ROCKET ENGINE WITH CONTINUOUSLY ROTATING LIQUID-FILM DETONATION

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The possibility of organizing a continuous-detonation combustion of a liquid fuel film in an annular combustor of a Detonation Liquid-propellant Rocket Engine (DLRE) has been demonstrated. The near-limit mode of the longitudinally pulsating "film" detonation (LPD) and the continuous spinning "film" detonation (CSD) modes with one and two detonation waves circulating in the annular gap of the combustor are recorded in the fire tests.

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Introduction

Currently, there are several promising trends of development of Liquid-propellant Rocket Engines (LREs) in space propulsion technology. One of such trends is to replace continuous deflagrative (subsonic) combustion by continuous detonative (supersonic) combustion of the propellant mixture in the LRE combustor. The transition to continuous detonative combustion is advisable because the thermodynamic cycle efficiency of the detonative combustion engine is higher than that of the conventional deflagrative combustion engine [1, 2] (theoretically, by 13%–15% [2]). Moreover, in the DLRE, the combustor and the nozzle are more compact and the detonative combustion is characterized by low emissions of hazardous pollutants. The energy efficiency of using continuous detonative combustion in a DLRE was experimentally proven in our previous studies with gaseous hydrogen – gaseous oxygen DLRE [3, 4]. The specific impulse was shown to increase up to 7%–8% when deflagrative combustion was replaced by detonative combustion in the same engine at the same supply pressures of mixture components.

Most of experimental studies are performed with DLREs operating on gaseous components (hydrogen [3–7], methane [5, 6, 8, 9], ethylene [10], etc.)*. There are only a few publications on applying liquid fuels in DLREs. The first experiments with continuous (rotating) detonative combustion of a liquid fuel – gaseous oxygen mixture in an annular combustor were carried out by Bykovskii and Zhdan [6]. They used kerosene, benzene, and acetone as liquid fuels and gaseous oxygen as oxidizer. Their annular combustors had the external diameter/length equal to 50/100, 100/100, and 280/60 mm and an annular gap of 10 mm in width. Liquid fuel was injected in the combustor through distributed triple-orifice injectors with axial injection of liquid fuel and two inclined impinging side jets of gaseous oxygen. The measured velocities of heterogeneous (spray) detonation ranged from 1750 to 2350 m/s depending on the fuel and the combustor used. The maximum deficit of the measured detonation velocity with respect to the thermodynamic value calculated for the overall fuel-to-oxidizer equivalence ratio attained 30%.

*Air-breathing rotating detonation engines and pulsed detonation rocket engines are beyond the scope of this article.

At present, all prospective concepts of DLREs are based on the distributed spraying of liquid fuel in the combustor like in conventional LREs. These concepts imply that the annular combustor of the DLRE is continuously filled with two-phase gas–droplet reactive mixture and the latter is burned out in a single or several heterogeneous (spray) detonation waves continuously rotating in the annular gap of the combustor. The shock waves leading the detonation induce very fast fragmentation of liquid sprays and droplets as well as fast liquid evaporation, turbulent and molecular mixing of fuel vapor with oxygen, and spontaneous volumetric ignitions in the resultant mixture [11].

In this paper, another concept of DLRE is considered. This concept is based on the so-called "film" detonation which was studied extensively in the past century. Unlike spray detonation, film detonation propagates in a stratified two-phase medium consisting of gaseous oxidizer and liquid fuel film deposited on bounding surfaces. The combustible fuel mixture in film detonation is formed because of partial prevaporization of the film ahead of the detonation front as well as due to aerodynamic fragmentation of the film by the gas flow behind the leading shock wave of the detonation front, evaporation of microdroplets entrained in the flow, and turbulent and molecular mixing of fuel vapor with oxidizer. As in spray detonations, energy release in film detonation proceeds due to spontaneous volumetric ignitions of the resultant mixture and subsequent fast afterburning.

In 1952, Loison [12] observed detonation in such a system because of transmitting gas detonation to an air-filled tube with a thin film of a liquid fuel applied to the wall. In a large series of works by Troshin with coworkers (see, e. g., [13–15]), film detonation was initiated by exploding lead azide charges, blasting caps, etc. in tubes 6 to 30 mm in diameter and 1.6 to 3.5 m in length. In these tubes, various liquid fuels (petroleum oils, viscous lubricants, and individual hydrocarbons) and carbon in the form of carbon black were applied as films and layers of tens of micrometer to millimeter thickness onto the inner surface of the tubes, and various oxidizer gases (oxygen or oxygen-enriched air) were used at an initial pressure of 1 to 40 atm. The measured velocities of film detonations ranged from 900 to 1900 m/s. The maximum deficit of the measured detonation velocity with respect to the thermodynamic value calculated for the overall fuel-to-oxidizer equivalence ratio (within the detonability limits of premixed compositions) attained 60%; however, film detonations did not exhibit a fuel-rich concentration limit. Further studies were later performed by Nicholls with coworkers [16–18] and Gelfand with coworkers [19–21], and were revisited recently by us [22, 23].

The heterogeneous gas–film system has several important advantages for use in DLREs. Firstly, the gas–film system can be additionally used for active thermal protection of the walls of the DLRE when the film is fed to the highly heated sections of the combustor. Secondly, in such a system, detonation can propagate virtually at any thickness of the liquid film (see, e. g., [14, 16]) which reduces the requirements for the accuracy of dosing of fuel and increases the reliability of the operation process. Thirdly, in the stratified gas–film system, which is characterized by a relatively small area of the interface (in comparison with the gas–droplet system), the preliminary evaporation of the liquid ahead of the propagating detonation wave is insignificant, which prevents various disturbances in the operation process like flame flashback, etc.).

The objective of this work was to experimentally prove the possibility of organizing the continuous detonative combustion of a liquid fuel film in an annular combustor of a DLRE.

Experimental Installation and Test Procedure

Figure 1 shows a schematic of the DLRE demonstrator with a combustor in the form of an annular gap between the cylindrical central body and a coaxial outer cylindrical wall. This schematic is different from the DLRE schemes in which gaseous or liquid fuel is supplied to the combustor via distributed fuel injectors in the form of gas jets or liquid sprays. Here, the liquid fuel is supplied to the combustor through the outer surface of a porous ring insert of finite length under the pressure of a displacing gas (nitrogen) and forms a thin liquid film on the inner surface of the porous ring insert. The oxidizer (gaseous oxygen) is fed to the combustor through an annular gap in the axial direction, thus promoting uniform spreading of the film along the inner surface of the porous insert. Film detonation is initiated with the help of an external initiator via transmitting the initiating shock wave

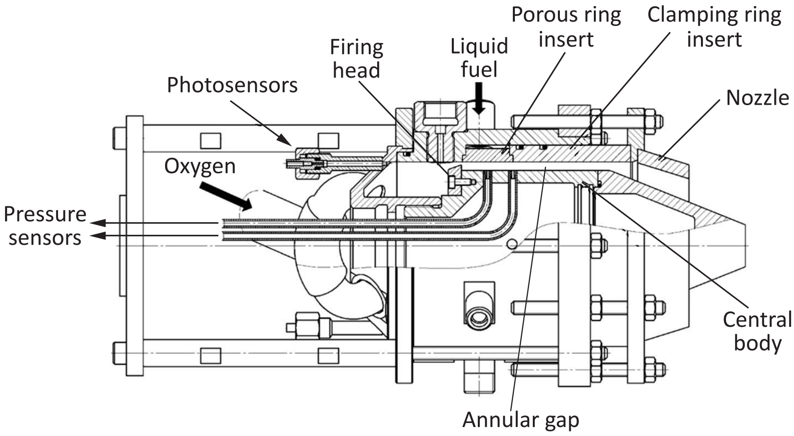


Figure 1 Schematic of DLRE

into the annular combustor through the DLRE nozzle. The shock wave propagating above the liquid film ensures rapid mixture formation and subsequent volumetric combustion of the resulting mixture leading to the formation of a self-sustained detonation wave. The detonation wave is capable of circulating in the annular combustor once the conditions necessary for its existence remain unchanged ahead of the wave front.

The annular combustor of the DRE demonstrator (see Fig. 1) is composed of 4 elements: a central body with a diameter of 90 mm and a length of a cylindrical section of 90 mm with a cone nozzle 101 mm long made of copper; a porous ring insert with an internal diameter of 98 mm, a length of 30 mm, and a thickness of 9 mm made of a permeable material; clamping impermeable ring insert with an inner diameter of 98 mm, a length of 70 mm, and a thickness of 11 mm made of copper; and the firing head in the form of a knife — a thin copper disk with a sharp edge blocking a part of the annular section at the entrance to the combustor, leaving a gap of 1.2 mm. All elements of the annular combustor are mounted in a cylindrical casing with a single end-flange made of stainless steel. The casing contains holes for the supply of liquid fuel (n-pentane) and the flange contains the holes for the supply of gaseous oxidizer (oxygen). The fuel is chosen

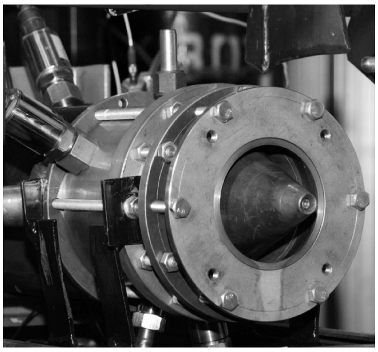


Figure 2 Detonation LRE with the short nozzle attached

Figure 3 Porous ring insert

for reasons of high volatility of vapor (the boiling point of n-pentane at atmospheric pressure is 36 °C). In subsequent studies, n-pentane will be replaced by less volatile liquid fuels. In several tests, a tapering nozzle with a length of 34 mm and a cone angle of 35° was attached to the open end of the combustor (Fig. 2).

The main element of the combustor is a porous ring insert (Fig. 3). The insert is manufactured from coarse-grained nickel powder (PNK, Russian State standard 9722-79), consisting of particles with the size ranging from 70 to 100 μm, using the technology of powder metallurgy. The molding of the insert was carried out in an elastic tool that repeated the shape of the final product under conditions of cold isostatic pressing at a pressure of 200 MPa in the CIP 62330 hydrostat. The pore former, ammonium bicarbonate $(NH_4)_2CO_3$ (in an amount of 10 %(vol.)) was added to the sintered material for obtaining the required permeability. The pore former volatilizes at a sufficiently low temperature and forms through channels. The necessary strength of the material meeting permeability requirements is achieved by selecting proper sintering conditions. The rational sintering conditions were: 2 h of sintering in a hydrogen atmosphere at a temperature of 900 °C.

Permeability of the porous ring insert was preliminarily measured with the help of special equipment, which made it possible to plot the calibration dependencies of the consumption of liquid fuel on the pressure of the displacement gas.

The data acquisition system for the DLRE operation process includes (see Fig. 1) two photosensors, low-frequency static pressure sensor, three high-frequency pressure sensors PT1, PT2, and PT3, and thermocouples. The photosensors with a bandwidth of $F_{-3\mathrm{dB}} > 2$ MHz are based on the BPW34 photodiode and the AD8066 operational amplifier. They are mounted in the end flange in the middle of the annular gap of the combustor. Low- and high-frequency pressure sensors are installed at the ends of the tubular waveguides inserted into the central body and communicating with the annular gap of the combustor. The low-frequency static pressure sensor (Courant-DA 2.5 MPa) measures the average static pressure in the combustor at a distance of 15 mm downstream from the firing head. Three high-frequency pressure sensors (Kistler 211B3) measure pressure pulsations at three points located at an angular distance of 120° from each other in one cross section of the combustor at a distance of 30 mm downstream from the firing head. Thermocouples (K type) measure the temperatures of the central body, porous ring insert, and clamping ring insert.

The oxygen flow rate is calculated based on the measured rate of the pressure drop in the oxygen receiver. The consumption of liquid fuel is measured by a turbine flowmeter.

Measurement errors: error in the frequency of the operation process (using pressure pulsation sensors) does not exceed 3%; error in the average static pressure in the combustor does not exceed 1%; error in wall temperature does not exceed 10%; and errors in mass flow rates of fuel components are not more than 10%.

Figure 4 Photo of the DLRE exhaust plume in one of the fire tests

A typical fire test of the DLRE demonstrator lasts 1 s. In addition to the operation process with combustion of the fuel mixture, this time includes the opening and closing time of the quick-acting fuel and oxidizer valves. All tests were carried out at an ambient temperature of $-3 \cdots +3$ °C. Figure 4 shows a typical photograph of an exhaust plume of the DLRE demonstrator in a fire test.

Results and Discussion

The most important result of these experiments is the proof of the possibility of organizing the continuous detonative combustion of a liquid fuel film in an annular combustor of the DLRE demonstrator. In the fire tests, both a near-limit LPD and CSD modes with one and two film detonation waves circulating in the annular gap of the combustor have been registered.

Figure 5 shows the primary recordings of two photosensors (curves *1* and *2*, right axis), the low-frequency static pressure sen-

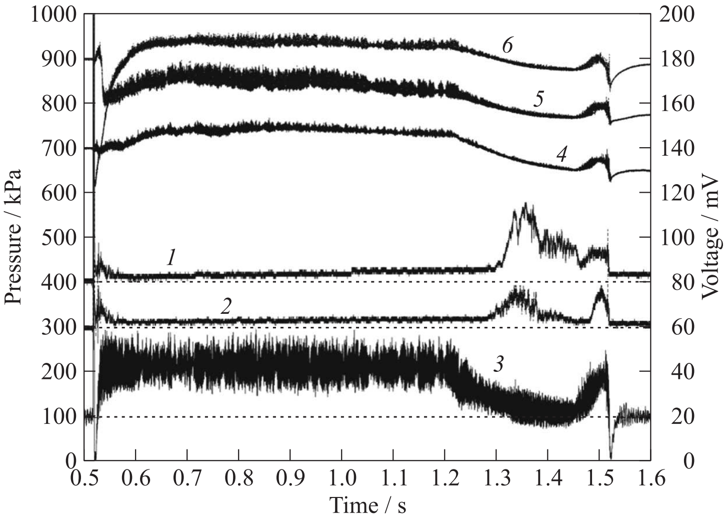


Figure 5 Recordings of photosensors (*1* and *2*), static pressure sensor in the combustor (*3*), and high-frequency pressure sensors (*4*, *5*, and *6*) in one of the fire tests

sor in the combustor (curve *3*, left axis), and three high-frequency pressure sensors (curves *4*, *5*, and *6*, left axis) in one of the fire tests (without an attached nozzle) with fuel component mass flow rates of 160 (oxygen) and 40 g/s (n-pentane) corresponding to a total fuel-to-oxidizer equivalence ratio of ~ 0.9. In the time interval from 700 to 1100 ms, an approximately constant luminescence intensity and a constant absolute mean static pressure in the combustor (0.22 MPa) are recorded. During the test, the temperature of the uncooled central body became much higher (about 100 °C) than the temperature of the clamping ring insert (about 50 °C) despite the total mass of the central body and the conical nozzle (2.7 kg) was larger than the mass of the clamping ring insert (2.1 kg). This effect is presumably due to cooling of the clamping-ring inner surface by the liquid film. The temperature of the porous ring insert cooled by displaced liquid fuel did not exceed 10 °C. Since this temperature is less than the boiling temperature of n-pentane, one can assume that the fuel enters the annular gap of the combustor in the liquid state and forms a liquid film on the inner surface of the porous ring insert.

Fourier analysis of the records of high-frequency pressure sensors in the test relevant to Fig. 5 reveals a dominating frequency of the operation process of 2.85 kHz (Fig. 6), i. e., the characteristic time of the quasi-stationary operation process in the combustor is ~ 350 μs. Estimates show that during this time, the displacing system for sup-

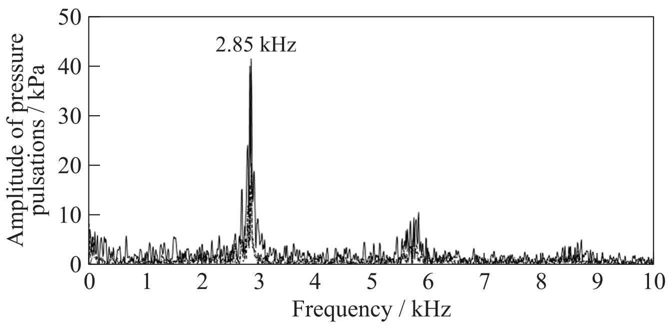


Figure 6 Fourier transform of a fragment of records of three high-frequency pressure sensors

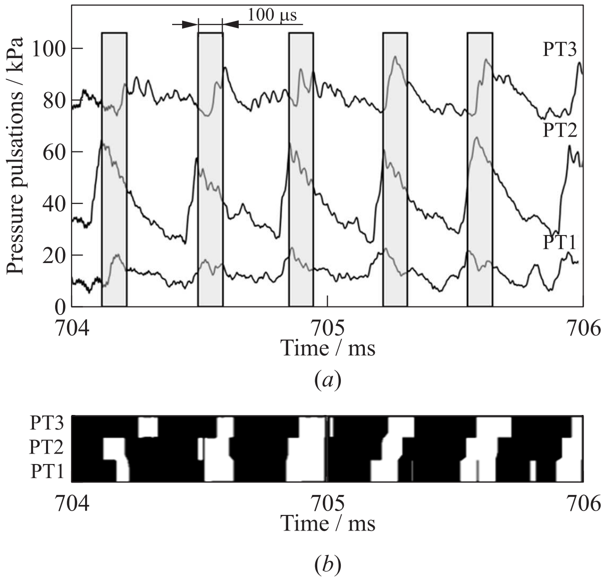


Figure 7 A fragment of the records of high-frequency pressure sensors (a) and its "visualization" according to [27] (b) for the LPD mode

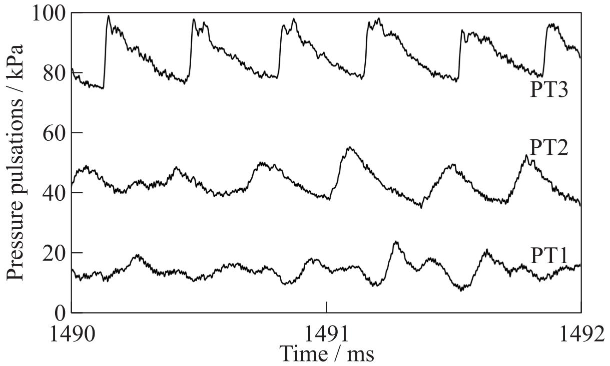
plying liquid fuel to the combustor provides the formation of a liquid film of a thickness of about 5 μm on the inner surface of the porous ring insert. An analysis of the phases of pressure pulsations shows that in the fire test under consideration, a near-limit LPD mode is realized, which is similar to the modes detected earlier in [24–26] when operating with gaseous components.

As a matter of fact, Fig. 7a shows a fragment of the records of three high-frequency pressure sensors of 2-millisecond duration at the very beginning of the time interval 700–1100 ms. The records show regular pressure pulsations with steep fronts, and the phases of pressure pulsations on all three sensors are virtually (to within ~ 100 μs) the same. This is clearly illustrated by the "visualization" of the records of those pressure sensors shown in Fig. 7b. The records are "visualized" according to the procedure described in [27]. Plotted along the abscissa is the time (the same time interval as in Fig. 7a)

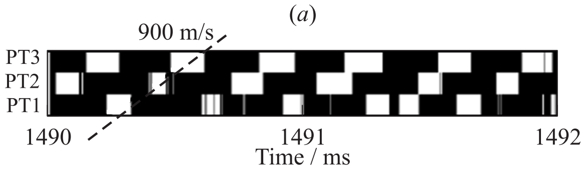
and three pixels plotted along the ordinate correspond to pressure sensors PT1, PT2, and PT3. The white and black colors of the pixels in Fig. 7*b* correspond to the maximum and minimum values of the measured amplitude of the pressure pulsation (the pulsation amplitude is maximal at the detonation front and minimal in the cold gas). The pressure waves are seen to arrive to the positions of sensors PT1, PT2, and PT3 almost simultaneously but periodically, with a certain cycle. This situation is possible when a detonation wave periodically (at a frequency of ~ 2.85 kHz) arises in the annular gap and propagates upstream with a large axial and relatively small tangential velocity components.

An indirect confirmation of this implication can be found in the results of measurements reported in [24–26], where the space–time wave dynamics of the onset, propagation, and attenuation of the LPD were studied, and pressure records similar to those shown in Fig. 7 were obtained. Considering that the maximum rate of filling of the annular combustor with oxygen is approximately on the order of the speed of sound (~ 300 m/s), and the minimal (at the limit of propagation) detonation velocity in the gas–film system is ~ 1000 m/s [12, 14, 22, 23], the onset of LPD should occur at a distance $(1000 - 300) \cdot 0.00035 \approx 0.25$ m from the firing head. It can be thus assumed that detonation periodically arises near the combustor exit as in experiments [24–26]: a detonation explosion occurs either as a result of local spontaneous ignition of a fresh fuel mixture on the developed contact surface with the hot products of the previous detonation wave or due to shock compression of a portion of a fresh fuel mixture in the end-shock penetrating the combustor after the attenuation of the previous detonation wave. After local onset, the detonation wave propagates upstream towards the firing head, occupying the entire volume of the annular gap. In this case, the distance traveled by the wave is comparable with the estimate obtained above.

In addition to the near-limit LPD mode, in a number of firing tests, the CSD modes with one and two detonation waves circulating in the annular gap of the combustor were detected. For example, Fig. 8*a* shows a fragment of the records of three high-frequency pressure sensors at the end of the operation process during the interval lasting 2 ms (in the time interval from 1490 to 1492 ms) in the same fire test as shown in Fig. 5. The frequency of pressure pulsations



(*a*)



(*b*)

Figure 8 A fragment of the records of high-frequency pressure sensors (*a*) and its visualization (*b*) for the CSD mode with a single rotating detonation wave

obtained with the help of Fourier transform is $\sim$ 2.9 kHz. As in Fig. 7*a*, regular pulsations of pressure with steep fronts are seen on the records; however, the pulsation phases are different. The "visualization" of the records in Fig. 8*b* shows that a mode with one detonation wave rotating at a tangential speed of about 900 m/s is realized in the combustor during the time interval under consideration. The true normal velocity of the detonation wave is estimated as $\sim$ 1000 m/s since the detonation front is inclined to the combustor axis due to the finite filling rate of the combustor by the fresh mixture.

In one of the tests with an attached nozzle and with mass flow rates of fuel mixture components of 150 (oxygen) and 80 g/s (*n*-pentane), corresponding to a total fuel-to-oxidizer equivalence ratio of $\sim$ 2.0, the absolute mean static pressure in the combustor was 0.25 MPa, and the dominating frequency of the operation process turned out to be as high as $\sim$ 4.7 kHz. Analysis of phases of pressure pulsations showed that in this test, an operation process with two detonation waves continuously rotating in an annular gap with a tangential velocity of $\sim$ 730 m/s was recorded. If one takes into account the finite filling rate of the combustor by the fresh mixture, then the true normal velocity of the detonation wave will be somewhat higher ($\sim$ 800 m/s). Such low propagation velocities of the detonation front are possible only if the ignition of the mixture is not determined by the temperature behind the leading shock wave: it is too low for fast spontaneous ignition of the fuel vapor. Following [26], under these conditions, the steady-state propagation of the detonation wave in the annular gap can be ensured only by ignition of the fuel mixture behind the shock wave reflected from the compressive external wall, followed by energy release in a turbulent flame. It is worth emphasizing that the reflection of the leading shock wave from the compressive external wall is the intrinsic feature of the continuous detonation process in annular combustors [28, 29]. As for turbulence, its intensity in the recirculation zone downstream from the firing head is very high [28].

Concluding Remarks

Thus, the possibility of organizing the continuous detonative combustion of a liquid fuel film in an annular combustor of a DLRE has been proved experimentally. In such a DLRE, the liquid fuel film is used both to provide a stable operation process and for active thermal protection of the combustor walls.

Further work will be directed to a systematic study of the parametric domains of existence of LPD and CSD modes for both liquid n-pentane and less volatile liquid hydrocarbons.

Acknowledgments

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