ZEL'DOVICH THERMODYNAMIC CYCLE AND PERSPECTIVES OF ITS APPLICATION IN CHEMICAL RAMJET AND ROCKET PROPULSION

S. M. Frolov, V. S. Aksenov, P. A. Gusev, V. S. Ivanov, S. N. Medvedev, and I. O. Shamshin

Center for Pulse Detonation Combustion
N. N. Semenov Institute of Chemical Physics
Russian Academy of Sciences
Moscow, Russia
e-mail: smfrol@chph.ras.ru

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 can substantially exceed the efficiency of Brayton cycle with constant-pressure combustion. Later, the theoretical conclusions of [1] were confirmed by thermodynamic calculations and multidimensional gasdynamic calculations involving various dissipative processes. Thus, thermodynamic calculations in [2] show that the efficiency of Zel'dovich cycle (cycle with detonation combustion) can be 20%–30% higher than the efficiency of Brayton cycle, whereas multidimensional gasdynamic simulation of liquid-propellant rocket engine (LRE) operation in a continuous-detonation mode conducted in [3] yielded an efficiency value exceeding by 13%–15% that of conventional LRE. Despite the fact that the theoretical conclusions on the advantage of Zel'dovich cycle are not questioned [4, 5], there are no direct experimental evidences of these findings so far. The objective of this paper is to prove experimentally the energy efficiency of the Zel'dovich cycle by direct comparison of thrust performances of LRE prototype operating in continuous-detonation and continuous-combustion modes. For this purpose, a test bench and LRE prototype were designed and fabricated.

The test bench consists of tanks for hydrogen (volume of 0.64 m^3) and oxygen (volume of 0.32 m^3), high-performance fast-response valves, fuel manifolds of a large cross section, thrust table with a calibrated load cell, and instrumental systems measuring thrust and supply pressure of fuel components. The maximum mass flow rate of fuel mixture was close to 1.5 kg/s.

The LPE prototype is an annular combustion chamber with an injector head attached from one side and a nozzle from the other side. The chamber is formed by two coaxial cylinders 90 mm high: an internal cylinder 40 mm in diameter is

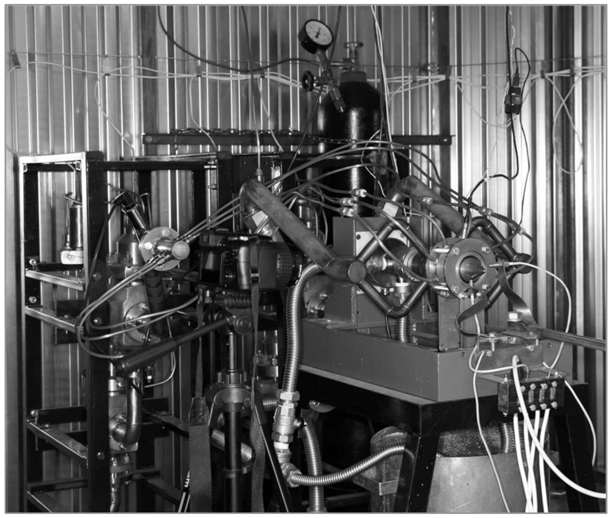

Figure 1 Photo of the test bench with LRE prototype

embedded in a hollow outer cylinder 50 mm in diameter so that the gap between the cylindrical surfaces is 5 mm. 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 radial holes 0.8 mm in diameter each drilled in the outer wall of the chamber 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 the 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 LRE prototype has a modular design, which allows variation of all basic geometric dimensions and replacement of injector head and nozzle. Figure 1 shows the photograph of the test bench with the LRE prototype deployed at outdoor experimental site.

The test stand 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-second 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 downstream from hydrogen holes with a relative angular position of 90°. These tools allow

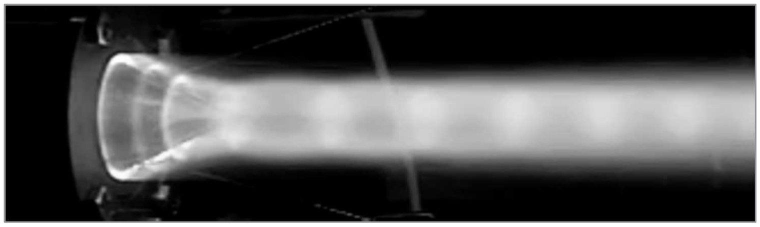

Figure 2 Photo of supersonic jet issuing from the LRE prototype nozzle

identification of engine operation mode (continuous detonation or combustion), evaluation of the speed of detonation waves at continuous-detonation mode, registration of the number of detonation waves, simultaneously circulating over the injector head and their circulation direction, and measurement of average static pressure in the chamber. 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 along with high-speed video recording. Figure 2 shows the supersonic jet issuing from the LPE prototype nozzle.

Figure 3 shows the primary experimental data obtained at relatively low mass flow rates of the mixture (up to 0.1 kg/s) in terms of the measured thrust on the absolute pressure of hydrogen supply at different absolute pressures of oxygen supply. All experiments presented in Fig. 3 are performed during one day at ambient temperature 22–24 °C. The absolute measurement errors of thrust and fuel mixture mass flow rate are estimated as 2 N and 2 g/s, respectively. The left side of each series of symbols (closed and partially closed squares) corresponds to the continuous-detonation operation mode, whereas the right one

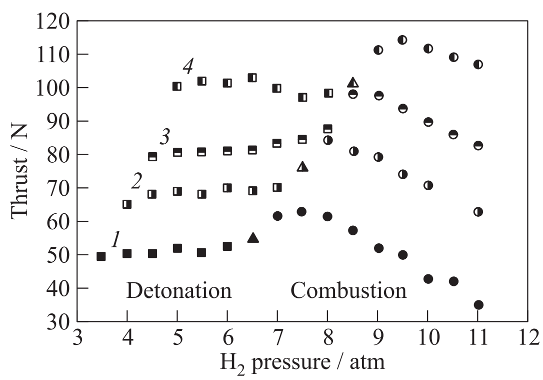

Figure 3 Thrust vs. hydrogen supply pressure at different oxygen supply pressures: series *1* — 3.5 atm; *2* — 4; *3* — 4.5; and series *4* — 5 atm

(closed and partially closed circles) corresponds to the continuous-combustion operation mode. Triangles in some series of experiments correspond to a transient operation mode with clear and relatively long-term (at least 10% of operation time) manifestations of symptoms of both modes in ionization currents and in high-speed video recording. The points plotted in Fig. 3 are well reproducible if the operation conditions are fixed. It is seen that the 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, an increase of the hydrogen supply pressure leads to transition from the continuous-detonation mode to the continuous-combustion one, as the oxygen supply pressure increases, the transition point is shifted to a higher pressure of hydrogen supply.

Processing of the data presented in Fig. 3, allows the direct evidence for energy efficiency of Zel'dovich cycle to be obtained. Figure 4 shows the ratio of specific impulse to the mass flow rate of fuel mixture vs. fuel-to-oxidizer equivalence ratio Φ. Specific impulse is defined as a ratio of the measured thrust to mass flow rate of fuel mixture and to the gravity acceleration. The mass flow rate of fuel mixture is determined by the 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). Equivalence ratio Φ is assessed as a ratio of the mass flow rate of hydrogen to the stoichiometric mass flow rate of hydrogen.

Figure 4 shows that in the adopted plane, the points of all four experimental series (see Fig. 3) are grouped around two approximation curves: curve for the continuous-detonation mode (solid curve and closed squares labeled "Deto-

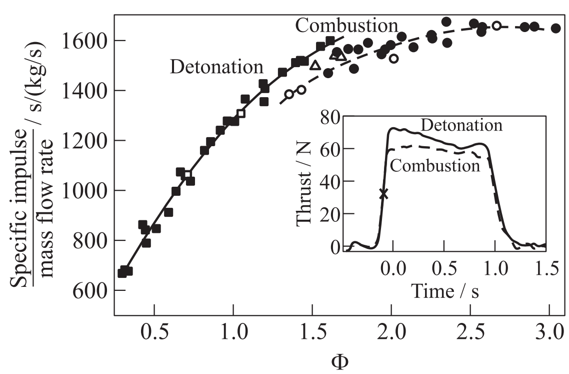

Figure 4 The ratio of specific impulse to fuel–mixture mass flow rate vs. mixture composition. Insert shows time histories of thrust at engine operation in the continuous-detonation mode (0.056 kg/s, $\Phi = 1.55$) and continuous-combustion mode (0.053 kg/s, $\Phi = 1.75$)

nation") and curve for the continuous-combustion mode (dashed curve and closed circles labeled "Combustion"). Open triangles in Fig. 4 correspond to the transient operation mode mentioned above. These points were not included in the approximations. Clearly, at a fixed mass flow rate, the specific impulse of LRE prototype operating in the continuous-detonation mode is higher. For example, at equivalence ratio $\Phi = 1.6$–1.7, the ordinates of the solid curve points exceed by 6%–7% the ordinates of the dashed curve points.

The absolute values of specific impulse in the discussed experiments are relatively low. At $\Phi = 1.7$ and at a mass flow rate of fuel components 0.1 kg/s, they amount to 160 and 150 s, respectively. The insert in Fig. 4 illustrates the obtained effect. It shows the measured time histories of thrust in two experiments with very similar values of the mass flow rates (0.056 and 0.053 kg/s) and equivalence ratios ($\Phi = 1.55$ and 1.75) of fuel mixture corresponding to different operation modes: continuous-detonation (solid curve labeled "Detonation" in the insert) and continuous-combustion (dashed line labeled "Combustion" in the insert). Note that the thrust plotted in Fig. 3 is defined as the mean integral thrust value 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 insert in Fig. 4).

To be 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-millimeter instead of 90-millimeter 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 as for the engine with chamber height of 90 mm, i. e., the height of the combustion chamber (45 and 90 mm) is sufficient to ensure complete combustion of the fuel mixture.

It follows from Fig. 4 that at fixed values of equivalence ratio Φ and mass flow rate of the fuel mixture, the LRE prototype of the chosen design can operate in solely one mode, either in continuous-detonation mode, or in a continuous-combustion mode. To further demonstrate the advantage of the Zel'dovich cycle over the Brayton one, the other series of tests was performed in which the injector head was changed: instead of the injector head with 72 radial holes used to supply hydrogen, a new 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. Open squares and circles in Fig. 4 correspond to the experiments of this series when the engine operates in the continuous-detonation mode (open squares) and in continuous-combustion mode (open 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" which lies below the solid curve "Detonation" by 6%–7%. 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 appreciate scatter of closed and open 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.

Thus, it has been proved experimentally that Zel'dovich thermodynamic cycle with continuous-detonation combustion of a hydrogen–oxygen mixture in the annular combustion chamber is more efficient than the Brayton cycle with continuous combustion of the same mixture, other conditions being equal. Specific impulse of the LRE prototype operating in the continuous-detonation mode is 6%–7% higher than that measured when it operates in the continuous-combustion mode.

Acknowledgments

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