OPERATION AND PERFORMANCE OF ROTATING DETONATION ROCKET ENGINE FUELED BY NATURAL GAS: EXPERIMENTAL STUDIES

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The experimental investigations of detonation liquid rocket engine (DLRE) operating on natural gas (NG) – oxygen and liquid propane (LP) – oxygen mixtures have been performed to examine the impact of the DLRE configuration and fuel supply parameters on the operation process and thrust performance. In experiments with NG, the absolute pressures of NG and oxygen supply were up to 30 and 15 atm, respectively; fuel mixture mass flow rate was varied from 0.05 to 0.7 kg/s; the overall fuel mixture composition was varied from fuel lean (with equivalence ratio 0.5) to fuel rich (with equivalence ratio 2.0). The maximum thrust and the maximum specific impulse obtained in this experimental series was 85 kgf and 185 s, respectively, at the maximum average pressure in the combustor of about 10 atm. It is shown that the increase of static pressure in the combustor results in the increase of both engine thrust and specific impulse. With the growth of the specific mass flow rate of fuel mixture, the operation process, on the one hand, becomes more stable, and on the other hand, the number of detonation waves simultaneously rotating in one direction in the combustor annulus increases.

1 Introduction

At present, space propulsion engineering addresses a number of promising areas of development. One of them is the use of liquefied NG (LNG) as a propellant, and the other is the use of continuous-detonation combustion of the fuel mixture in a liquid rocket engine (LRE). The expediency of the transition to LNG–oxygen fuel couple is mainly due to

(1) an increased specific impulse compared to kerosene–oxygen LRE;

(2) the availability and low cost of LNG;

(3) significantly less soot formation during combustion; and

(4) high environmental characteristics compared with kerosene [1].

The expediency of transition to a continuous-detonation combustion is mainly due to higher efficiency of the thermodynamic cycle with detonative combustion as compared with the conventional cycle using relatively slow combustion at constant pressure [2]. Other advantages of a DLRE are:

(1) a compact combustion chamber with an increase in the total pressure;

(2) short nozzle;

(3) high combustion efficiency; and

(4) low concentrations of harmful substances in the exhaust gas.

In theory, the replacement of kerosene by LNG in a traditional LRE promises the gain in the specific impulse of 3%–4%, and the transition from a traditional LRE to the engine with detonative combustion promises the gain of 13%–15% [3]. The energy efficiency of the detonative LRE was proved experimentally in [4–6] for the hydrogen–oxygen fuel couple. The first experiments with continuous-detonation combustion of methane–oxygen mixture in the annular combustor were made in [7]. Similar experiments were carried out in [8–10]. Described in [9] are the experiments with thrust measurements of the DLRE operating on NG–oxygen mixture at relatively low pressure in the annular combustor. The maximum value of specific impulse obtained in [9] was 107 s. Natural gas used in [9,10] contained 92.8% methane, 3.9% ethane, 1.1% propane, 0.4% butane, 0.1% pentane, 1.6% nitrogen, and 0.1% carbon dioxide.

In this paper, the study started in [9, 10] has been continued. The purpose of the research was to investigate experimentally the impact of the DLRE configuration and fuel supply parameters on the operation process and thrust performance.

2 Experiments

2.1 Test stand and engine

The test stand consists of a receiver for methane or NG (0.16 m^3) and oxygen (0.32 m^3), high-speed valve system, fuel manifolds of large cross section, a thrust table and precision measurement system of thrust, pressures of fuel components supply, and ionization currents in the combustor [9,10]. The maximum possible mass flow rate of the fuel mixture at this test stand is about 1.5 kg/s. The test stand is equipped with a remote control system.

Figure 1 shows a photo of the DLRE (Fig. 1*a*) and its scheme (Fig. 1*b*). The DLRE is an annular combustor with the injector head on the one side and a jet nozzle with a conical central body on the other side. The annular combustor is formed by two coaxial cylinders of 100-millimeter height: 90-millimeter inner diameter cylinder nested within a hollow outer cylinder of 100 mm in diameter, so that the gap between the cylindrical surfaces is 5 mm. The injector head consists of a replaceable thin disc with a sharpened edge attached to the inner cylinder of the combustor so that it forms an annular slit of width δ with the outer combustor wall. Oxidant (gaseous oxygen) is supplied to the combustor through this annular slit in the axial direction. Fuel (NG) is fed through the equally distributed radial holes 0.8 mm in diameter drilled in the outer wall of the combustor in the cross section located at a distance of 0.5 mm downstream from the disc. The number of radial holes is 144. During firing, the DLRE is water cooled.

In one test series, a profiled washer was installed between the inner cylinder of the combustor and a conical central body. This washer

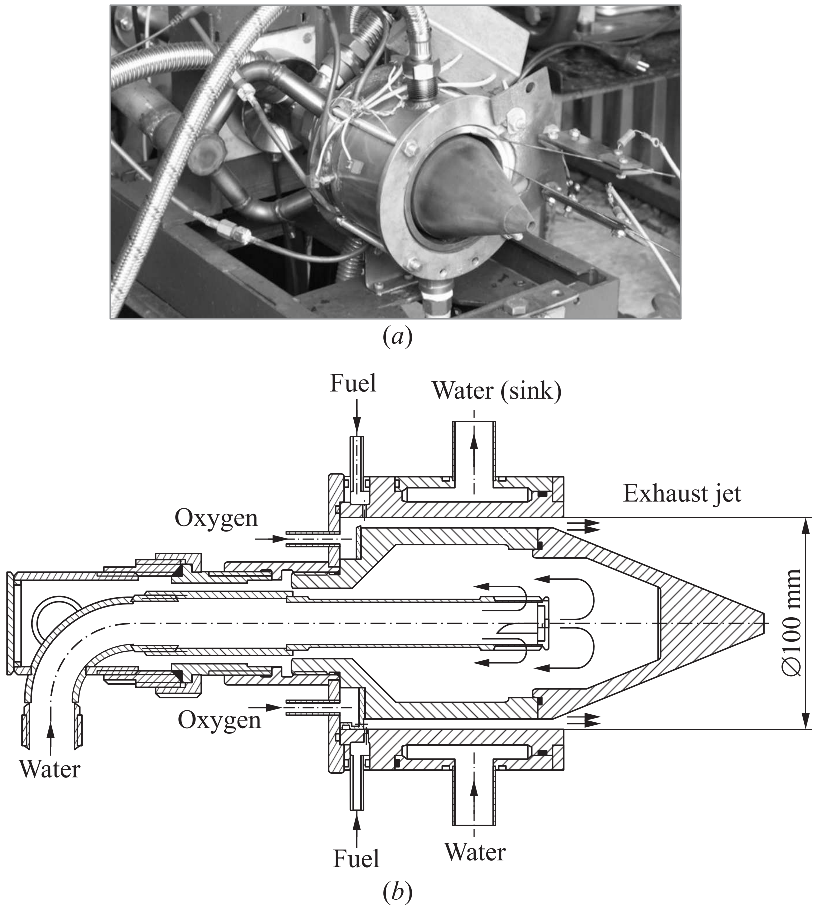


Figure 1 Photograph of the DLRE (*a*) and its schematic (*b*)

was aimed to increase the operation pressure by blocking the cross-sectional area of the combustor outlet by 50%. In the other test series, a converging-diverging (CD) conical nozzle extension was attached to the edge of the external cylinder of the combustor (see Fig. 1*b*). In this DLRE configuration, the minimum cross-sectional area was also 50% of the cross-sectional area of the annular combustor channel. In some tests, the position of the replaceable thin disc relative to the fuel injector holes was adjusted using rigid pads of different thicknesses.

All tests were performed under normal atmospheric conditions.

2.2 Test methodology and data acquisition

The fire test began with sending a digital signal to the opening of the oxygen supply valve, then (after 100 ms) to the opening of the NG supply valve, then (after 100 ms) to the ignition, was normally continued for 1 s, and thereafter, followed by successive cutoff of oxygen and NG supply.

The registration system included three ionization probes and the low-frequency sensor of absolute static pressure, all located in one combustor cross section near the injector head with a relative angular position of 90°. This registration system allowed to identify the operation mode (continuous detonation or continuous combustion), to measure the rotational speed of detonation waves in the annular gap of the combustor when operating in continuous-detonation mode, to determine the direction of detonation rotation, propagation velocity, and the amount of detonation waves while circulating over the injector head, and to measure the mean static pressure in the vicinity of the bottom of the combustor. Besides measurements of ionization currents, thrust (using a calibrated load cell) and static pressure (using calibrated low-frequency pressure transducers) were measured in the collectors supplying oxygen and NG directly into the DLRE annular gap, as well as high-speed video recording using multiple high-speed digital cameras was conducted.

Mixture composition was determined based on the mass flow rates of fuel components entering the combustor. The latter were determined by the pressure drop in the receivers supplying gaseous oxygen and NG. Figure 2 shows an example of the experimental dependences of the pressure in the oxygen and NG receivers when feeding oxygen through the annular slit of width $\delta = 1$ mm. It is seen that after a short transient of $\sim$ 100-millisecond duration, the pressure in the receivers decreases linearly in time. The sharp drop in pressure during the transient is due to the filling of manifolds after the opening of the shutoff valve. Pressure drop during the experiment was always less than 10% of the initial pressure in the receiver, i.e., the supply pressures of fuel compo-

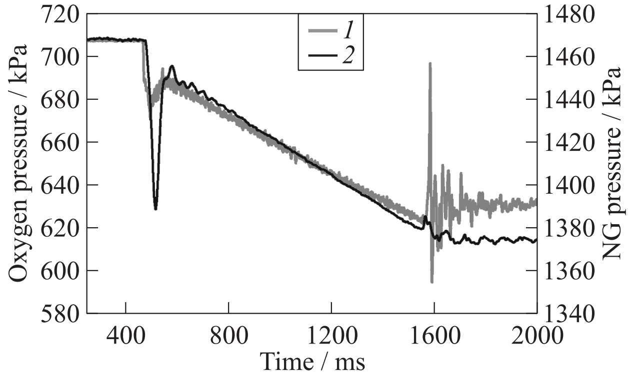


Figure 2 Experimental pressure histories in oxygen and NG receivers: *1* — pressure of gaseous oxygen; and *2* — pressure of NG

nents into the injector head of the combustor was almost constant. The fact that the supply pressure of the fuel components during the test remained approximately constant distinguishes the present experiments from experiments [7], in which the supply pressure decreased during a test significantly.

To initiate detonation in the DLRE, a powerful spark discharge at the outlet section of the combustor was used. Spark discharge was created in the gap between the tungsten electrode and the grounded casing of the combustor. The electrode was mounted directly on the engine body and was connected to an AC (alternating current) generator with a voltage of 10 kV and a frequency of 100 Hz.

Figure 3 shows an example of overpressure records in the oxygen and NG collectors, as well as in the combustor in the fire test of DLRE with the annular slit of width $\delta = 2.5$ mm and with a CD nozzle extension attached. Hereinafter, the inserts in figures show schematically the corresponding DLRE configuration and the annular slit width δ. It can be seen that during the test, the pressure in the collectors and in the combustor is almost constant. On the one hand, the average chamber pressure ($P_c \approx 0.6$ MPa) is less than the feed pressure of oxygen ($P_{O_2} \approx 0.7$ MPa) by 0.1 MPa, i.e., $P_{O_2}/P_c \approx 1.17$, which indicates a relatively small pressure drop when supplying oxygen through the

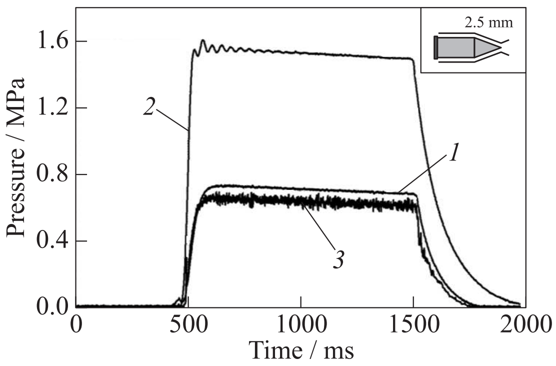


Figure 3 Example of overpressure histories in oxygen (*1*) and NG (*2*) collectors and in the combustor (*3*) during firing a DLRE of the configuration shown in the insert

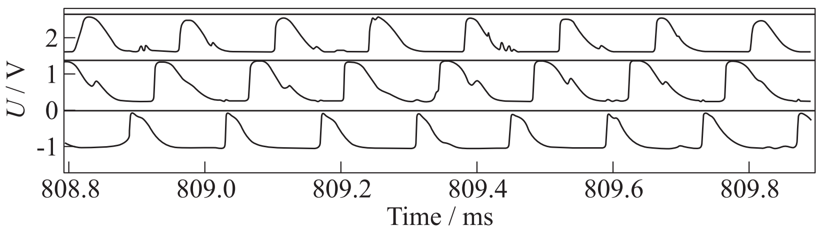


Figure 4 Example of a record of continuous-detonation operation process with one detonation wave in NG–oxygen mixture

annular slit with $\delta = 2.5$ mm (in the experiments of [7], $P_{O_2}/P_c = 2.3$ when $P_c \approx 0.3$ MPa). On the other hand, the ratio of NG feed pressure ($P_{CH_4} \approx 1.5$ MPa) to the average pressure in the combustor is significantly higher ($P_{CH_4}/P_c \approx 2.5$), i.e., the supply of NG through the radial holes of 0.8 mm in diameter is accompanied by a large pressure loss.

Figure 4 shows an example of signal records of three ionization probes during DLRE operation in a continuous-detonation mode. The probe signals are registered in the form of a voltage on the load resistance of 2 Ohm. All three signals have strong repetitive pulses of large amplitude. The pulse frequency ($\sim$ 7.6 kHz) and a time shift between signals of different probes show that in this case, a single detonation wave circulates in the combustor at a velocity of $D \approx 2200$ m/s.

For express-analysis of probe records, a methodology of fast Fourier transform was applied. As a result, a graph of the characteristic frequency f of the operation process vs. time was obtained. Typically, the process frequency is a multiple to the characteristic frequency of detonation wave rotation in the combustor. Based on the measured frequency, one can readily determine the number n and the velocity D of the detonation waves rotating in the annulus. Figure 5 shows an example of an experiment with five detonation waves simultaneously rotating in the annulus of the combustor in one direction. Clearly visible is the base frequency at the level of $f \sim 23$ kHz. At a more detailed

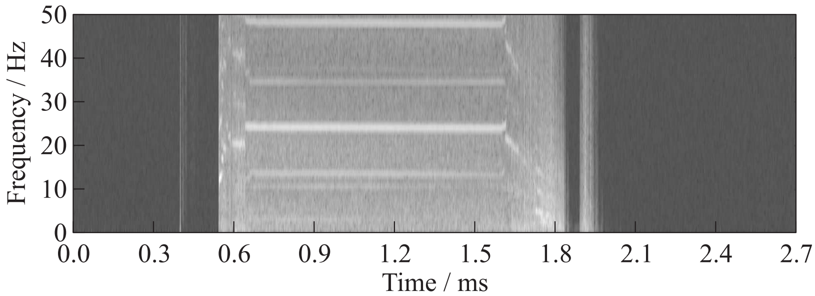


Figure 5 Fast Fourier transform of the data obtained with the ionization probes for DLRE operation with five detonation waves

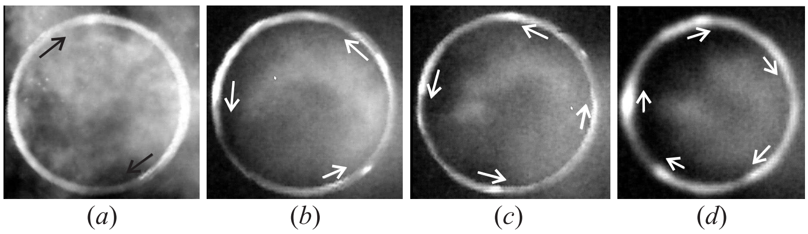


Figure 6 High-speed video frames (200,000 frames/s) in the DLRE operating with two (a), three (b), four (c), and five (d) detonation waves

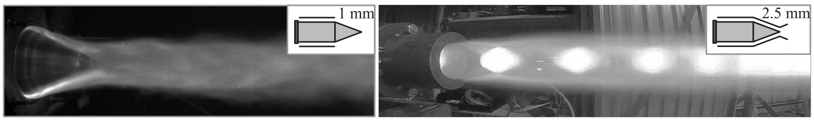


Figure 7 Photos of exhaust jets in firing tests of DLRE without (*a*) and with (*b*) CD nozzle extension

examination of Fig. 5, one can see transients at the initial and final stages of the DLRE operation when the base frequency and, thus, the amount of detonation waves vary.

To confirm the findings obtained from the analysis of ionization probe records, another method of detonation registration in the DLRE combustor was additionally used, namely, high-speed videorecording of the operation process at 200,000 frames/s from the side of the exhaust jet. This registration confirmed the presence of detonation in the annular combustor, the amount and rotation speed of detonation waves, and other information obtained on the basis of ionization probe methodology. Figure 6 shows the examples with videorecording of two, three, four, and five detonation waves in the DLRE.

Figure 7 shows examples of the exhaust jet images for the DLRE without (Fig. 7*a*) and with (Fig. 7*b*) CD nozzle extension.

Finally, Fig. 8 shows an example of the measured time history of DLRE thrust in one of the firing tests. The average thrust in this test was $T \approx 84$ kgf.

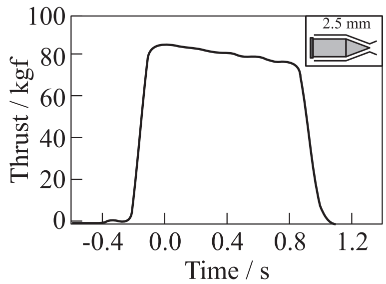


Figure 8 Example of the measured time history of DLRE thrust

2.3 Experimental results

With the DLRE of different configurations (with different widths of the annular slit δ, with and without washer, and with and without

CD nozzle extension), a series of fire tests (about 200 tests all in all) with NG–oxygen fuel was performed at fuel mixture mass flow rates ranging from 0.05 to 0.7 kg/s. Varied in the tests were the absolute pressures of NG (up to 30 atm) and oxygen (up to 15 atm) supply. The composition of the fuel mixture was changed from fuel lean with fuel-to-oxygen equivalence ratio $\Phi = 0.5$ to fuel rich with $\Phi = 2.0$. The experimental results were well reproducible, except for some tests with the initial conditions at the edge of existence of different operation modes.

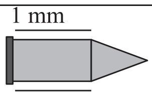
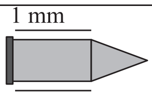
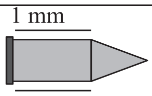
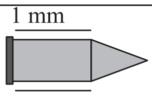
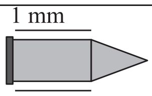
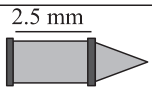
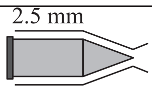
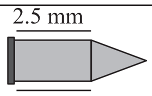
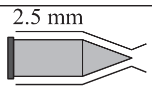
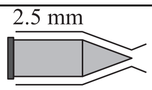
The table shows the conditions of 10 sample tests with the indication of DLRE configuration, the width of the annular slit δ, oxygen and NG absolute pressures $P_{\mathrm{O_2}}$ and $P_{\mathrm{CH_4}}$ in collectors, fuel mixture mass flow rate G, specific (per unit area of injector holes for fuel mixture supply) mass flow rate G_{sp}, fuel-to-oxygen equivalence ratio Φ, as well as the results of the tests in terms of the average absolute pressure in the combustor P_c near the injector head, the number of detonation waves n, detonation velocity D, frequency f of detonation rotation, thrust R, and specific impulse I_{sp} calculated as thrust T divided by gG, where g is the acceleration of gravity.

The values of thrust T shown in Table 1 were obtained by averaging the thrust curve (see, e. g., Fig. 8 corresponding to Test 9 in Table 1) over the time interval from 0 to 0.4 s, i. e., after the establishment of a quasi-stationary mode of DLRE operation. Note that the values of thrust and specific impulse in Table 1 are different from those reported earlier in [10] due to the systematic error of about 15% found in thrust measurements. To avoid this error, the load cell was carefully fixed and calibrated within a wide range of measured thrusts.

In Tests 1 to 5, the DLRE of basic design with the annular slit width of $\delta = 1$ mm without washer and CD nozzle extension was used. In Test 5, the replaceable thin disc was displaced 2 mm downstream relative to the fuel injector holes, so that NG was injected radially 1.5 mm upstream from the annular slit.

In Tests 6 to 10, the annular slit was expanded to $\delta = 2.5$ mm. In addition, in Test 6, a washer blocking 50% of the combustor outlet cross section was installed. In Test 7, the washer was replaced by a CD nozzle extension (see Fig. 1*b*), in which the minimum cross-sectional area was also 50% of the cross-sectional area of the annular combustor channel. In Test 8, neither washer, nor CD nozzle extension was used.

Results of ten selected tests

No.	Configuration	P_{O_2}, atm	P_{CH_4}, atm	G, kg/s	G_{sp}, kg/s/m^2	Φ	P_c, atm	n	D, m/s	f, kHz	T, kgf	I_{sp}, s
1[a]		8	21	0.70	2243	0.87	1.0	—	—	—	19	24
2		8	19	0.46	1474	1.1	4.5	4	1880	24	64	122
3		6	14	0.35	913	1.15	3.3	4	1650	21	47	133
4		6	14	0.37	1186	1.1	3.2	3	2090	20	47	128
5[b]		6	13	0.30	962	1.12	3.2	1	2320	7	38	127
6		7	16	0.35	418	1.1	6.7	1	2200	7	53	150
7		8	15	0.36	430	1.1	7.6	1	1500	5	60	167
8[c]		3	10	0.16	191	1.0	1.9	1	2200	7	21	127
9		10	21	0.46	550	1.2	9.3	1	1500	5	84	181
10[c]		7	15	0.36	430	1.15	6.6	1	—	5	59	162

[a]Test without ignition.
[b]Replaceable thin disc displaced 2 mm downstream.
[c]Near-limiting mode with a detonation wave pulsating longitudinally rather than circulating in the tangential direction.

Finally, Tests 9 and 10 were made with CD nozzle extension at different supply pressures of NG and oxygen.

In Test 1, the fuel mixture components were purged through the DLRE without ignition to measure the baseline thrust created by the cold flow.

In Tests 2 to 4, stable operation modes with four and three equidistant detonation waves simultaneously circulating in the same tangential direction were detected. Despite Tests 3 and 4, were made at similar initial conditions in terms of DLRE configuration and absolute pressures P_{O_2} and P_{CH_4} in collectors, the experimental results were somewhat different: in Test 3, four detonation waves were detected whereas in Test 4, the number of detonation waves was three. This difference is attributed to the fact that the initial conditions for Tests 3 and 4 are at the margin of existence of the operation mode with four detonation waves.

In Test 5 with the DLRE of basic configuration, a steady operation mode with a single detonation wave circulating in a tangential direction was observed.

In Tests 3, 6, and 7, the mass flow rate of fuel mixture was maintained approximately constant (0.35–0.36 kg/s). With an increase in pressure in the combustor, both thrust and specific impulse increased monotonically: in Test 3 with the combustor pressure of 3.3 atm, the thrust and the specific impulse were 47 kgf and 133 s, respectively, and in Test 7, these values increased to 60 kgf and 167 s, respectively, at an average pressure in the combustor of 7.6 atm.

With the growth of the specific mass flow rate of fuel mixture (from 191 $kg/s/m^2$ in Test 8 to 418, 430, and 913 $kg/s/m^2$ in Tests 6, 7, and 3), the operation process in the combustor, on the one hand, was becoming more stable and, on the other hand, the number of detonation waves simultaneously rotating in the combustor in one direction increased.

Thus, in Test 8, a near-limiting operation mode with rotating-to-pulse detonation transition was observed: in this test, the detonation wave was running in the longitudinal rather than in the tangential direction, periodically recovering near the DLRE outlet.

At the specific mass flow rate on the level of 420–430 $kg/s/m^2$ (Tests 6 and 7), the operation mode with one detonation wave stably circulating in the tangential direction was detected. Finally, in Test 3, four equidistant detonation waves were stably circulating in the combustor. Replacement of the flow washer in Test 6 by the CD nozzle extension in Test 7 under otherwise similar conditions led to increased thrust performance, but the detonation velocity was greatly reduced (down to 1500 instead of 2200 m/s) approaching the limiting values.

Interestingly, the increase of the mass flow rate of fuel mixture from 0.36 kg/s in Test 7 to 0.46 kg/s in Test 9 in the DLRE of the same configuration with CD nozzle extension did not lead to a change in the operation mode. In both tests, the DLRE operated with one detonation wave rotating in the tangential direction at a velocity of 1500 m/s, although the thrust and the specific impulse in Test 9 increased to 84 kg/s and 181 s, respectively. Decreasing of supply pressures of fuel components as compared to Test 9 other conditions being the same led to the establishment of the near-limiting operation mode with the detonation wave pulsating longitudinally.

It is worth noting that at the mass flow rate of fuel mixture close to that in Test 4, the thrust in Test 10 appeared to be higher than in Test 4: 59.0 instead of 47 kgf.

The reason for the reduction of the detonation velocity in the DLRE with CD nozzle extension will be the subject of further research.

Concluding Remarks

The experimental investigations of DLRE operating on NG–oxygen mixture have been performed to examine the impact of the DLRE configuration and fuel supply parameters on the operation process and thrust performance. In experiments, the absolute pressures of NG and oxygen supply were up to 30 and 15 atm, respectively; fuel mixture mass flow rate was varied from 0.05 to 0.7 kg/s; and the overall fuel mixture composition was varied from fuel lean (with equivalence ratio 0.5) to fuel rich (with equivalence ratio 2.0). The maximum thrust and the maximum specific impulse obtained in this experimental series was 85 kgf and 185 s, respectively, at the maximum average pressure in the combustor of about 10 atm. It is shown that the increase of static pressure in the combustor results in the increase of both engine thrust and specific impulse. With the growth of the specific mass flow rate of fuel mixture, the operation process, on the one hand, becomes more stable, and on the other hand, the number of detonation waves simultaneously rotating in one direction in the combustor annulus increases. The replacement of the washer by the profiled CD nozzle extension with other conditions being similar leads to increased thrust performance, but the detonation velocity is greatly reduced (down to 1500 instead of 2200 m/s), approaching the limiting values. The reason for this decrease in the detonation velocity will be the subject of further research.

Acknowledgments

The work was supported by the Russian Ministry of Education and Science under the State Contract No. 14.609.21.0002 (Contract ID RFMEFI60914X0002) "Development of technologies for the use of liquefied natural gas (methane, propane, butane) as fuel for rocket and space technology and the creation of a new generation of stand demonstrator rocket engine" under the Federal Target Program "Research and development in priority areas of scientific and technological complex of Russia for 2014–2020."

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