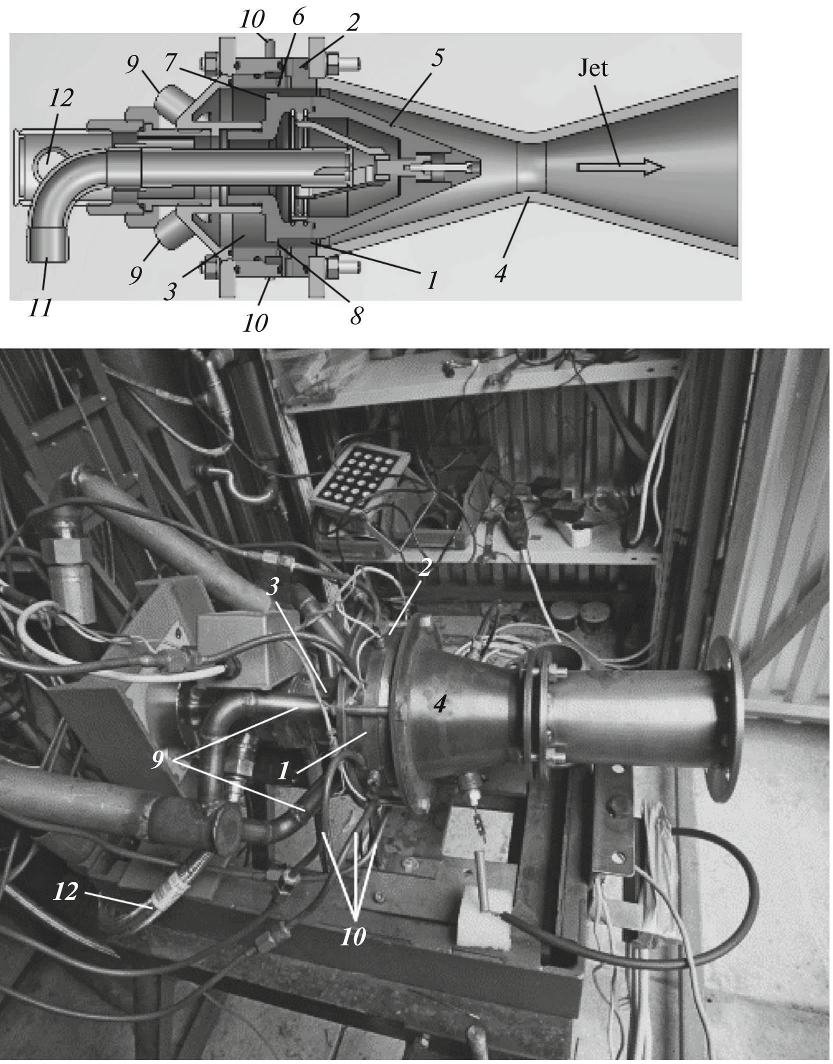

Fig. 1. Schematic of the DRE and a photograph of its installation on a test stand.

computer modeling according to a published procedure [12].

Figure 1 presents a schematic of the DRE and a photograph of a test stand, on which a DRE demonstrator was mounted. The demonstrator was designed based on the results of multivariant numerical calculations of the operation process and the thrust characteristics of the engine. The main element of the DRE is annular combustor *1*; at its inlet, injector head *2* and oxidizer manifold *3* are installed in series, and at its outlet, convergent-divergent nozzle *4* with conical center body *5* were placed. The throat area of nozzle *4* is 50% of the cross-sectional area of annular combustor *1*. Annular combustor *1* is formed by the lateral surfaces of two coaxial cylinders with an annular space 5 mm wide (100 mm o.d., 90 mm i.d.). Injector head *2* is a plurality of 144 holes *6*, 1 mm in diameter, located at regular intervals on the outer surface of annular combustor *1*, 1 mm downstream (toward nozzle *4*) of disk *7* with sharp edges forming 2.5-mm-wide annular gap *8* with the outer wall of combustor *1*. The oxidizer (gaseous oxygen) is fed through passages *9* to manifold *3* and then enters combustor *1* through annular gap *8*. The fuel (natural gas containing 92.8 vol % methane) is fed to injector head *2* through fuel passages *10* and then enters combustor *1* through holes *6*. All the heat stressed elements of the DRE are cooled using a water-cooling system, in which cooling water is supplied through channel *11* and removed through pipe *12*. A specific feature of combustor *1* is its small length: only 19 mm.

The detonation initiation system consists of an electric discharger installed at the outlet section of the annular combustor and a generator of voltage pulses (amplitude 10 kV, frequency 100 Hz). The electric discharger is a thin tungsten electrode, the end part of which is at a distance of $\Delta = 2–3$ mm from the conical center body. Voltage application to the electrode causes an arc discharge in the interval Δ, which initiates one or several detonation waves. A detonation wave, occupying a certain part of the combustor length, continuously circulates within the annular gap so that all the propellant mixture that has entered the combustor burns out in a single rotation of the detonation wave within the annular gap. The detonation products escape into the environment through nozzle *4*.

The system of diagnostics of fast processes in the annular combustor includes a low-frequency static pressure sensor and three ionization probes, which are installed at the same section of the combustor 9 mm downstream of the plurality of fuel feed holes *6* (Fig. 1), and an analog-to-digital converter connected to a PC. The error of measuring the mean static combustor pressure is within 1%. The diagnostic system based on ionization probes was tested previously and showed high efficiency as applied to detonation processes [13]. The error of measuring the detonation velocity using ionization probes is within 5%. The flow rates of the propellant components (natural gas and oxygen) are determined from the readings of low-frequency absolute static pressure sensor in the oxygen and fuel manifolds. The error of measuring the flow rates is within 3%. The thrust produced by the engine is measured with a diaphragm-type compression strain gage (load cell). The error of measuring the thrust is within 3%.

A typical firing test of the DRE lasts 1 s. Along with the time of the operation process of detonation combustion of the propellant mixture, this time also includes the time of opening and closing of quick-acting fuel and oxidizer valves. During the time of the operation process (about 0.5 s), the ionization probes detect thousands of detonation wave rotations within the annular gap of the combustor. The results of the tests showed that, throughout the studied range of the flow rates of the propellant components, in the operation process in the DRE combustor, there is a single detonation wave, rotating continuously within the annular gap at a frequency of ~6 kHz, which corresponds to a rotation speed of ~1900 m/s. This marks this DRE out from the known analogs, in which an increase in the flow rates of the propellant compounds and, correspondingly, in the mean combustor pressure leads to degeneration of detonation combustion into deflagration combustion because of an increase in the number of detonation waves rotating simultaneously in the annular combustor.

The maximum mean pressure P_m in the DRE combustor that was reached in the firing tests was 32 atm at a flow rate of the propellant mixture of $G = 1.14$ kg/s (Table 1). The maximum values of the thrust F and the specific impulse at sea level I_s were 3 kN (308 kgf) and 270 s, respectively. The specific impulse at sea level is calculated by the formula $I_s = F/(Gg)$, where g is the gravitational acceleration. Figures 2 and 3 give examples of the readings of the static pressure sensor in the DRE combustor and the load cell in firing test no. 6 in Table 1. It is seen that the operation process reaches a steady-state mode in ~200 ms after the beginning of the test, and then the mean chamber pressure and the DRE thrust remain approximately constant for ~0.5 s. Next, the fuel and oxidizer valves are closed, and the pressure decreases to atmospheric pressure. Figure 4 represents the data of Table 1 as the experimental dependence of the specific impulse at sea level on the mean static pressure in the DRE combustor.

Table 1. Results of some of the DRE firing tests

No.	P_m, atm	G, kg/s	Φ*	F**, N	I_s, s
1	5	0.25	1.30	363 (37)	148
2	9.5	0.45	0.96	843 (86)	190
3	12.8	0.58	1.10	1215 (124)	214
4	13.5	0.65	1.30	1284 (131)	202
5	19	0.87	1.10	2087 (213)	245
6	24	1.00	1.20	2548 (260)	260
7	32	1.14	1.20	3018 (308)	270

* Φ is the fuel–air equivalence ratio in the propellant mixture.
** The parenthesized F values were measured in kgf; 1 kgf = 9.80665 N.

Thus, in this work, we designed, built, and tested the demonstrator of the DRE using the natural gas–oxygen propellant system, in which a high (270 s) specific impulse at sea level at a relatively low (32 atm) mean combustor pressure was experimentally obtained for the first time. For comparison, note that the well-known Russian RD 170-A liquid-propellant rocket engine using deflagration combustion of the kerosene–oxygen propellant system has a specific impulse at sea level of 263 s at a combustor pressure of

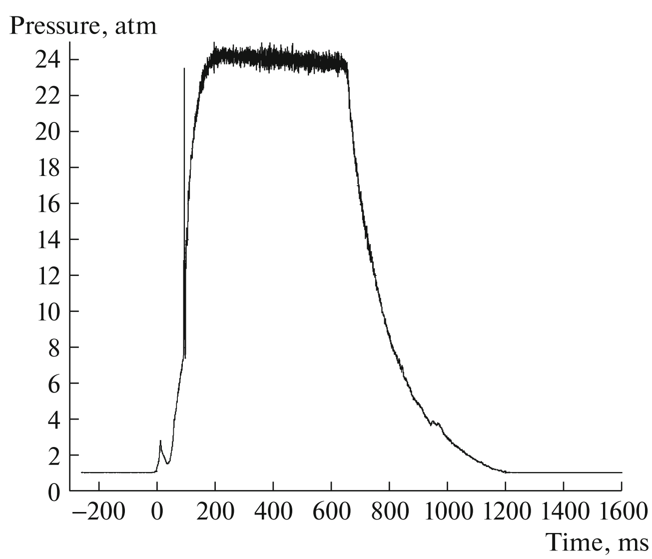

Fig. 2. Example of the readings of the static pressure sensor in the DRE combustor.

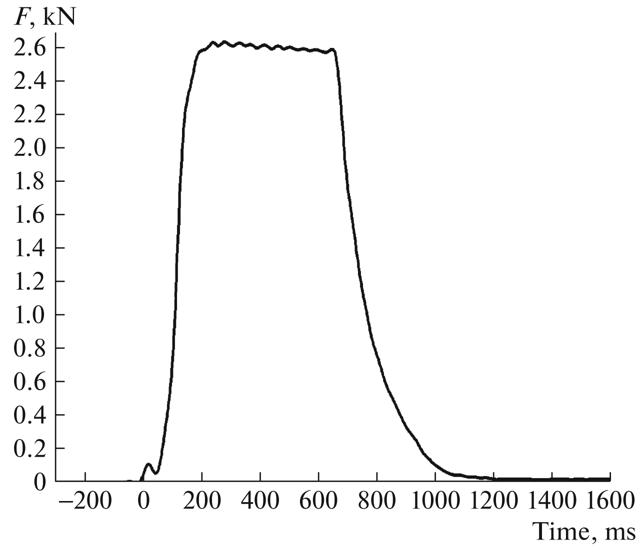

Fig. 3. Example of the thrust readings of the load cell.

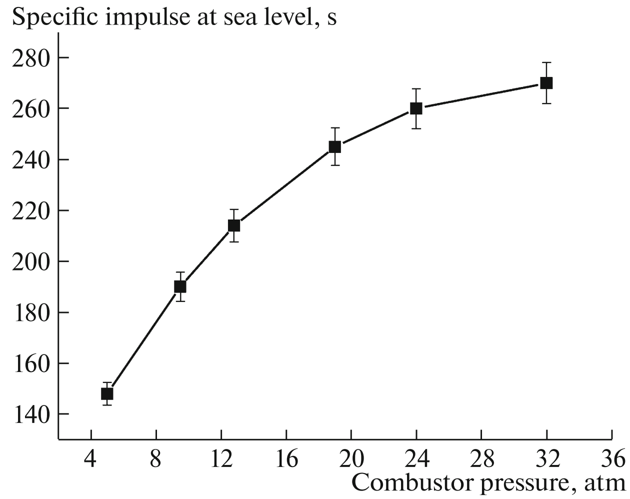

Fig. 4. Experimental dependence of the specific impulse at sea level on the mean static pressure in the DRE combustor.

61 atm (according to the data provided by NPO Glushko Energomash). Comparison of these characteristics shows that the specific impulse at sea level in the DRE is close to that in the deflagration-combustion engine but is produced at half as high a mean combustor pressure. This means that the energy efficiency of detonation combustion exceeds that of deflagration combustion. Moreover, such a decrease in the DRE combustor pressure leads to improvement of the weight–size characteristics of the turbopump unit.

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