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Experimental proof of Zel'dovich cycle efficiency gain over cycle with constant pressure combustion for hydrogen–oxygen fuel mixture

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ABSTRACT

The objective of work outlined in this paper was to prove experimentally the energy efficiency of Zel'dovich thermodynamic cycle (cycle with detonative combustion of fuel) by direct comparison of thrust performances of liquid-propellant rocket engine (LRE) prototypes operating in continuous-detonation and continuous-combustion modes using gaseous hydrogen as fuel and gaseous oxygen as oxidizer. For this purpose, a test rig and two LRE prototypes were designed and fabricated. It has been proved experimentally that Zel'dovich thermodynamic cycle with continuous-detonation combustion of hydrogen–oxygen mixture in two different LRE prototypes is more energy efficient than the cycle with continuous constant-pressure combustion of the same mixture, other conditions being equal. Thus, at predetermined limitations on supply pressures of fuel components and at a fixed mass flow rate of fuel mixture the specific impulse of the LRE prototypes operating in the continuous-detonation mode appeared to be 6–8% higher than the specific impulse of the same LRE prototypes operating in the continuous-combustion mode.

Introduction

In 1940, Zel'dovich proposed the idea of using detonation combustion of fuel in ramjet and rocket propulsion [1]. He estimated the thermodynamic efficiency of the cycle with detonation combustion of fuel and showed that it substantially exceeds the efficiency of the cycle with constant-pressure combustion and always exceeds the efficiency of Hamphrey cycle with constant-volume combustion. Later, theoretical conclusions of Zel'dovich were confirmed by thermodynamic calculations and multidimensional gasdynamic calculations involving various dissipative processes. Thus, thermodynamic calculations in Refs. [2–4] showed that the efficiency of "Zel'dovich cycle" (cycle with detonation combustion) can theoretically be up to 20–30% higher than the efficiency of the cycle with constant-pressure combustion, whereas multidimensional gasdynamic simulation of liquid-propellant rocket engine (LRE) operation in a continuous-detonation mode conducted in Refs. [5,6] yielded efficiency exceeding that of conventional LRE by 13–15%. Despite the fact that theoretical conclusions on the advantage of

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Zel'dovich cycle with fuel conversion in propagating detonation waves over the cycle with steady-state constant-pressure combustion are not questioned [4,7,8], there were no direct experimental evidences of these findings so far, except for our recent accomplishments briefly reported in Refs. [9,10] and related to a small-size LRE prototype.

The objective of work outlined in this paper was to extend the experimental campaign launched in Refs. [9,10] and to prove experimentally the energy efficiency of Zel'dovich cycle by direct comparison of thrust performances of two different-size LRE prototypes operating in continuous-detonation and continuous-combustion modes using gaseous hydrogen as fuel and gaseous oxygen as oxidizer.

Test rig and prototypes of liquid-propellant rocket engine

The outdoor test rig consists of receivers for hydrogen (volume of 0.64 m^3) and oxygen (volume of 0.32 m^3), high-performance fast-response valves, fuel lines of large cross-section, thrust table with a calibrated load cell, and measurement systems of thrust and supply pressure of fuel components. The maximum mass flow rate of fuel mixture in the rig is 1.5 kg/s.

Two LRE prototypes are designed according to Voitsekhovskii concept described in detail in Ref. [11]. Each prototype is an annular combustion chamber with an injector head attached from one side and a nozzle from another side. Fig. 1 shows the photographs of the prototypes.

In the first (smaller) prototype, shown in Fig. 1a, the chamber is formed by two coaxial cylinders 90 mm high: internal cylinder 40 mm in diameter is embedded in a hollow outer cylinder 50 mm in diameter so that the gap between the cylindrical surfaces is 5 mm. This LRE prototype was previously used in the experimental campaign of [9,10] and will be further referred to as the 50-mm-diameter LRE prototype. The injector head consists of a thin disc with a sharpened edge that is attached to the end of the inner cylinder of the chamber so that the annulus between the edge and the outer wall of the chamber is 1 mm wide, and 72 or 60 radial holes each of 0.8-mm diameter in the outer wall of the chamber disposed in one cross section at an axial distance of 0.5 mm downstream from the disc. Oxygen is supplied to the combustion chamber axially through the annulus of the injector head, and hydrogen is supplied through the radial holes. The nozzle is formed by a conical center body with an apex angle of 50° attached to the other end of the inner cylinder. To ignite fuel mixture, a tungsten electrode is placed near the outer-cylinder exit section. Because of large thermal loads, the combustion chamber is water-cooled and is made of copper. The 50-mm-diameter LRE prototype has a modular design, which allows variation of all basic geometric dimensions and replacement of injector head and nozzle.

In the second (larger) prototype, shown in Fig. 1b, the chamber is formed by two coaxial cylinders 100 mm high: internal cylinder 90 mm in diameter is embedded in a hollow outer cylinder 100 mm in diameter so that the gap between the cylindrical surfaces is also 5 mm. This LRE prototype has been designed and fabricated purposefully for this investigation and will be further referred to as the 100-mm-diameter LRE prototype. Similar to the smaller prototype, the injector head of the 100-mm-diameter LRE prototype consists of a thin disc with a sharpened edge that is attached to the end of the inner cylinder of the chamber so that the annulus between the edge and the outer wall of the chamber is also 1 mm wide. Contrary to the smaller prototype, here, 144 (rather than 72 or 60) radial holes 0.8 mm in diameter are disposed in the outer wall of the chamber in one cross section at an axial distance of 0.5 mm downstream from the disc. The nozzle is formed by a conical center body with an apex angle of 40° attached to the other end of the inner cylinder.

The test rig is equipped with a remote control system. Fire test begins with the digital signal to open an oxygen valve, then (after 100 ms) a hydrogen valve, and (after 100 ms) to trigger ignition; and, upon 1-s operation, to successively close the oxygen and hydrogen valves.

The measuring system includes three ionization probes and a low-frequency pressure sensor all mounted in the outer wall in one cross section 10 mm downstream from hydrogen holes with a relative angular position of 90°. These tools allow identification of engine operation mode (continuous-detonation, continuous-combustion, or transient mode), evaluation of the speed of detonation waves at continuous-detonation mode, registration of the number of detonation waves simultaneously rotating over the injector head and their rotation direction, and measurement of average static pressure in the chamber, just similar to the capabilities of our measuring system described in Refs. [12], which was

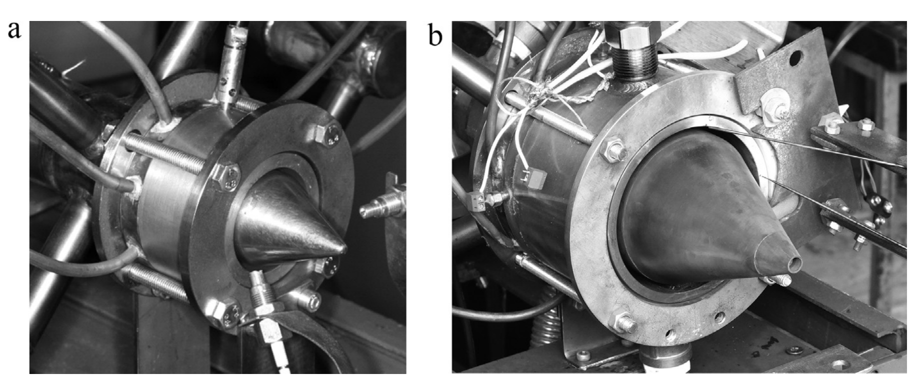

Fig. 1 – Photographs of two LRE prototypes with the annual combustor 50 mm (a) and 100 mm (b) in outer diameter.

successfully used in studies of a large-scale hydrogen–air continuous-detonation combustor. In addition to measurements of ionization currents, static pressure, and thrust, measurements of static pressure (with low-frequency pressure sensors) in the mains of oxygen and hydrogen supply are made together with high-speed video recording of the operation process in the annular combustion chamber. Water temperature in the water-cooling system is measured by thermocouples.

Results and discussion

Experiments with 50-mm-diameter LRE prototype

Fig. 2 shows the primary experimental data obtained in the 50-mm-diameter LRE prototype of Fig. 1a at relatively low mass flow rates of fuel mixture (up to about 0.1 kg/s) in terms of measured thrust versus absolute pressure of hydrogen supply at different absolute pressures of oxygen supply. All experiments (57 runs) presented in Fig. 2 by points are performed at ambient temperature 23±1 °C within several days. The maximum absolute measurement errors of thrust and fuel mixture mass flow rate are estimated at 2 N and 2 g/s, respectively, based on instrumental errors of load cell and pressure sensors and their calibration tests. Thus, the errors of the measured thrust are about the sizes of squares and circles in Fig. 2.

The left side of each series of points (closed and properly half-closed squares) in Fig. 2 corresponds to the continuous-detonation operation mode, which is well identified by high-amplitude regular peaks in ionization currents and (usually) two uniformly rotating equidistant bright-glow detonation waves in high-speed video recording. The right side of each series of points (closed and respectively half-closed circles) corresponds to the continuous-combustion operation mode, which is identified by relatively low-amplitude (an order of magnitude lower than in the continuous-detonation mode) irregular pulsations in ionization currents and uniform faint glow in high-speed video recording. Closed and respectively half-closed stars in some series of experiments correspond to transient operation mode with clear and relatively long-term (at least 20% of operation time) manifestations of symptoms of both modes in ionization currents and in high-speed video recording. The points plotted in Fig. 2 are well reproducible from run to run at fixed operation conditions (within 1% in terms of thrust measured during one day and/or at different days).

It is seen from Fig. 2 that thrust depends on the flow rates of fuel components and on fuel mixture composition, the maximum thrust being reached at a ratio of hydrogen-to-oxygen supply pressures of 1.9–2.1. In each experimental series, increase of hydrogen supply pressure leads to a transition from continuous-detonation to continuous-combustion operation mode, and with increasing oxygen supply pressure, the transition point is shifted to a higher pressure of hydrogen supply.

Processing of data presented in Fig. 2, allows the direct evidence for energy efficiency of Zel'dovich cycle to be obtained. Fig. 3 is the formal attempt to group the experimental points of different series into the clusters of points for the two operation modes – continuous-detonation and continuous-combustion. As seen, such clustering of the points has been achieved on the plot of the ratio of specific impulse to the mass flow rate of fuel mixture versus fuel-to-oxidizer equivalence ratio Φ. Specific impulse is defined as the ratio of measured thrust to mass flow rate of fuel mixture and to the acceleration of gravity. The mass flow rate of fuel mixture is determined by pressure drop in oxygen and hydrogen mains during a certain time interval in each experiment, assuming adiabatic expansion of gases (pressure drop of hydrogen and oxygen in each experiment did not exceed 0.20–0.25 atm).

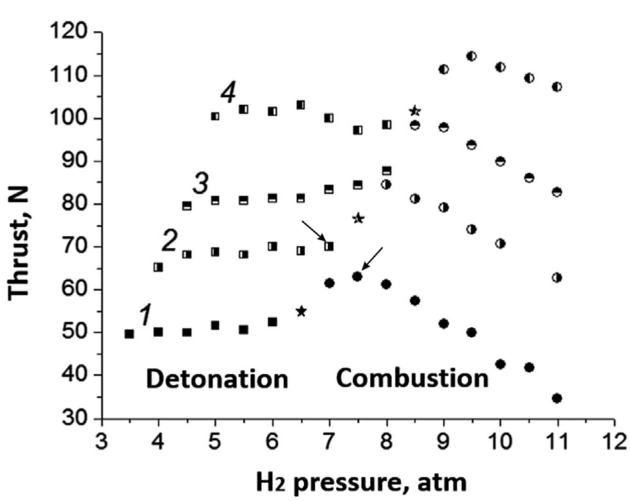

Fig. 2 – Trust vs. hydrogen supply pressure at different oxygen supply pressures (series 1–3.5 atm, 2–4 atm, 3–4.5 atm, 4–5 atm) for the 50-mm-diameter LRE prototype.

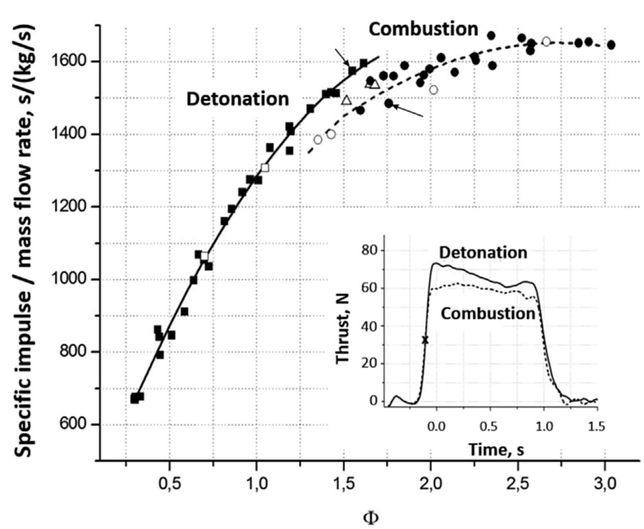

Fig. 3 – The ratio of specific impulse to fuel-mixture mass flow rate vs. mixture equivalence ratio for the 50-mm-diameter LRE prototype. Insert shows time histories of thrust at engine operation points marked by arrows: continuous-detonation mode (0.056 kg/s, Φ = 1.55) and continuous-combustion mode (0.053 kg/s, Φ = 1.75).

Equivalence ratio Φ is defined as the ratio of the mass flow rate of hydrogen to the stoichiometric mass flow rate of hydrogen.

Fig. 3 indicates that in the adopted plane, the points of all four experimental series (see Fig. 2) are grouped around two root-mean-square (RMS) approximation curves: curve for continuous-detonation mode (solid curve and closed squares labeled "Detonation") and curve for continuous-combustion mode (dashed curve and closed circles labeled "Combustion"). Open triangles in Fig. 3 correspond to the transient operation mode mentioned above. These points were not included in the approximations. Clearly, at a fixed fuel-mixture mass flow rate the specific impulse of the 50-mm-diameter LRE prototype operating in continuous-detonation mode is higher. For example, at equivalence ratios $\Phi = 1.6–1.7$ the ordinates of points on the solid curve exceed the ordinates of points on the dashed curve by 6–7%. Taking into account high reproducibility of experimental points in Fig. 2 this finding can be treated as reliable. Moreover, measurements of cooling water temperature indicate that the continuous-detonation mode exhibits higher heat loss than the continuous-combustion mode. In view of it, the conclusion on the superiority of the Zel'dovich cycle is somewhat conservative. Note that neighboring points (squares) on the "Detonation" curve as well as neighboring points (circles) on the "Combustion" curve are (in general) related to significantly different conditions in terms of mass flow rates and specific impulse.

The maximum absolute values of specific impulse in the discussed experiments are relatively low. The insert in Fig. 3 illustrates the obtained effect. It shows the measured time histories of thrust in two experiments with close values of fuel-mixture mass flow rate (0.056 and 0.053 kg/s) at equivalence ratios $\Phi = 1.55$ and 1.75 shown in Fig. 3 (and in Fig. 2) by arrows and corresponding to different operation modes: continuous-detonation (solid curve labeled "Detonation" in the insert) and continuous-combustion (dashed curve labeled "Combustion" in the insert). Despite the fact that the equivalence ratio in the continuous-combustion mode ($\Phi = 1.75$) is closer to the location of thrust maximum ($\Phi = 1.9–2.1$, see Fig. 2), the measured thrust is seen to be higher in the continuous-detonation mode. Note that thrust plotted in Fig. 2 is defined as the mean integral value of thrust over a time interval of 0.4 s measured from the inflection point on the ascending branch of the curve (shown by cross in the inset of Fig. 3). Since the frequency of detonation rotation in the experiments was 30–35 kHz, 12,000 to 14,000 detonation rotations were registered for the time interval of 0.4 s, which was large enough to conclude whether engine operation in the detonation mode is stable and steady.

To make sure that the obtained effect is not associated with incomplete combustion of fuel mixture in the continuous-combustion mode, an additional experimental series with a shorter combustion chamber of 45-mm instead of 90-mm height was performed. The rest of the construction of the LRE prototype was not changed. It turned out that in the continuous-combustion mode under the same supply pressures of oxygen and hydrogen the measured thrust remained the same (within 1%) as for the engine with chamber height of 90 mm, i.e. the height of the combustion chamber (both 45 and 90 mm) is sufficient to ensure complete combustion of the deficient component of fuel mixture. Note that in the LRE prototype of chosen design combustion is stabilized by annular recirculation zone behind the thin disc attached to the end of the inner cylinder.

It follows from Figs. 2 and 3 that at fixed values of equivalence ratio Φ and fuel-mixture mass flow rate the LRE prototype of chosen design can operate in solely one mode: either in continuous-detonation or in a continuous-combustion mode. To further demonstrate the advantage of Zel'dovich cycle over the cycle with constant-pressure combustion, the other series of tests was performed with the replacement of the injector head: instead of the injector head with 72 radial holes used to supply hydrogen the injector head with 60 radial holes of the same diameter was applied. Other engine elements were not changed. This modification yielded the continuous-combustion mode at lower Φ than in experiments with the initial injector head. Empty squares and circles in Fig. 3 correspond to the experiments of this series when the engine operates in continuous-detonation mode (empty squares) and in continuous-combustion mode (empty circles). It is clearly seen that the points in this experimental series are in good agreement with the points of other series in both operation modes and naturally continue the dashed curve "Combustion" down to $\Phi = 1.35$. In the interval $\Phi = 1.35–1.65$, where solid and dashed curves overlap, solid curve "Detonation" is above the dashed curve "Combustion" by 6–7% taking into account a scatter of points with respect to solid and dashed curves. Interestingly, the points relevant to transient operation mode (empty triangles) are lying systematically above the dashed curve. This can be treated as indirect indication of higher energy efficiency of continuous-detonation mode, because this mode partly contributes to the measured thrust. The appreciable scatter of closed circles with respect to dashed curve at $\Phi > 1.65$ can be explained by conditional attribution of some experimental points to continuous-combustion rather than to transient operation mode. Detailed analysis of ionization probe records corresponding to closed circles above the dashed curve "Combustion" in Fig. 3 revealed short-term sporadic high-amplitude perturbations of ionization current inherent in continuous-detonation mode and indicating a sort of unstable combustion. If these points are attributed to the transient operation mode and not included in the RMS approximation, the scatter of the remaining closed circles would be smaller but the resultant gain of Zel'dovich cycle over the cycle with constant-pressure combustion would be the same (6–7%). Note that at $\Phi > 2.5$ ionization probe records never exhibit sporadic perturbations inherent in continuous-detonation mode.

It is worth emphasizing that the representation of the experimental data on the unusual plot given by Fig. 3 should be treated as formal rather than physically significant. This representation was solely used to cluster the specific sets of experimental points in two distinct manifolds for the sake of comparison of thrust performances. Therefore, any generalization of the results should be avoided.

Experiments with 100-mm-diameter LRE prototype

Fig. 4 presents the matrix of 59 experiments (crosses) with the 100-mm-diameter LRE prototype of Fig. 1b in the plane

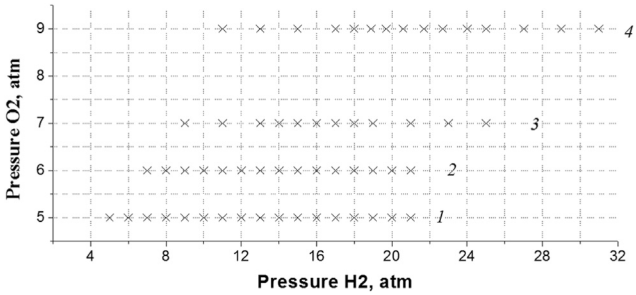

Fig. 4 – The matrix of 59 experiments with the 100-mm-diameter LRE prototype.

"absolute pressure of oxygen supply vs. absolute pressure of hydrogen supply." Four series of experiments were performed with fixed values of oxygen supply pressures: 5 atm (series 1 in Fig. 4), 6 atm (2), 7 atm (3), and 9 atm (4). The absolute pressure of hydrogen supply was varied from 5 to 31 atm. The experiments of series 1 and 2 are performed at ambient temperature 6±1 °C and those of series 3 and 4 at −2±1 °C within several days.

Fig. 5 shows the experimental data in terms of mass flow rate vs. equivalence ratio (Fig. 5a) and specific impulse vs. equivalence ratio (Fig. 5b) for these four series. The left side of each series of points (closed and properly half-closed squares) corresponds to the continuous-detonation operation mode, whereas the right side of each series of points (closed and respectively half-closed circles) corresponds to the continuous-combustion operation mode. Closed and respectively half-closed stars in some series of experiments correspond to transient operation mode. The points plotted in Fig. 5 are well reproducible from run to run at fixed operation conditions.

It is seen from Fig. 5a and b that the mass flow rate of fuel mixture in tests with the 100-mm-diameter LRE prototype was varied from 0.18 to 0.36 kg/s, the chemical composition of the fuel mixture was varied from fuel-lean ($\Phi = 0.3$) to fuel-rich ($\Phi = 2.9$). The maximum specific impulse was on the level of 150–160 s, which is close to the tests with the 50-mm-diameter LRE prototype. Our attempt to group the experimental points by dividing the specific impulse by the mass flow rate,

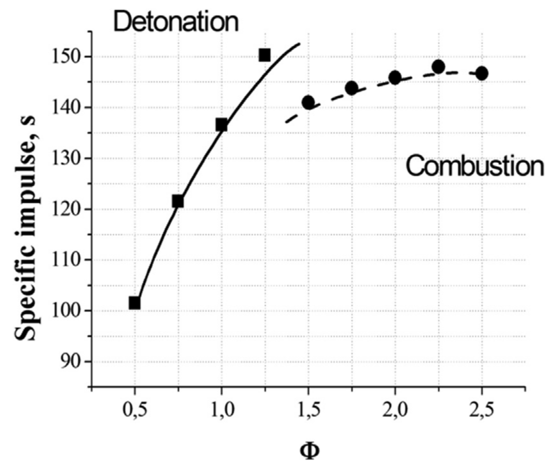

Fig. 6 – Specific impulse vs. equivalence ratio at a fixed fuel-mixture mass flow rate of 0.32 kg/s for the 100-mm-diameter LRE prototype.

i.e., using the same plane as that of Fig. 3, failed: the points of different series relevant to continuous-detonation and continuous-combustion modes did not collapse to two distinct curves. Therefore, for analyzing the results of Fig. 5a and b we used a different procedure described below.

Fig. 5a and b allow plotting the dependences of specific impulse vs. mass flow rate at fixed equivalence ratios. Since these dependences appear to be very close to linear dependences one can obtain based on them the dependence of the specific impulse on the equivalence ratio at a fixed mass flow rate. Fig. 6 shows such a dependence for a fixed mass flow rate of 0.32 kg/s corresponding to the continuous-detonation mode with the lowest mass flow rate in the experimental series 4 (see Fig. 5a). Closed squares in Fig. 6 are related to the continuous-detonation mode, closed circles are related to the continuous-combustion mode. The solid and dashed curves labeled "Detonation" and "Combustion" represent the RMS approximation of squares and circles, correspondingly.

Clearly, at a fixed fuel-mixture mass flow rate the specific impulse of 100-mm-diameter LRE prototype is higher when it operates in the continuous-detonation mode. For example, at equivalence ratios $\Phi = 1.3$–1.4 the ordinates of points on the

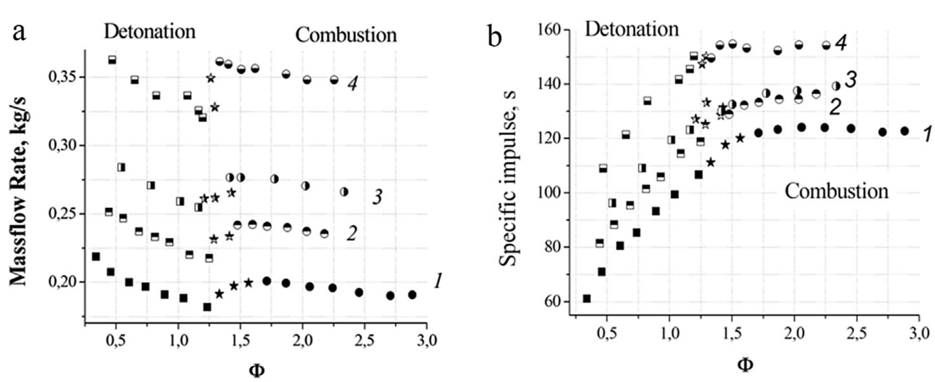

Fig. 5 – Experimental data for the 100-mm-diameter LRE prototype in terms of mass flow rate vs. equivalence ratio (a) and specific impulse vs. equivalence ratio (b).

solid curve exceed the ordinates of points on the dashed curve by at least 7–8%. As compared to the 50-mm-diameter LRE prototype the gain in specific impulse is 1–2% higher, as could be expected because of smaller relative heat losses in the larger LRE prototype.

Concluding remarks

It has been proved experimentally that Zel'dovich thermodynamic cycle with continuous-detonation combustion of hydrogen–oxygen mixture in two different-size LRE prototypes is more energy efficient than the cycle with continuous constant-pressure combustion of the same mixture, other conditions being equal. Thus, at predetermined limitations on supply pressures of fuel components and at a fixed mass flow rate of fuel mixture the specific impulse of the LRE prototypes operating in the continuous-detonation mode appeared to be 6–8% higher than the specific impulse of the same LRE prototypes operating in the continuous-combustion mode. It should be borne in mind that the design of the LRE prototypes used in the experiments is in general not optimal for achieving the maximum specific impulse in both operation modes. Therefore, the quantitative differences in the specific impulse could depend on the geometry of LRE prototype nozzles and on the values of the supply pressure of fuel components. These issues will be investigated in further experiments.

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