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Wind Tunnel Testing of a Detonation Ramjet Model at Approach Air Stream Mach Number 5.7 and a Stagnation Temperature of 1500 K

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Abstract—The mode of continuous detonation combustion of hydrogen in the annular combustor of a model of a detonation air-breathing ramjet at the approach air stream Mach number 5.7 and a stagnation temperature of 1500 K was experimentally detected for the first time in a pulsed wind tunnel. The thrust and fuel-based specific impulse of the ramjet model were 1550 N and 3300 s, respectively.

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Supersonic continuous detonation combustion of fuel–air mixture in air-breathing ramjet (ABR) is an alternative to steady-state subsonic deflagration combustion studied from the 1950s onward [1]. Transition to continuous detonation combustion in ABR solves problems of ensuring fast turbulent and molecular mixing of fuel with air and reaching high completeness of combustion at the shortest distances from fuel nozzles. In this combustion mode, a strong detonation-leading shock wave continuously circulates across the airflow in the annular combustor, causing enormous shear stresses in crossed jets of fuel and oxidizer and in transverse shock waves reflected by the combustor walls, which results in aerodynamic disintegration and mixing of the jets. In a shock-compressed gas, chemical transformations occur in a self-ignition mode at very high rates. The possibility of continuous detonation combustion of hydrogen in detonation ABR (DABR) has recently been proven [2–4] in fire tests of a DABR model of original design while blowing with an air flow at Mach 4 to 8 in the Tranzit-M pulsed wind tunnel (Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia) [5]. The maximum values of the fuel-based specific impulse and average thrust of the tested DABR model [2–4] were about 3600 s (at Mach 6) and 2200 N (at Mach 5), respectively. However, because of specific features of the Tranzit-M wind tunnel, the fire tests [2–4] were carried out at low (300 K) stagnation temperature, which was inconsistent with the conditions of a flight at the given Mach numbers. Conversion of the obtained propulsion performance to the flight conditions at equal relative heat inputs showed that the specific impulse and thrust should be 4000 s and 2400 N at Mach 5 and 3300 s and 1400 N at Mach 6 [4].

The purpose of this work was to fill in this gap and perform fire tests of a DABR model in the AT-303 pulsed wind tunnel (Khristianovich Institute of Theoretical and Applied Mechanics), which allows increasing air flow stagnation temperature to 1500 K.

The AT-303 pulsed wind tunnel is intended for aerodynamic tests within the Mach number range from 5.7 to 20 at elevated Reynolds numbers. The main part of this wind tunnel is a prechamber unit, in which a working gas is stored. Before a test, the working gas (air) in the main prechamber is compressed to a pressure of 200 atm and heated to a temperature of 800–900 K. After actuation of a fast-acting gate, the working gas is compressed by hydraulic pistons to a pressure of 1800 atm, heated to a temperature of 1500 K, and flows to the test prechamber, where the total pressure decreases and the flow is straightened upstream of the nozzle inlet. In the AT-303 wind tunnel, interchangeable axisymmetric shaped nozzles 400 mm in cross-sectional diameter are used. The nozzles pro-

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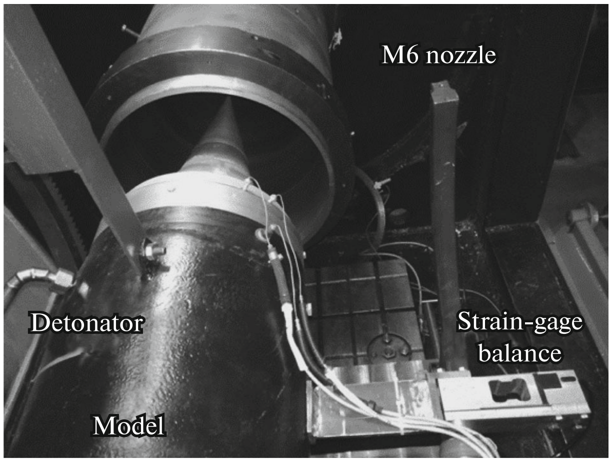

Fig. 1. Photograph of the DABR model in the test section of the AT-303 impulse wind tunnel.

duce a homogeneous gas flow at a given Mach number; this flow flows past a model being tested, which is mounted in the test section of the wind tunnel. The test section is designed as a rectangular Eiffel chamber and comprises two compartments with optical windows for visualizing the flow pattern. The gas flows from the test section to a vacuum chamber through a diffuser, which is a cylindrical duct 1200 mm in diameter.

Figure 1 presents a photograph of the DABR model mounted in the test section of the AT-303 wind tunnel on a strain-gage balance at an angle of attack of 0° at a distance of 200 mm between the nozzle exit section and the leading edge of the outer cowl. The design of the model is the same as in the previous works [2–4] and was developed based on the results of calculations according to a published procedure [6]. The model includes an air intake with the center body decelerating the supersonic incoming airflow at Mach 5 in three oblique shocks to a supersonic flow at local Mach ~2.5 at the minimum cross section of the air intake. The model also contains a divergent annular combustor, in which the air flow is accelerated to Mach ~4. The diameter of the leading edge of the outer cowl of the model is 284 mm. The outer diameter of the combustor is 310 mm. The total length of the model is 1050 mm. To control the detonation combustion, the DABR model allows throttling the flow at the combustor outlet cross section by attaching a round-edged flat throttle disk to the aft end of the center body. The disk is 5 mm thick and 240 mm in diameter and throttles the annular space of the combustor by 50%. Hydrogen is fed from a 0.08-m^3 receiver via a line with a fast-acting pneumatic valve to the combustor through a ring of 200 uniformly distributed radial holes 0.8 mm in diameter. The ring of holes is located at the center body 10 mm downstream of the minimum cross section of the air intake.

The thrust is measured by the strain-gage balance using two T40A sensors with a maximum load of 2000 N each. The process performance in the combustor is monitored by ionization probes, sensors of the static or total pressure in the air intake, and sensors of the static and total pressures at the combustor outlet. The monitoring of fast processes of combustion and detonation by ionization probes was tested previously and showed high efficiency [2–4, 7]. In the center body of the combustor, 12 ionization probes are installed. Six of them (circumferential probe set) are uniformly spaced on the circumference 40 mm downstream of the ring of holes through which hydrogen is fed. The other seven probes (one of which is the same as one of the probes mounted on the circumference) are uniformly positioned longitudinally along the generatrix of the center body at an interval of 30 mm and constitute an axial probe set. Such a monitoring system can identify a detonation combustion mode in the combustor and measure the characteristic frequency of the process in the combustor, and also the velocity and propagation direction of the detonation wave. The flow pattern in the air intake is observed using high-speed schlieren video recording.

The duration of testing the process in the wind tunnel is 50 ms. To ensure a constant hydrogen flow rate in the combustor during this time, hydrogen feed is begun 100 ms before the pressure in the test prechamber reaches a given value (~12 atm), and the feed is continued for 500 ms. The average calculated air flow rate through the DABR model during this time in all the tests was ~2.1 kg/s, with the tests being reproduced with high accuracy. Figure 2 illustrates the time dependence of the air pressures P_{main} and P_{test} in the main and test prechambers of the wind tunnel, respectively, and the air temperature T_0 in these prechambers.

As previously [2–4], the process in the combustor is initiated by a hydrogen–oxygen detonator (Fig. 1). The detonator is an ignition chamber 20 mm in diameter and 30 mm in length with an attached detonation tube 10 mm in diameter and 200 mm in length. The detonator initiation time is synchronized with the opening of the fast-acting gate of the wind tunnel. The process in the combustor is initiated simultaneously with the moment the hydrogen flow rate reaches the value given by a test schedule.

The most important result of the tests is the detection of stable continuous detonation combustion of hydrogen in the supersonic airflow in the combustor of the DABR model. Below, we describe in detail the results of the tests of the DABR model while blowing with a Mach 5.7 air flow at an average stagnation temperature of ~1500 K and a total air-to-fuel equivalence ratio of about 1.25 (at a hydrogen flow rate of 0.048 kg/s), with a throttle disk being installed. Figure 3 gives an example of the visualization of the readings of the ionization probes in a continuous spinning deto-

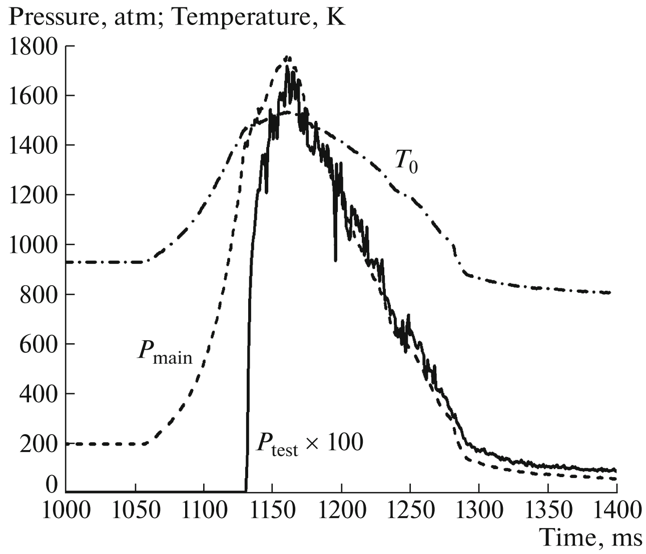

Fig. 2. Time dependence of the air pressures P_{main} and P_{test} in the main and test prechambers of the wind tunnel, respectively, and the air temperature T_0 in these prechambers.

nation mode. The readings were visualized according to a published procedure [7]. The top and bottom images in Fig. 3 were obtained by processing the signals of the circumferential and axial probe sets, respectively. The white and black colors in these readings denote the highest and lowest measured conduction currents in the medium (the conduction current is the highest in the hot detonation products and is the lowest in the cold gas). The top image in Fig. 3 exhibits regular bright bands of equal inclination, which suggest the continuous propagation of the detonation wave in one tangential direction at constant apparent velocity. The characteristic frequency of the inclined bands in this image is close to 1320 Hz, which gives that the apparent velocity of propagation of the detonation wave in the tangential direction is about 1300 m/s. The bottom image in Fig. 3 shows that the front of the detonation wave is inclined to the combustor axis at an angle of 45°; therefore, the normal detonation velocity is close to 1840 m/s; i.e., the velocity deficit with respect to the thermodynamic value for a homogeneous stoichiometric mixture is only 7%. It should be emphasized that hydrogen and air in the tests were fed to the combustor separately, and the local composition of the fuel–air mixture in the detonation propagation region was unknown. The height of the regular black triangles in the bottom image approximately corresponds to the detonation wave height (~150 mm).

Let us show, by the example of the results of these tests, how the propulsion performance of the DABR model is determined. The thrust is found by comparing the records of the instantaneous forces acting on the DABR model in the cases of the "cold" (without ignition) and "hot" (with ignition) starts under identical initial conditions. The time shift between the parameters of these starts for the AT-303 wind tunnel does not exceed 1 ms. Figure 4 presents an example of the primary records of the instantaneous forces acting on the DABR model for a period of time from 1000 to 1500 ms after the beginning of the test. Here, the negative and positive instantaneous forces are directed downstream and upstream, respectively, and to the test mode of the wind tunnel, the period of time from 1150 to 1200 ms corresponds. The records of the instantaneous forces in Fig. 4 represent not only aerodynamic forces but also vibrations of the mechanical system comprising the strain-gage balance and the DABR model. Nonetheless, one can see that the hydrogen ignition during the hot start leads to a decrease in the negative component of the instantaneous forces to nearly zero. The difference of the instantaneous forces acting on the DABR model in the cases of the hot and cold starts is the thrust developed by the DABR model. Calculation of the average thrust from the records in Fig. 4 within the given period of time gives ~1550 N. The fuel-based specific impulse (~3300 s) can be found by dividing the average thrust (1550 N) by the mass flow rate of hydrogen during the hot start (0.048 kg/s) and by the gravitational acceleration (9.8 m/s^2). Note that these values of the specific impulse and the average thrust are close to the values obtained previously [4] by converting the results of the model tests to Mach 6 flight conditions (3300 s and 1400 N, respectively).

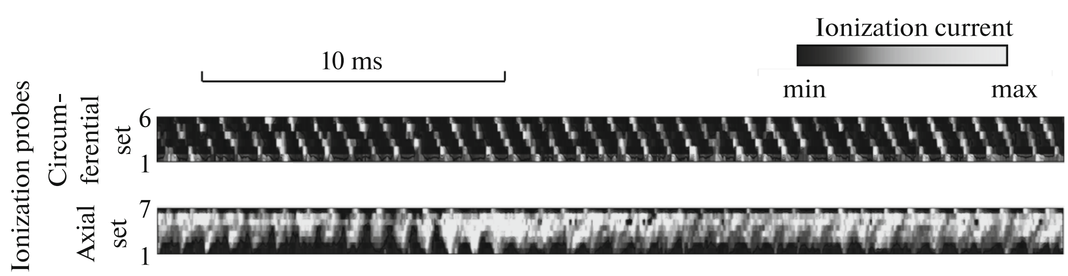

Fig. 3. Example of the visualization of the readings of the ionization probes in the fire test of the DABR model in a continuous spinning detonation mode.

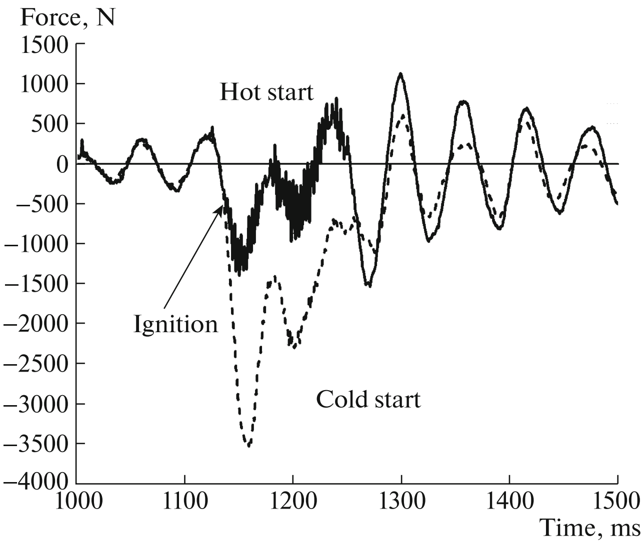

Fig. 4. Example of the records of the instantaneous forces acting on the DABR model during the cold (dashed curve) and hot (solid curve) starts.

It should be noted that the performed fire tests were mainly dominated by continuous spinning detonation modes, remarkably, with only one detonation wave. The schlieren video records showed that the shock pattern in the air intake during the hot and cold starts persisted, and no mode giving rise to a detached shock wave was observed even at high hydrogen flow rates corresponding to a total air-to-fuel equivalence ratio of 0.7. With increasing total air-to-fuel equivalence ratio to 1.4, the continuous spinning detonation mode failed, and there occurred a limiting mode of longitudinally pulsating detonation of hydrogen, which was detected before [2–4]. A further increase in the total air-to-fuel equivalence ratio to 1.6 caused a failure of the combustion in the combustor. All the tests were carried out using a throttle disk, which obviously reduces the propulsion performance of the model. As was shown [2–4], a throttle disk is necessary only for initiating the process and may be jettisoned. Instead of a throttle disk, a nozzle or pneumatic throttle valve can be used.

Thus, we for the first time experimentally detected the mode of continuous detonation combustion of hydrogen in the annular combustor of the DABR model under conditions of approach air stream Mach number 5.7 and a stagnation temperature of 1500 K in the pulsed wind tunnel. The average thrust developed by the ramjet model in one of the tests at a total air-to-fuel equivalence ratio of 1.25 was about 1550 N, and the fuel-based specific impulse was 3300 s. In the performed fire tests at a total air-to-fuel equivalence ratio from 0.7 to 1.4, there occurred a continuous spinning detonation mode, with the air intake always operating without a detached shock wave. Within the total air-to-fuel equivalence ratio range from 1.4 to 1.6, there was a limiting mode of longitudinally pulsating detonation of hydrogen. At a total air-to-fuel equivalence ratio above 1.6, the combustion in the combustor failed.

The tests demonstrated that a continuous-detonation ABR has high propulsion performance and can be considered an alternative concept to a conventional deflagration-combustion ABR. Moreover, it is expected that the new ABR concept will have better weight and size characteristics owing to, first, fast turbulent and molecular mixing of the propellant components in the detonation wave, second, much higher combustion rate (in self-ignition mode behind the traveling shock wave), and third, reduced internal drag of the combustor (absence of steps, cavities, etc.).

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