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PHYSICAL CHEMISTRY

Demonstrator of Continuous-Detonation Air-Breathing Ramjet: Wind Tunnel Data

S. M. Frolov[a,b,*], V. I. Zvegintsev[b], V. S. Ivanov[a], V. S. Aksenov[a,b], I. O. Shamshin[a,b], D. A. Vnuchkov[c], D. G. Nalivaichenko[c], Academician A. A. Berlin[a], and Academician V. M. Fomin[c]

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Abstract—First experimental investigations were carried out into the detonation combustion of hydrogen in a demonstrator of an original-design air-breathing ramjet while blowing with an air flow at Mach 4 to 8 in an impulse wind tunnel, and for the first time under these conditions, continuous spin and longitudinal pulsed modes of detonation combustion of hydrogen in an annular combustor were detected.

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Using detonation combustion of fuel–air mixture in air-breathing ramjet (ABR) is considered a breakthrough trend of development of modern aerospace engine manufacturing. The energy efficiency of detonation engines was first described theoretically by Zel'dovich [1] and has recently been proven experimentally in our works [2–4]. The most promising modes of detonation combustion in flow are continuous spin detonation (CSD) [5] and pulsed detonation [6].

The possibility of CSD of fuel (hydrogen) in ABR was studied theoretically [7–9] and experimentally [10]. Three-dimensional calculations [8] proved the possibility of CSD at supersonic speed of the flow of a premixed homogeneous hydrogen–air mixture in the ABR combustor under conditions corresponding to Mach 4 flight, and other three-dimensional calculations [9] proved the possibility of CSD in an original design ABR in atmospheric Mach 5.0 flight at an altitude of 20 km with separate hydrogen feed to an annular combustor. Experimental studies were successfully performed [10] into the CSD of hydrogen–air mixture in an annular combustor with a connected air duct under conditions that modeled supersonic Mach 4 flight. The duration of the continuous detonation combustion of hydrogen in those experiments [10] exceeded 3 s, which made it possible to detect several thousands of revolutions of detonation wave in the annular space when the air flow at the combustor inlet was at Mach 1.93.

The purpose of this work was to experimentally investigate the detonation combustion of hydrogen in a demonstrator of an ABR of the published design [9] while blowing with an air flow at Mach 4–8 in the Transit-M impulse wind tunnel at the Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia.

The Transit-M impulse wind tunnel is designed for aerodynamic tests at Mach 4–8 at elevated Reynolds numbers. The main part of the wind tunnel is a prechamber unit, which is a source of a working gas and determines the wind tunnel performance. The initial amount of the working gas before test is accumulated simultaneously in the main prechamber and additional chambers, which totals 0.11 m^3 of compressed gas at a pressure up to 200 atm. Within the main prechamber is a fast-acting indestructible gate, which shuts off the gas flow to an auxiliary prechamber and an axisymmetric supersonic nozzle. After gate actuation, the compressed gas flows to the prechamber, where the total pressure decreases and the flow is straightened upstream of the nozzle inlet. In the wind tunnel, interchangeable shaped nozzles 300 mm in cross-sectional diameter are used. The nozzles produce a homogeneous gas flow at Mach 4–8; 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 an axisymmetric 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 pipe 400 mm in diameter. The

[a] *Semenov Institute of Chemical Physics, Russian Academy of Sciences, Moscow, 119991 Russia*
[b] *MIFI National Research Nuclear University, Moscow, 115409 Russia*
[c] *Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
**e-mail: smfrol@chph.ras.ru, sergei@frolovs.ru*

total length of the setup including the exhaust diffuser is 7600 mm, and the width and height of the setup are 870 and 1470 mm, respectively.

The demonstrator of the detonation ABR was designed based on the results of calculations according to a published procedure [9]. The demonstrator includes an air intake with an inlet cone slowing down the supersonic incoming air flow at Mach 5 in three oblique shocks to a supersonic flow at maximum local Mach ~2.5 at the minimum cross section of the air intake (conditional "critical cross section" of the air intake). The demonstrator 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 cowling of the air intake is 284 mm. Such a size ensures the calculated flow at the combustor inlet without the influence of the boundary layer formed on the wind tunnel nozzle walls. The outer combustor diameter is 310 mm. The total length of the demonstrator is 1050 mm.

To control the detonation combustion, the demonstrator allows for throttling the flow at the combustor outlet cross section by attaching round-edged flat throttle discs to the aft edge of the central body of the annular combustor. The discs are 5 mm thick and 200, 220, and 240 mm in diameter (hereinafter referred to as D200, D220, and D240, respectively) and throttle the annular space of the combustor by 30, 40, and 50%, respectively. Hydrogen is fed from a 0.08-m^3 receiver via a line with a fast-acting pneumatic valve to the demonstrator combustor through a ring of 200 uniformly distributed radial holes 0.8 mm in diameter. The ring of holes is located at the central body 10 mm downstream of the conditional critical cross section of the air intake.

Preliminary three-dimensional calculations of the cold flow in the flow duct of the wind tunnel with the mounted model showed that, for the initiation and stable operation of the setup, the ABR demonstrator should be placed so that the distance between the wind tunnel nozzle outlet section and the leading edge of the outer cowling of the air intake of the demonstrator is no less than 70 mm. Figure 1 presents a photograph of the flow duct of the wind tunnel with the mounted ABR demonstrator and the calculated local Mach number distribution while blowing with an air flow at Mach 5.

A system for monitoring the process in the combustor includes ionization probes and also sensors of the static or total pressure at the combustor inlet and outlet. The monitoring of fast processes of combustion and detonation by ionization probes was tested previously and showed high efficiency [11]. An ionization probe designed for measuring the conduction current in the hot combustion products is introduced into the combustor so that the distance between the bare probe tip and the combustor wall is ~1 mm. In the central body of the combustor, 12 ionization probes are installed. Six of them are uniformly spaced on the circumference 40 mm downstream of the ring of holes through which hydrogen is fed, and 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 central body at an interval of 30 mm. Such a monitoring system can identify detonation combustion mode in the combustor (CSD or longitudinal pulsed detonation (LPD)) and measure the characteristic frequency of the process in the combustor, and also the velocity and propagation direction of the detonation wave. Moreover, this system can distinguish between the detonation and deflagration combustion [11]; however, under the considered conditions, deflagration combustion of hydrogen was not observed. Along with recording these flow parameters, the static pressure is measured at the wind tunnel nozzle outlet section, and also the total pressure is measured in the prechamber, vacuum chamber, hydrogen receiver, and hydrogen feed header. During the tests, the combustion process is recorded through the optical windows in the test section of the wind tunnel by high-speed digital video cameras.

The process in the combustor is initiated by an ad hoc hydrogen–oxygen predetonator. The predetonator 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 mixture is ignited by a standard automotive spark plug. The predetonator is mounted on the outer wall of the combustor of the demonstrator 150 mm downstream of the conditional critical cross section of the air intake. Hydrogen and oxygen are fed to the predetonator combustor through tubes 4 mm in diameter. After a predetonator ignition signal is given, the detonation tube is initially filled with the hydrogen–oxygen mixture for ~200 ms, and then the mixture is ignited, a deflagration-to-detonation transition occurs in the detonation tube, and a generated detonation wave enters the annular space of the demonstrator combustor. According to the readings of the ionization probes, the duration of the action of the detonation pulse produced by the predetonator on the process in the combustor does not exceed ~10 ms. The predetonator initiation time is synchronized with the opening of the fast-acting gate of the wind tunnel and the hydrogen feed valve in the combustor. The process in the combustor is initiated simultaneously with the moment the air and hydrogen flow rates reach the values given in the design of experiment. Hydrogen is fed to the demonstrator combustor for 150 ms: it is for this time that the process is studied. Further, the pressure in the vacuum chamber noticeably increases, which leads to disturbance of the design flow conditions in the supersonic nozzle of the wind tunnel.

In a series of fire tests, studies were made into the initiation and stability of the process of the detonation combustion of hydrogen at Mach numbers of the

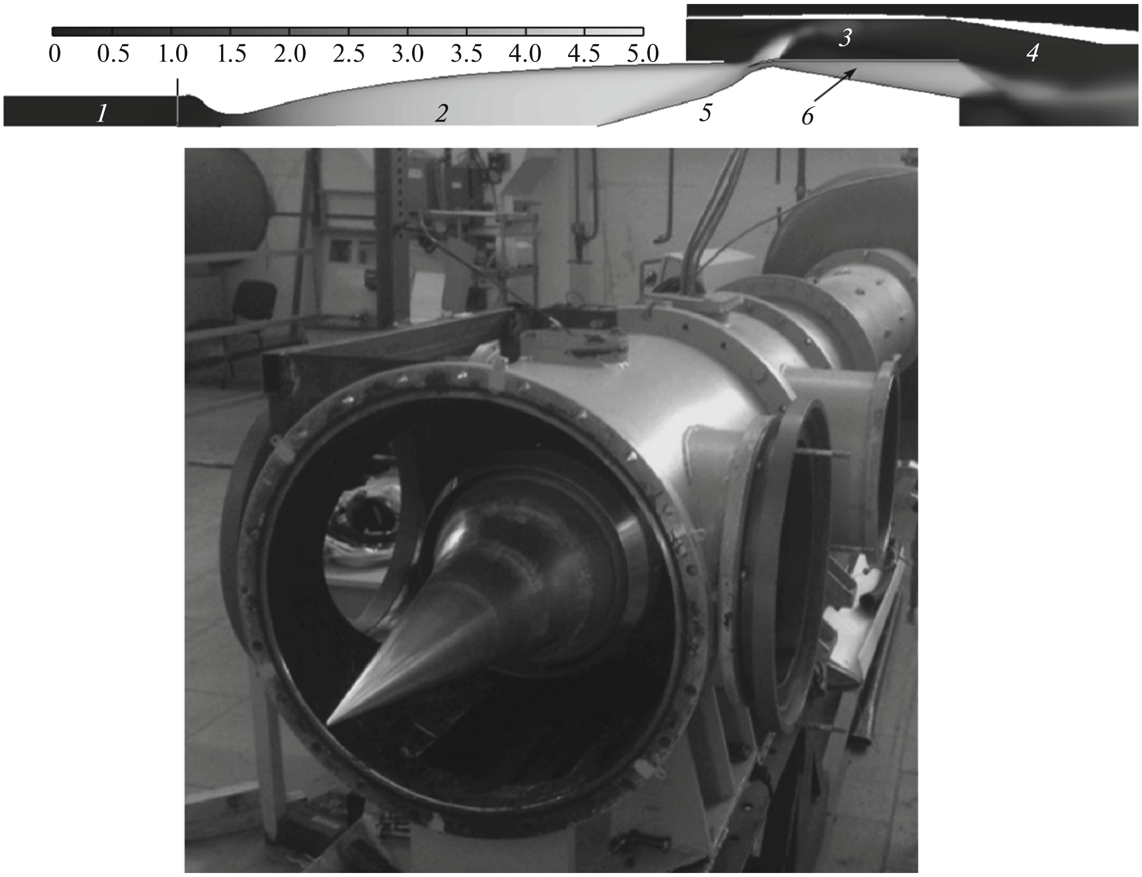

Fig. 1. Photograph of the flow duct of the wind tunnel with the mounted ABR demonstrator and the calculated local Mach number distribution while blowing with an air flow at Mach 5. The numbers indicate the main parts of the setup: (*1*) prechamber, (*2*) axisymmetric supersonic nozzle, (*3*) test section of the wind tunnel, (*4*) diffuser, (*5*) air intake, and (*6*) combustor of the ABR demonstrator.

incoming air flow of 4 to 8. Most of the tests were carried out at Mach 5. The table presents the test parameters: Mach number M, stagnation pressure P_0 and temperature T_0; static pressure P_{st} and static temperature T_{st} of the incoming air flow; estimated air mass flow rate G_a through the flow duct of the demonstrator; hydrogen mass flow rate G_h; and type of the throttle disc mounted at the combustor outlet. The estimated air mass flow rate through the flow duct of the demonstrator was determined by three-dimensional gas-dynamic calculations (Fig. 1). Depending on the Mach number of the incoming air, the composition of the mixture, and the geometry of the combustor, two modes of the combustion were detected in the tests: CSD and LPD of hydrogen.

Note that all the tests of the detonation combustion of hydrogen were performed using throttle discs (mainly D220) because, without throttling the flow, we failed to initiate CSD or LPD of hydrogen in the combustor by the designed hydrogen–oxygen predetonator. Three-dimensional calculations of the cold blowing demonstrated that the installation of a throttle disc at the combustor outlet gives rise to an oblique shock within the combustor; the base of the oblique shock is 50 mm upstream of the disc, and the vertex of the oblique shock is at the outlet section of the outer wall of the combustor.

Figure 2 presents the visualization (according to a published procedure [11]) of the readings of the ionization probes on a time interval of 5 ms in the modes

Test parameters

M	P_0, atm	T_0, K	P_{st}, kPa	T_{st}, K	G_a, kg/s	G_h, kg/s	Throttling disc	Process
4	8		5.2	71	4.8	0.12	D200/D220	CSD
5	20–24	290	4.5	50	7–8	0.06–0.20	0/D200/D220	CSD/LPD
6	30–35		2.2	37	7	0.12–0.20	D200/D220	CSD/LPD
8	54		0.6	22	5	0.05–0.17	D220/D240	LPD

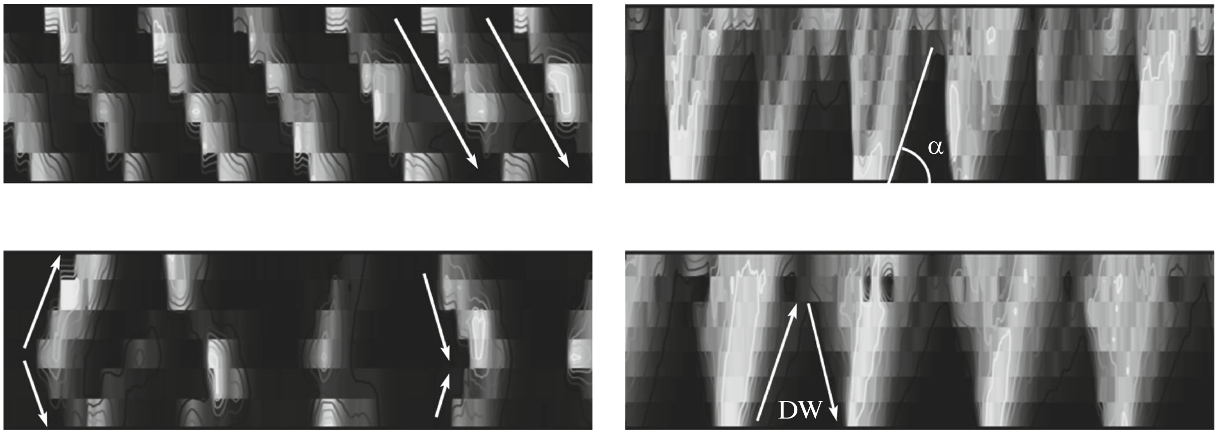

Fig. 2. Visualization of the readings of the ionization probes in the form of the circumferential (left) and longitudinal (right) unfolded views in the modes of CSD (top) and LPD (bottom) of hydrogen in the combustor of the ABR demonstrator. DW stands for detonation wave.

of CSD (top) and LPD (bottom) of hydrogen in the form of the unfolded views of the signals of the probes mounted on the circumference of the combustor (circumferential unfolded view, left) and the probes installed along the generatrix of the central body (longitudinal unfolded view, right). In these unfolded views, white and black colors denote the highest and lowest measured conduction currents in the medium (the conduction current is the highest in the hot detonation products). In the CSD mode, the circumferential unfolded view shows characteristic bright bands of equal slope, which suggests the continuous propagation of the detonation wave in one tangential direction at constant velocity. The characteristic frequency of the inclined bands is close to 1250 Hz, which at the known perimeter of the combustor gives that the apparent velocity of propagation of the detonation wave in the tangential direction is about 1200 m/s. The corresponding longitudinal unfolded view of the signals demonstrates that the detonation wave height is close to 200 mm. Calculating the time difference between the signals of the last and first downstream ionization probes installed along the generatrix of the central body of the combustor, one can estimate the angle between the detonation wave propagation direction and the combustor axis and determine an approximate value of the normal velocity of propagation of the detonation wave in the CSD mode at 1500–1700 m/s. From the angle α (Fig. 2), the rate of filling of the combustor with a fresh mixture in the near-wall region ahead of the detonation front can be estimated at ~550–750 m/s, which corresponds to local Mach numbers of 1.5–2.0. Calculated from the experimental data, the shape and velocity of the detonation wave and also the rate of filling of the combustor with a fresh mixture generally agree with the published calculated data [9].

The process in the LPD mode in the circumferential unfolded view of the signals of the ionization probes is recorded as bright bands with pronounced kinks—leading points corresponding to the advanced arrival of the detonation wave at one probe or another from the side of the outlet section of the combustor. In this case, the bright bands extending to both sides of the leading point represent the propagation of the detonation wave along the circumference of the combustor at a velocity of 1800 m/s. The characteristic frequency of the process in the LPD mode is ~900 Hz. The longitudinal unfolded view of the signals in this mode suggests that the periodic reinitiation of detonation occurs in the fresh mixture at a distance of 200–250 mm of the conditional critical cross section of the air intake, and the generated detonation wave propagates upstream at an apparent velocity of about 1000 m/s, i.e., the detonation velocity is ~1550–1750 m/s.

Figure 3 gives an example of the readings of the total pressure at the nozzle outlet section (sensor *1*, curve *1*), the static pressure at the combustor inlet (sensor *2*, curve *2*), the total pressure at the combustor outlet (sensor *3*, curve *3*), and the static pressure in the vacuum chamber of the wind tunnel (sensor *4*, curve *4*) in one of the tests at Mach 5 and G_h = 0.12 kg/s with a throttle disc of the D220 type. In this test, the stable process in the CSD mode occurs. The process is initiated in 180 ms after sending a signal for opening the fast-acting gate of the wind tunnel. The ignition is accompanied by a significant increase in the pressure in the combustor (curves *2* and *3*). Simultaneously, at sensor *4* mounted in the vacuum chamber (curve *4*) and at sensor *1* installed at the nozzle outlet section of the wind tunnel (curve *1*), the static pressure begins to increase. The pressure curves at these sensors are smooth and rise at equal rates. This may mean that the flow conditions at the inlet of the air intake of the demonstrator vary in time because of changes in the conditions in the vacuum chamber, rather than because of the penetration of perturbations from the combustor. This assumption is confirmed by high-speed video recording of the flow region at the

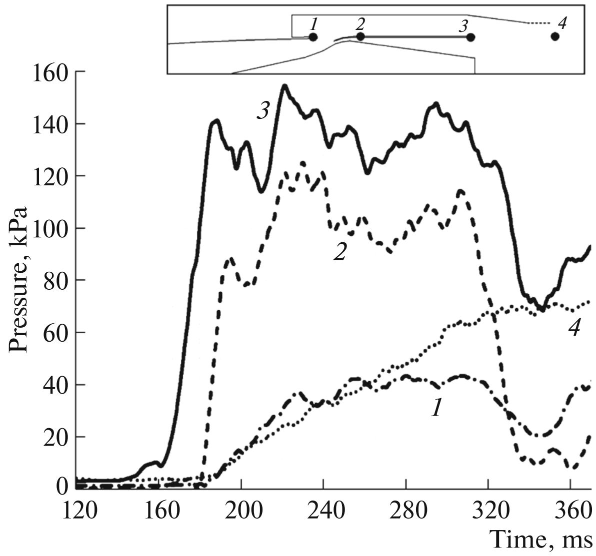

Fig. 3. Readings of (*1*) the total pressure at the nozzle outlet section, (*2*) the static pressure at the combustor inlet, (*3*) the total pressure at the combustor outlet, and (*4*) the static pressure in the vacuum chamber of the wind tunnel. Points *1–4* indicate the positions of the respective sensors.

demonstrator inlet. The video recording showed that the initiation of the process is accompanied by a short-term discharge of the combustion products through the air intake; however, after the process reaches a steady mode, no glow of the detonation products is observed at the inlet of the air intake.

Figure 4 illustrates the dependence of the measured total pressure at the combustor outlet (Fig. 3, sensor *3*) on the calculated air-to-fuel equivalence ratio in the fire tests at Mach numbers of the incoming air flow of 4 to 8 with various throttle discs (D200 and D220). The dashed and dotted horizontal lines are the total pressure levels at the combustor outlet in the cold blowing at Mach numbers of the incoming air flow of 5 and 8, respectively. The rightmost points at Mach 5 and 8 represent the limiting modes of detonation combustion: a further decrease in the hydrogen flow rate leads to loss of detonation. The pressure at the combustor outlet is maximal at calculated Mach 5.

Thus, in this work, we for the first time experimentally demonstrated the possibility of the stable detonation combustion of hydrogen in the supersonic flow in the demonstrator of the original-design ABR while blowing with the air flow at Mach 4 to 8 in the impulse wind tunnel. In the annular combustor of the demonstrator, the CSD and LPD modes were detected. The possibility of a compact multimode ABR with detonation combustion of hydrogen was experimentally demonstrated. In our further studies, we will determine the thrust characteristics of the demonstrator.

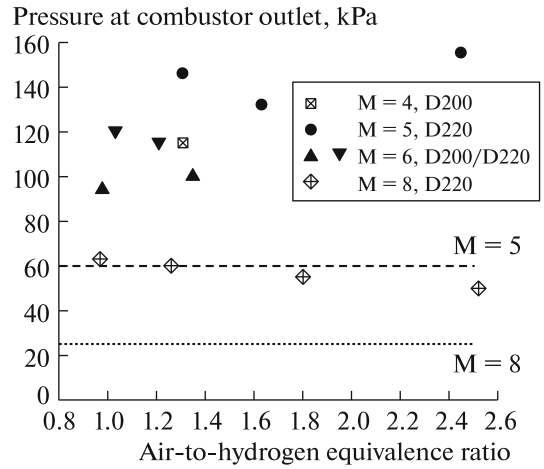

Fig. 4. Dependence of the total pressure at the combustor outlet on air-to-hydrogen equivalence ratio in the fire tests of the ABR demonstrator with throttle discs D200 and D220 (points at Mach 4, 5, 6, and 8) and in the cold blowing with throttle disc D220 (dashed and dotted horizontal lines at Mach 5 and 8, respectively).

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