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## TECHNICAL SCIENCES

# A Detonation Afterburner

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**Abstract**—For the first time, a detonation afterburner (DA) for continuous detonation combustion of TS-1 aviation kerosene was developed, manufactured, and tested. Test fires of the DA in combination with a TJ100S-125 small-sized single-circuit turbojet engine were carried out on a ground test bench. In the test fires, stable modes of continuous detonation combustion of aviation kerosene were registered: a near-limit mode of longitudinally pulsating detonation (LPD) and a spin detonation (SD) mode with one detonation wave. Compared to a conventional afterburner, at the same in-chamber pressure, the specific fuel consumption in the DA was 30% lower and the specific thrust and thrust boosting coefficient were 30% higher. It is shown that, when operating in the LPD mode, the average heat flux to the DA walls is about 0.5 MW/m$^2$ and, in the SD mode, 0.86 MW/m$^2$. These values indicate the high potentiality of the DA when used in advanced jet engines.

**Keywords:** turbojet engine, afterburner, detonation combustion, aviation kerosene, longitudinally pulsating detonation, spin detonation, specific fuel consumption.

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In [1–3], experimental evidence of the energy efficiency of the Zel'dovich detonation cycle as applied to liquid rocket engines (LREs) was presented. It was shown that, when deflagration combustion of fuel components is replaced with detonation combustion, the specific impulse of an LRE increases by 7–8%, other conditions being equal [1, 2]. Moreover, in a detonation LRE, the same specific impulse is obtained at half the pressure in the combustion chamber in an LRE with conventional combustion, which improves the mass and size characteristics of the turbopump [3].

The aim of this study was to prove experimentally the energy efficiency of the Zel'dovich cycle in relation to air-breathing jet engines operating on standard TS-1 aviation kerosene.

To this end, we set and solved the problem of boosting the thrust of a small-sized single-circuit turbojet engine TJ100S-125 using a detonation afterburner (DA). The TJ100S-125 turbojet engine (TJE), which is equipped with a single-circuit centrifugal compressor, an axial turbine, and a tapering jet nozzle with a diameter of 100 mm, runs on standard TS-1 aviation kerosene and has a maximum thrust of 1250 N and a specific fuel consumption exceeding 1.0 kg/kgf/h. To maintain the gas temperature in front of an uncooled turbine sufficiently low (less than ~1200°C), the TJE runs on kerosene–air mixtures with a high fuel–air equivalence ratio of 4.0 to 6.0. Excess oxidizer that has not reacted in the main combustion chamber can be used to boost the thrust of the TJE using a DA with an additional supply of kerosene to the stream of combustion products; i.e., we install a DA instead of a standard turbojet nozzle and use the oxidizer supplied to the TJE as efficiently as possible, burning it in the detonation mode. In this case, the energy efficiency of the DA can be estimated by comparing its specific characteristics with those of conventional afterburners in double-circuit TJEs with the same in-chamber pressure.

The shape and geometric dimensions of the DA were obtained based on multivariate parametric three-dimensional numerical simulations using the computational technology of the N.N. Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences (ICP RAS) [4]. The experimental sample of the DA was manufactured at the ICP RAS

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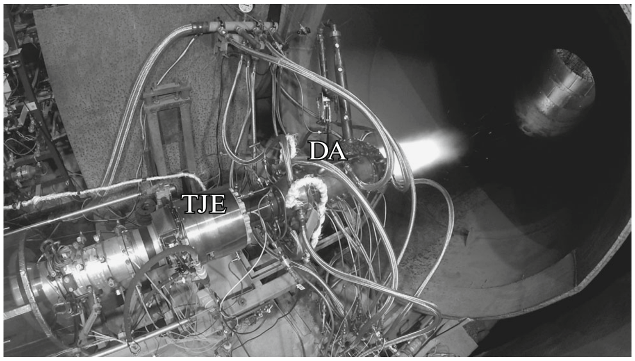


**Fig. 1.** Photo of the turbojet–afterburner assembly in one of the test fires.

and tested at the IS-1M test bench of M/U 15650-16 in combination with the small-sized single-circuit TJE TJ100S-125.

The DA is an axisymmetric annular combustion chamber with smooth walls with an outer diameter of 200 mm and a length of 800 mm, equipped with a replaceable tapering jet nozzle. To reduce the influence of the DA on the operation of the TJE due to the high backpressure arising from detonation, the entrance to the DA has a local narrowing of the flow path and the area of the critical section is equal to the cross-sectional area of the standard nozzle of the TJE. Kerosene is supplied to the DA through two belts of radial holes with a diameter of 0.15 mm (240 in total), evenly distributed on the outer and inner walls of the annular gap at a distance of 10 mm downstream from the critical section. Replaceable nozzles of the DA have outlet section diameters of 100, 120, 140, and 150 mm. At the entrance to the DA, there are oxygen supply manifolds, which make it possible to recover its mass fraction to 23%, as in air. The inner and outer walls of the DA, as well as the support pylons and a part of the nozzle, are cooled with water. By measuring the temperature of the cooling water, the average heat fluxes into the DA walls are estimated. The combined TJ100S-125–DA assembly is installed on a test bench with a load cell and is launched in various operating modes of the TJE. The combustible mixture in the DA is ignited using an aviation spark plug and/or a predetonation tube. The maximum duration of test fire with the supply of kerosene to the DA is 10 s. Figure 1 shows a photograph of the assembly in one of the test fires.

The operation process parameters in the DA are recorded using four static pressure sensors and four pressure pulsation sensors. The sensors are mounted on waveguide tubes (6 × 1 mm) with a length of 800 mm. The measurement system also includes thermocouples, flow meters, a load cell, and video cameras. The fact of detonation combustion is identified based on the readings of pressure pulsation sensors. During normal combustion, pressure pulsations in the DA do not exhibit any regularity and have a small amplitude. During detonation combustion, the dominant pulsation frequency is recorded; it corresponds to the frequency of arrival of the detonation wave at the location of the corresponding sensor, and the pulsations themselves have a pronounced triangular profile with steep fronts and large amplitudes. Figure 2 shows an example of recordings of pressure pulsation sensors in one of the test fires with sequential ignition of a combustible mixture in the DA, first, using a spark plug (6.24 s) and, then, using a predetonation tube (6.33 s). In this test, spark-plug ignition leads to normal combustion with irregular pressure pulsations of small amplitude, whereas transmission of the detonation wave from the predetonation tube to the DA leads to detonation combustion of the mixture with regular pressure pulsations (see insert in Fig. 2) of high amplitude with steep fronts.

Most test fires were carried out with recovery of the mass fraction of oxygen in the combustion products of the TJE to 23% and with the operation of the TJE at 83–85% of the maximum thrust. In this case, the total air–fuel equivalence ratio in the DA reached 0.6–1.8; i.e., almost all of the air that had not burned in the main combustion chamber was burned up in the DA. In the test fires, stable modes of continuous detonation combustion of aviation kerosene were registered—a near-limit LPD mode with a characteristic pressure pulsation frequency of 0.2–0.4 kHz and an average heat flux to the DA walls of ~0.50 MW/m$^2$ and the SD mode with a characteristic pressure pulsation frequency of 1.0–1.5 kHz and an average heat flux into the DA walls of 0.86 MW/m$^2$,—as well as the normal combustion at constant pressure (CCP), stabilized on the DA support pylons. The LPD mode in annular combustion chambers was previously registered in [5, 6] in experiments with hydrogen. In this mode, detonation is periodically reinitiated in the exit part of the DA and propagates upstream the flow of the fresh combustible mixture towards the kerosene supply holes. The SD mode is characterized by a significantly higher frequency due to the rotation of one detonation wave in the annular gap in the vicinity of the kerosene supply holes at a speed of about 1000 m/s.

Compared to a conventional afterburner with the same in-chamber pressure, the thrust characteristics of the DA running on detonation combustion of kerosene proved to be significantly better: the specific fuel consumption in the DA is, on average, 30% lower and the specific thrust and thrust boosting coefficient are, on average, 30% higher. To understand the reason of the improvement, consider Fig. 3, which shows the records of static pressure sensors in the DA in one of the test fires, in which the transition from the near-limit LPD mode to the CCP mode followed by a return to the LPD mode was detected. Static pressure sensors (PSs) are located at a distance of 50 mm (PS1), 170 mm (PS4), 290 mm (PS7), and 410 mm

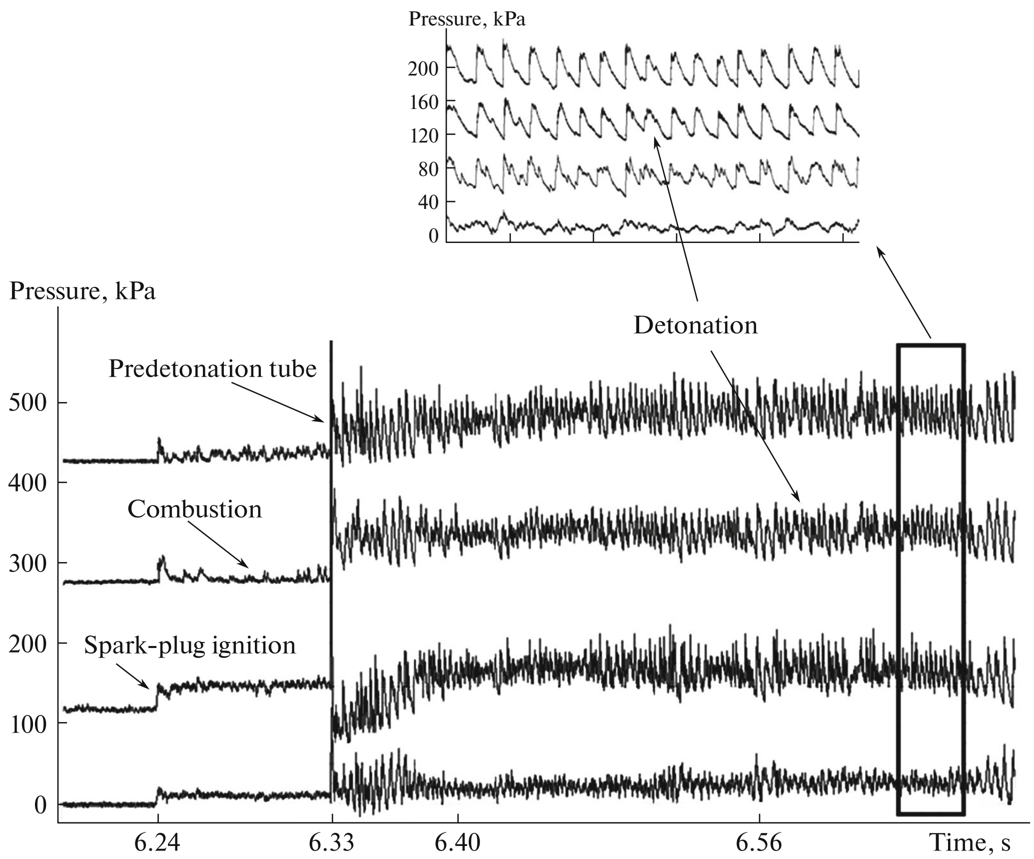


**Fig. 2.** Records of pressure pulsation sensors in a test fire with sequential ignition of a combustible mixture in the DA, first, using a spark plug and, then, using a predetonation tube.

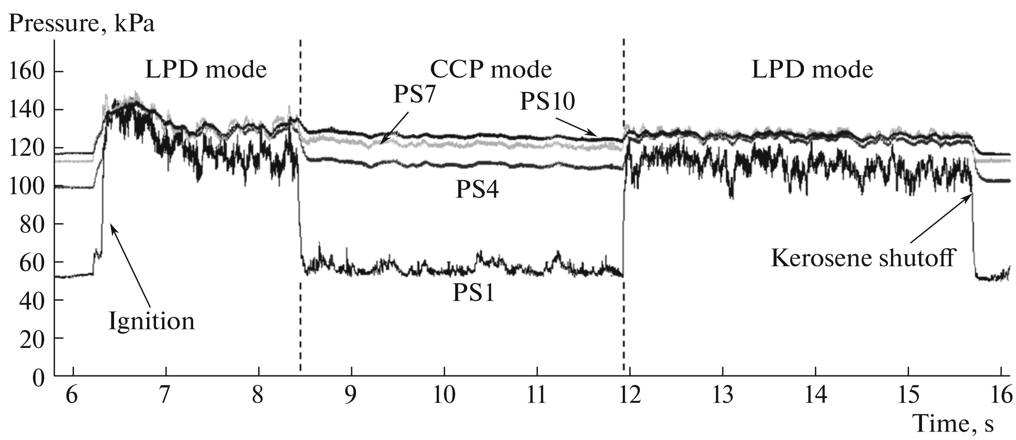


**Fig. 3.** Records of static pressure sensors PS1, PS4, PS7, and PS10 in a test fire with a short-term change of operation modes: LPD–CCP–LPD.

(PS10) downstream from the critical section of the DA. It can be seen that, in the LPD mode, the pressure at sensors PS1 and PS4 is much higher than in the CCP mode, especially at the PS1 sensor, which is closer to the holes of kerosene supply. Sensors PS7 and PS10 show a slight change in pressure during the LPD–CCP and CCP–LPD transitions. The overpressure recorded by sensors SP1 and SP4 creates additional force on the inner surfaces of the DA and significantly increases the overall thrust of the TJE–DA assembly. The fact that the static pressure at the DA exit (PS10 sensor) for the LPD and CCP modes is

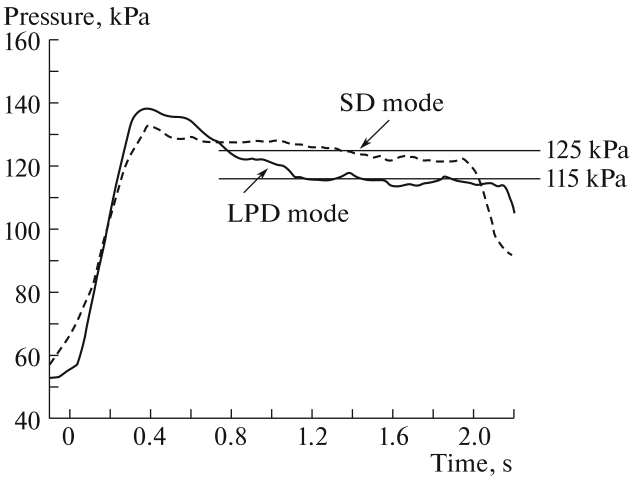


**Fig. 4.** Comparison of the records of sensor PS1 in the test fire of the DA in the LPD and SD modes.

almost the same indicates a small difference in the completeness of combustion in these modes. It should be noted that, during the steady operation of the DA in the SD mode, the increase in the static pressure detected by sensor PS1 is 10–15% higher than in the LPD mode in close operation modes of the assembly (Fig. 4).

Thus, for the first time, we designed, manufactured, and tested a DA running on the continuous detonation combustion of TS-1 aviation kerosene. In the test fires, stable modes of continuous detonation combustion of kerosene were registered. Compared to a conventional afterburner, at the same level of in-chamber pressure, the specific fuel consumption in the DA was 30% lower and the specific thrust and thrust boosting coefficient were 30% higher. The improvement in the specific characteristics of the DA is explained by a significant increase in the average static pressure in the flow region occupied by longitudinally pulsating or spin detonation. The results obtained evidence the high potentialities of the DA in relation to advanced jet engines.

## FUNDING

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