Wind tunnel tests of a hydrogen-fueled detonation ramjet model at approach air stream Mach numbers from 4 to 8

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Experimental studies of an axisymmetric hydrogen-fueled detonation ramjet model 1.05-m long and 0.31 m in diameter with an expanding annular combustor were performed in a pulse wind tunnel under conditions of approaching air stream Mach number ranging from 4 to 8 with the total temperature of 290 K. In a supersonic air flow entering the combustor, continuous and longitudinally pulsating modes of hydrogen detonation with the corresponding characteristic frequencies of 1250 and 900 Hz were obtained. The maximum measured values of fuel-based specific impulse and total thrust were 3600 s and 2200 N.

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Introduction

Use of detonative combustion of the fuel–air mixture in a ramjet is considered as an alternative direction in the development of modern propulsion systems for high-speed aerospace vehicles. The energy efficiency of detonation engines was first discussed theoretically by Zel’dovich [1] and has recently been substantiated experimentally in Refs. [2–4]. The most promising schemes for the organization of detonative combustion in the flow include schemes with pulsed detonation in tubes and tube bundles [5,6] and continuous spin detonation (CSD) in annular combustors [7–9]. References [5–9] contain information on various aspects of continuous detonation and pulsed detonation engines operating on oxygen, or oxygen-enriched air, or air as oxidizer and various fuels, however most of relevant publications in the open literature deal with hydrogen as a fuel.
Continuous detonation combustion of hydrogen–air mixtures was studied experimentally in annular combustors of different design and scale elsewhere [7–15]. Various modes of self-sustained detonative combustion are reported therein including modes with one detonation wave (DW) and several DWs simultaneously rotating in the combustor annulus in the same or opposite circumferential directions, as well as the longitudinal pulsed detonation (LPD) mode arising at certain limiting conditions of hydrogen and air supply. In the LPD mode, the detonation is reinitiated at a position close to the combustor outlet and propagates upstream as a supersonic reaction front occupying the entire cross section of the combustor [11,13].

The possibility of organizing the CSD of hydrogen in a ramjet was studied theoretically in Refs. [16–18] and experimentally in Refs. [19–21]. Three-dimensional calculations in Ref. [17] proved the possibility of CSD in a supersonic flow of the premixed hydrogen–air mixture in a ramjet combustor under conditions corresponding to the atmospheric flight with the Mach number of \( M = 4 \). Three-dimensional calculations in Ref. [18] proved the possibility of CSD in the hydrogen-fueled axisymmetric ramjet with an annular combustor in the atmospheric flight at the altitude of 20 km with \( M = 5 \) with hydrogen injection into the annular combustor through the circumferential slit in the central body. In Ref. [19], the results of successful experimental studies of the CSD in the hydrogen−air mixture in an annular combustor attached to air conduit are reported for the conditions simulating a supersonic flight with \( M = 4 \). The duration of continuous detonation combustion of hydrogen in experiments [19] was more than 3 s, which allowed the authors to register a few thousand revolutions of the DW in the annular gap under conditions when the Mach number of the air flow at the inlet to the combustor was 1.93. Reported in Ref. [20] are the results of experimental investigations of the detonative combustion of hydrogen in a ramjet model in a pulse wind tunnel at the approaching air stream Mach number \( M \) ranging from 4 to 8. Two modes of detonative combustion of hydrogen were obtained, namely the CSD and LPD. The duration of detonative combustion of hydrogen in experiments [20] was very short (150–200 ms), which allowed the authors to register several dozen revolutions or longitudinal pulsations of the DW in the annular combustor under conditions when the average Mach number of the air flow at the combustor intake was about 2.5. Reported in Ref. [21] are the experimental studies of the continuous-rotating-detonation ramjet model designed for the flight with \( M = 4.5 \) at the altitude of 18.5 km with hydrogen as a fuel. The inner and outer diameters of the combustor were 80 and 120 mm, respectively. In free-jet tests in a wind tunnel the authors of [21] registered the CSD of hydrogen with the rotation frequency of a single DW equal to 8.35 kHz. Also reported in Ref. [21] are the results of thrust measurements: some thrust was detected but the total force acting on the ramjet model remained negative which was explained by an unoptimized nozzle.

The objective of this work is to study experimentally the detonative combustion of hydrogen in a detonation ramjet model of the scheme suggested in Refs. [18,20] under conditions of approaching stream Mach number \( M \) from 4 to 8 in a pulsed wind tunnel “Transit-M” of ITAM SB RAS.

### Experimental setup and data acquisition system

Pulsed wind tunnel “Transit-M” [22] (Fig. 1) is designed for aerodynamic tests in the range of Mach numbers from 4 to 8 at elevated values of Reynolds number (with the total temperature ranging from 290 to 500 K). The main element of the wind tunnel is the prechamber unit, the source of the working gas which determines the operation mode. Before the experiment, the initial mass of the working gas (air) is accumulated simultaneously in the primary prechamber and in the gas reservoir yielding together 0.11 m³ of compressed gas under a pressure of up to 200 atm. The primary prechamber is equipped with a fast-response non-destructible shutter that blocks the gas outlet into the secondary prechamber and then into an axisymmetric supersonic nozzle. After the shutter opens, the compressed gas flows into the secondary prechamber where the total pressure decreases and the flow becomes more uniform before entering the nozzle. In the construction of the wind tunnel, changeable shaped nozzles with a cutoff diameter of 300 mm are used. With the help of the nozzles, a uniform gas stream with a Mach number \( M \) ranging from 4 to 8 is created. This gas stream flows around the test model installed in the test section of the tunnel. The test section is made in the form of an axisymmetric Eiffel chamber and consists of two compartments with optical windows for visualizing the flow pattern. The gas from the test section flows into the vacuum tank through the exhaust diffuser, a cylindrical tube 400 mm in diameter. The total length of the installation, including the exhaust diffuser, is 7600 mm. The width and height of the installation are 870 and 1470 mm, respectively.

The design of the detonation ramjet model was developed based on the results of calculations in Ref. [18] (Fig. 2). The detonation ramjet model includes an air intake with a central body that ensures deceleration of the incoming...
supersonic airflow with Mach number $M = 5$ in three oblique shocks to a supersonic flow with a maximum local Mach number $M \approx 2.5$ in the minimum section of the intake (conditional “critical section” of the intake), and an expanding annular combustor in which the air flow accelerates to $M \approx 4$. The diameter of the leading edge of the outer cowl of the intake is 284 mm. Such a dimension ensures the design flow at the inlet of the annular combustor without the influence of the boundary layer formed on the walls of the wind tunnel nozzle. The outer diameter of the combustor is 310 mm. The total length of the detonation ramjet model is 1050 mm.

Fig. 2 – Schematic (a) and photograph (b) of the detonation ramjet model installed in the wind tunnel.
To ensure detonative combustion in the ramjet model, a provision is made for throttling the flow in the outlet section of the combustor by connecting flat throttling disks 5 mm thick and 200, 220 and 240 mm in diameter (hereinafter D200, D220 and D240) with rounded edges to the central body (see Fig. 2a). These disks block the outlet cross section of the annular combustor by 30%, 40% and 50%, respectively. Hydrogen is fed to the combustor through the annular set of 200 uniformly distributed radial holes (“fuel nozzles” in Fig. 2a) 0.8 mm in diameter placed in the central body 10 mm downstream from the conditional critical section of the intake. Hydrogen is supplied from the hydrogen receiver with a volume of 0.08 m³ through the manifold equipped with a high-speed pneumatic valve. The manifold enters the ramjet model through the tail tube as shown in Fig. 2a.

To properly install the detonation ramjet model in the wind tunnel, preliminary CFD calculations of “cold” flow (without combustion) in the wind tunnel with the model were performed. The calculations showed that for the successful starting of the operation process in the model the distance between the nozzle edge and the leading edge of the model-intake outer cowl should exceed 70 mm. Fig. 3 shows the calculated distributions of the local Mach number in the “cold” flow with the approaching stream Mach number M = 5 without (Fig. 3a) and with (Fig. 3b) the throttling disk. As seen, the throttling disk causes flow transformation in the wake of the ramjet model and, due to the subsonic flow at the periphery of the test section, results in flow transformation in the region close to the air intake (shown by the white arrow in Fig. 3b) of the model. Nevertheless, these changes do not affect much the flow in the annular combustor except for its tail part where a bow shock forms. The subsonic recirculation zone arising ahead of the throttling disk seems to play an important role in the initiation of detonative combustion in the model (see below).

The data acquisition system includes ionization probes, low-frequency (~1 kHz) static and total pressure sensors at the combustor inlet and outlet, strain gauges for thrust measurements, Schlieren photography and high-speed digital video cameras.

Registration of combustion and detonation processes by ionization probes was tested earlier and showed high efficiency [23]. The ionization probe (response time 2 μs) intended for measuring the conduction current in hot combustion products is introduced into the combustor in such a way that the distance between the thin bare end of the probe and the combustor wall is about 1 mm. Twelve ionization probes are installed in the central body of the combustor (see Fig. 2a): 6 probes are placed evenly around the circumference at a distance of 40 mm downstream from the hydrogen supply nozzles, and 7 probes (1 probe is common with the probes located in the circumferential direction) are placed evenly along the generatrix of the central body with a pitch of 30 mm. From now on, these two lines of ionization probes will be referred to as the circumferential and axial lines, respectively. The numbering of the probes starts from the common probe (No. 1) and proceeds counterclockwise for the circumferential line and downstream for the axial line. Such a measuring system allows one to identify the mode of detonative combustion (CSD or LD) and to measure the characteristic frequency of the operation process, as well as the velocity and direction of DW propagation. Moreover, it allows one to distinguish between detonative and deflagrative combustion [23]. However, under the conditions considered in this study, deflagrative combustion of hydrogen was not observed at all.

Static and total pressures are measured by low-frequency (~1 kHz) sensors at the edge of the supersonic nozzle of the wind tunnel, in the secondary prechamber (see Fig. 3), in the vacuum tank, in the hydrogen receiver, and in the hydrogen supply manifold, as well as at the combustor inlet and outlet.

For thrust measurements, two T40A strain gauges with a maximum load of 2000 N are used. The gauges are installed in the wake of the detonation ramjet model as shown in Figs. 2a and 4. Prior to the tests in the wind tunnel, the thrust measurement system was calibrated using a calibrated load cell of MS50 type with a maximum load of 5000 N. The calibration was made for static loads ranging from −2000 to +1000 N (positive values correspond to load direction opposite to the approaching air stream). The thrust measuring system was also used to measure the natural frequencies of ramjet model oscillations. The tests showed that the natural oscillation frequency in the axial direction (along the axis of wind tunnel) was 50–60 Hz. In the transverse (lateral) direction, the natural oscillation frequency was 5–7 Hz, but in the arrangement of the strain gauges shown in Fig. 4 the transverse oscillations are compensated.

Worth noting is the fact that the design of the realistic ramjet model and the thrust measuring system were not

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**Fig. 3** — Calculated distributions of the local Mach number in the “cold” flow (without combustion) with the approaching stream Mach number M = 5 without (a) and with (b) the throttling disk.
optimized in terms of the least aerodynamic drag. As seen in Fig. 4 (and in Fig. 2a), hydrogen supply manifolds, wires and cables are introduced to the model through the tail tube attached to the center body of the model along the symmetry axis. This bundle of manifolds, wires and cables is crossing the wind tunnel closely downstream from the model, thus producing an extra drag force. The thrust measuring system also produces an extra drag force despite the model mount and strain gauges are covered by a pylon-like screen with a sharp leading edge. In addition, a throttling disk used solely for the initiation of the operation process was not removed during tests and therefore produced an extra drag force. In general, the aerodynamic drag of the realistic ramjet model together with the thrust measuring system and with a throttling disk appeared to be about twice larger than the calculated value obtained in the preliminary CFD calculations of “cold” flow in the flow path of the wind tunnel with installed “perfect” detonation ramjet model.

During experiments, Schlieren photography and high-speed video recording of the combustion process is carried out through the optical windows of the test section of the wind tunnel.

To initiate the operation process in the combustor, a specially developed hydrogen-oxygen detonator is used (Fig. 5). The detonator comprises the ignition chamber and a detonation tube attached to it. The ignition chamber is a round tube 20 mm in diameter and 30-mm long. The detonation tube is a straight round tube 10 mm in diameter and 200-mm long. A standard automobile spark plug is used to ignite the mixture. The detonator is mounted on the outer wall of the combustor 150 mm downstream from the conditional critical section of the intake (see Fig. 2a). Hydrogen and oxygen are fed into the ignition chamber of the detonator through tubes 4 mm in diameter. After the control signal is applied to turn on the detonator, the detonation tube is filled with the hydrogen – oxygen mixture during about 200 ms and then the mixture is ignited, the arising flame accelerates providing the deflagration-to-detonation transition in the detonation tube, and the generated DW enters the annular gap of the combustor. According to the video records and records of the ionization probes, the characteristic time the detonation pulse created by the detonator influences the operation process in the combustor does not exceed 10 ms. The time of detonator triggering is properly synchronized with the opening of the fast-response shutter of the wind tunnel and with the opening of the hydrogen supply valve in the combustor. The operation process in the combustor is initiated once the flow rates of air and hydrogen reach the constant values preset by the program of the experiment. Hydrogen is supplied to the combustor during the time interval of 150 ms: the operation process is examined during just such an interval. After this interval, the pressure in the vacuum tank increases noticeably, which leads to the violation of the design flow in the supersonic nozzle of the wind tunnel.
The initiation and stability of the operation process with detonative combustion of hydrogen was studied at Mach numbers of the approaching air stream ranging from 4 to 8 at a constant total temperature $T_0 = 290$ K. The main part of the tests was performed for $M = 5$. Table 1 shows the parameters of the experiments: the Mach number ($M$), the total pressure ($P_0$), the static pressure ($P_{st}$) and the static temperature ($T_{st}$) of the approaching air stream, the total mass flow rate of air through the flow path of the wind tunnel ($G_A$), the estimated value of the mass flow rate of air through the flow path of the model ($G_{Am}$), mass flow rate of hydrogen ($G_{H2}$), and the type of the throttling disk installed at the combustor outlet. The value of the mass flow rate of air through the flow path of the model, $G_{Am}$, was estimated on the basis of CFD calculations (see Fig. 3).

Depending on the Mach number of the approaching air stream, the composition of the hydrogen – air mixture and the type of the throttling disk, two modes of the operation process were recorded in the experiments reported herein: with CSD and LPD of hydrogen. For analyzing the measurement data obtained during experiments, the following procedures were used.

Fig. 6 exemplifies the records of ionization probes in the circumferential and axial lines in the tests without (a) and with (b) throttling disk D220 at approaching air stream Mach number $M = 5$, all other conditions being equal. Shown in addition are the static pressure curves in the hydrogen supply manifold, the time instants of detonator triggering, and the videoframes of exhaust plumes in the firing tests without (a) and with (b) throttling disk at $M = 5$.  

Fig. 6 – Records of ionization probes, time instants of detonator triggering, and the videoframes of exhaust plumes in the firing tests without (a) and with (b) throttling disk at $M = 5$. 

<table>
<thead>
<tr>
<th>$M$</th>
<th>$P_0$, atm</th>
<th>$P_{st}$, kPa</th>
<th>$T_{st}$, K</th>
<th>$G_A$, kg/s</th>
<th>$G_{Am}$, kg/s</th>
<th>$G_{H2}$, kg/s</th>
<th>Throt. disk</th>
<th>Operation process</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>5.2</td>
<td>71</td>
<td>12.4</td>
<td>4.8</td>
<td>0.12</td>
<td>D200/D220</td>
<td>CSD</td>
</tr>
<tr>
<td>5</td>
<td>20–24</td>
<td>4.5</td>
<td>50</td>
<td>14–16</td>
<td>7–8</td>
<td>0.06–0.2</td>
<td>0/D200/D220</td>
<td>CSD/LPD</td>
</tr>
<tr>
<td>6</td>
<td>30–35</td>
<td>2.2</td>
<td>37</td>
<td>10</td>
<td>7</td>
<td>0.12–0.2</td>
<td>D200/D220</td>
<td>CSD/LPD</td>
</tr>
<tr>
<td>8</td>
<td>54</td>
<td>0.6</td>
<td>22</td>
<td>5</td>
<td>5</td>
<td>0.05–0.17</td>
<td>D220/D240</td>
<td>LPD</td>
</tr>
</tbody>
</table>
the videoframes of exhaust plumes. Clearly, in the absence of the throttling disk (see Fig. 6a) there is no evidence of combustion in the flow: all ionization probes show zero-level signals even at the time instant of detonator triggering. Video records in this test detect a short flash of light caused solely by detonator triggering. Use of the throttling disk changes the flow pattern drastically (see Fig. 6b). Detonator triggering results in the volumetric explosion in the combustor (overshooting of probe signals for about 10 ms in Fig. 6b) followed by sustained chemical activity: all ionization probes show oscillating signals of ionization current caused by appearance of high-temperature combustion products. Video records in this test detect continuous luminosity of the hot exhaust plume.

For the sake of convenience, the records of ionization probes are “visualized” according to the procedure of [23] as shown in the examples of Fig. 7. Fig. 7 presents the “visualization” of the records of ionization probes over a short time interval for two typical tests: one with the CSD mode (Fig. 6a) and another with the LPD mode (Fig. 6b). The records in the top frames are obtained by processing the signals of ionization probes in the circumferential line. The records in the bottom frames correspond to the signals of probes in the axial line. The procedure of [23] attributes the brightest color (“Max” in the scale of Fig. 7) to the highest ionization current recorded by a probe in the region with the highest temperature, and the darkest color (“Min” in the scale of Fig. 7) to the lowest ionization current recorded by a probe in the region with the lowest temperature. Thus, plotted along the Y-axes in the frames of Fig. 7 are the pixels corresponding to each consecutive ionization probe: 7 pixels (from No. 1 to No. 7) for the probes in the axial line and 6 pixels (from No. 1 to No. 6) for the probes in the circumferential line. Plotted along the X-axes in Fig. 7 is time in milliseconds. The white color (“Max”) of the pixels in Fig. 7 depicts high ionization current registered by the corresponding probe caused by high temperature in a DW.

**Fig. 7** — Visualization of the records of ionization probes in the circumferential (top) and axial (bottom) lines for (a) CSD and (b) LPD modes of hydrogen combustion in the detonation ramjet model. Dimensions are in millimeters.
Black color (“Min”) of the pixels denotes the absence of ionization current in the cold fresh reactants. Such visualization of ionization probe records allows determining the number of DWs, their apparent propagation velocity, their direction of motion, their rotation frequency, their height and many other specific features of the phenomenon, and allows studying the dynamics of various transient processes.

In the CSD mode, the characteristic light bands of some constant slope are observed which indicates the continuous propagation of the DW in one tangential direction at a constant apparent velocity. The characteristic frequency of the inclined bands in the top frame of Fig. 7a is close to 1250 Hz, which for a known combustor perimeter gives the apparent propagation velocity of the DW of about 1200 m/s in the tangential direction. The corresponding signals of the probes in the axial line (the bottom frame in Fig. 7a) indicate that the “visible” height of the DW is 180–200 mm. The actual height of the DW could be somewhat larger because the 40-mm long segment between the hydrogen supply nozzles and the circumferential line of ionization probes is free of the probes (see Fig. 2a). Taking into account that the distance from the hydrogen supply nozzles to the throttling disk along the generatrix of the central body is 550 mm and the flow downstream from the DW is supersonic [18], one comes to a conclusion that the detonation in the CSD mode propagates without influence of the throttling disk.

Calculating the time difference between the signals at the last (No. 7) and first (No. 1) ionization probes in the axial line (see Fig. 7a), one can readily estimate the angle of inclination of the DW to the combustor axis and determine the approximate value of the normal propagation velocity of the DW in the CSD mode: 1500–1700 m/s. This velocity is comparable with the Chapman–Jouguet detonation velocity in the homogeneous stoichiometric hydrogen–air mixture (1970 m/s).

Note that in our experiments we controlled only the overall mixture composition based on the measured mass flow rate of hydrogen and estimated mass flow rate of air through the ramjet model. Moreover, the propagation of a DW in the CSD mode is accompanied with momentum losses caused by lateral expansion of detonation products downstream and upstream from the reaction zone. These losses are known to decrease the detonation velocity.

From the value of the white-band inclination angle in the bottom frame of Fig. 7a it is possible to estimate the filling rate of the combustor by a fresh reactive mixture in the near-wall region ahead of the detonation front: 550–750 m/s, which corresponds to a local Mach number of 1.5–2.0. The shape of the DW and its propagation velocity estimated on the basis of the experimental data, as well as the filling rate of the combustor by the fresh reactive mixture are in general agreement with the calculated data reported earlier in Ref. [18].

The operation process with the LPD mode is visualized in the top frame of Fig. 7b in the form of light vertical bands indicating that a DW reaches all the probes in the circumferential line nearly simultaneously. Despite these bands are vertical, they exhibit fractures or “leading points.”

**Fig. 9** – Model schematic (a) and time histories of the local total and static pressures at the leading edge of the model intake (position 5): (b) $M = 5$, (c) 6, and (d) 8.
leading points correspond to somewhat earlier arrival of a DW to a particular ionization probe in the circumferential line. In this case, the light bands extending to either side of the leading point correspond to the apparent propagation of the DW along the circumference of the combustor at the velocity of about 1800 m/s. The characteristic frequency of the operation process in the LPD mode is ~900 Hz.

Examination of the records of the ionization probes in the axial line for the LPD mode indicates that the spontaneous periodical re-initiation of detonation occurs in the mixing layer between fresh mixture and combustion products at a distance of 180–250 mm downstream from the circumferential line of ionization probes (or 220–290 mm from the hydrogen supply nozzles). In fact, the height of black triangles in the bottom frame of Fig. 7b ranges from 180 to 250 mm. Taking into account that the distance from the hydrogen supply nozzles to the throttling disk along the generatrix of the central body is 550 mm, one comes to a conclusion that the detonation in the LPD mode is re-initiated in the essentially supersonic flow far upstream from the throttling disk and the recirculation zone attached to it (see Fig. 3b). The spontaneous periodical re-initiation of detonation is caused most probably by localized explosions due to collisions of multiple incident and reflected shock waves traversing the annular combustor. The DW thus re-initiated then propagates upstream with an apparent velocity of about 1000 m/s, i.e. the normal detonation velocity is 1550–1750 m/s.

Thus, the detonative combustion once initiated in the ramjet model with the attached throttling disk appears to be self-sustained in both modes, CSD and LPD, and the throttling disk seems to exert no influence on the operation process. It stands to reason that the throttling disk is required only for detonation initiation and can be removed afterwards. As a matter of fact, the mechanism of detonation initiation in the ramjet model is closely connected to the subsonic recirculation zone arising ahead of the throttling disk (see Fig. 3b). Detonation is initiated by the localized volumetric explosions of the fresh mixture accumulated in this recirculation zone upon arrival of hot detonation products from the detonator followed by spreading of these explosions over the entire combustor for about 10 ms (see Fig. 6b). This finding is substantiated by supplementary tests with replacing the hydrogen – oxygen detonator by an electrical discharger mounted in the central body upstream from the recirculation zone. In these tests, triggering of the electrical discharger resulted in the establishment of the operation modes very similar to those obtained with the use of the detonator. However, contrary to the detonator, the electrical discharger provided less reliable ignition at high approaching stream Mach numbers and we were forced to abandon its use.

Fig. 8 shows an example of pressure records in one of the experiments with $M = 5$, $G_{H2} = 0.12$ kg/s and throttling disk D220: total pressure at the nozzle edge (sensor 1 and curve 1),

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Fig. 10 – Model schematic (a) and time histories of the local Mach number at the leading edge of the model intake (position 5): (b) $M = 5$, (c) 6, and (d) 8. Dashed line shows the mean value of the Mach number during ramjet model operation.
static pressure at the combustor inlet (sensor 2 and curve 2), total pressure at the combustor outlet (sensor 3 and curve 3), and static pressure in the vacuum tank (sensor 4 and curve 4). In this experiment, a stable operation process with CSD is registered. It is seen from Fig. 8 that initiation of the process occurs 180 ms after opening the fast-response shutter of the wind tunnel. After ignition, there is a significant pressure rise in the combustor (curves 2 and 3). At the same time, the static pressure starts to build up at sensor 4 installed in the vacuum tank (curve 4) and at sensor 1 installed at the edge of the wind tunnel nozzle (curve 1), and the pressure curves for these latter sensors are smooth and rise at the same rate. This may mean that the flow conditions at the air intake of the detonation ramjet model vary with time due to a change in the conditions in the vacuum tank rather than due to the penetration of disturbances upstream from the combustor. This assumption is confirmed by high-speed video recording of the flow at the air intake. Video recording shows that the start of the operation process can be accompanied by a short-term emanation of combustion products upstream through the air intake, but after the establishment of steady operation process no luminosity of detonation products is observed at the air intake. In the tests, such phenomena were observed only at relatively low approaching stream Mach numbers ($M = 4$ and 5). Most likely, this phenomenon is caused by the initial volumetric explosion in the combustor (see Fig. 6b).

In most cases with relatively low mass flow rates of hydrogen, the flow at the combustor inlet is supersonic. For example, Fig. 9 shows the time histories of the measured local total $P_0'$ and static $P_{st}$ pressures for $M = 5$, 6 and 8 at the leading edge of the intake cowl (shown by point 5 in the model schematic in Fig. 9a). Based on the known relationship between $P_0'$ and $P_{st}$, the time histories of the local Mach number in this point have been reconstructed. Fig. 10 shows the corresponding time histories of the calculated Mach number at the leading edge of the intake cowl at $M = 5$, 6 and 8. Clearly, during the time interval from 0.2 s (ignition) to 0.35 s (fuel cut-off) the flow is supersonic (local Mach number is about 2) at $M = 6$ and 8 and is slightly subsonic at $M = 5$.

Fig. 11 shows the example of strain-gauge records and their processing procedure for one of the experiments with $M = 8$, $G_{H_2} = 0.027$ kg/s and throttling disk D220. There are three signals presented in Fig. 11a: two signals recorded by each of two strain gauges and a cumulative thrust curve which is the sum of these two signals corresponding to the total instantaneous force acting on the detonation ramjet model. The positive force is the force directed upstream the approaching air stream. In Fig. 11b, the cumulative thrust curve is processed by the Fourier filter to smoothen the high-frequency oscillations with a frequency exceeding 100 Hz. Finally, shown in Fig. 11c is the procedure of averaging the cumulative thrust curve by determining the instantaneous period of oscillations based on two neighboring maxima and minima and averaging the force value over each period. Note that for excluding the effect of curve filtering and averaging on the overall results of experiments (thrust and specific impulse, see below), all force parameters were evaluated using the unfiltered signals of strain gauges.

![Diagram](image-url)
The cumulative thrust curve in Fig. 11a shows that the aerodynamic drag of the detonation ramjet model attains the value of about \(-1000\) N (the initial negative peaks). However, once ignition is triggered (time instant 0.17 s), the thrust measuring system registers an abrupt jump in the cumulative force acting on the model. The cumulative force becomes slightly positive, thus indicating that the model produces thrust slightly exceeding its aerodynamic drag. Upon cut-off of fuel supply (0.32 s), the cumulative force jumps back to the negative value of \(-1000\) N corresponding to the aerodynamic drag of the model. Thereafter the absolute value of the aerodynamic drag gradually decreases to a zero-value due to airflow deceleration in the wind tunnel.

When analyzing the experimental results, it is useful to plot the cumulative thrust curve for the “hot” test (with hydrogen combustion) together with its analog for the “cold” test (without hydrogen combustion). The example of such a plot is presented in Fig. 12 for the experiment with \(M = 8\), \(G_{H2} = 0.023\) kg/s and throttling disk D220. It is seen from Fig. 12 that the initial (before 0.18 s) and the final (after 0.4 s) portions of the cumulative thrust curves for the “cold” and “hot” tests are nearly identical whereas they differ considerably in the time interval from 0.18 to 0.4 s. In this example, the detonation ramjet model is seen to exhibit a positive cumulative thrust of about 100 N at the approaching air stream Mach number \(M = 8\).

Using the data like those depicted in Fig. 12 and the data on hydrogen consumption in each particular “hot” test, one can determine the fuel-based specific impulse of the detonation ramjet model as:

\[
ISP = \frac{\int_{t=0}^{t=1} F_{\text{hot}}(t) \, dt - \int_{t=0}^{t=1} F_{\text{cold}}(t) \, dt}{gG_{H2}}
\]

(1)

where \(G_{H2}\) is the mass flow rate of hydrogen (the mass of hydrogen consumed in a “hot” test during 1-s interval), \(g\) is the acceleration of gravity, and \(F_{\text{hot}}(t)\) and \(F_{\text{cold}}(t)\) are the instantaneous cumulative thrust values in “hot” and “cold” tests, taken from the cumulative thrust curves. Note, that this definition of the fuel-based specific impulse should be treated as conservative because it includes hydrogen consumption during all transients.

Using the value of \(ISP\) defined by Eq. (1) one can evaluate the total thrust produced by the detonation ramjet model as:

\[
F = ISPgG_{H2}
\]

(2)

**Experimental results**

Fig. 13 shows the dependences of the measured total pressure at the combustor outlet (sensor 3 in Fig. 2a) on the ratio of...
measured mass flow rates of hydrogen $G_{H2}$ and mass flow rate of air $G_A$ through the flow path of the wind tunnel (Fig. 13a) and on the estimated air-to-fuel equivalence ratio in the combustor (Fig. 13b) for the firing tests with the Mach numbers of the approaching air stream ranging from $M = 4$ to $M = 8$ with different throttling disks (D200 and D220). The stoichiometric coefficient $\Phi_{st}$ for hydrogen – air mixture in the X-axis legend of Fig. 13b is equal to 35.3. The horizontal dashed lines show the total pressure levels at the combustor outlet obtained in the “cold” tests with the approaching air stream Mach numbers of 5 and 8. The extreme points on the left in Fig. 13a for Mach numbers 5 and 8 correspond to the limiting modes of detonative combustion: further decrease in hydrogen flow rate leads to failure of detonation initiation. The maximum total pressure at the combustor outlet is seen to be reached at the approaching air stream Mach number $M = 5$. The minimum estimated values of air-to-fuel equivalence ratio required for the establishment of detonative combustion in the CSD or LPD modes in the ramjet model are close to stoichiometric (Fig. 13b). Note however that this finding should be treated as preliminary because the mass flow rate of air through the flow path of the ramjet model, $G_{Am}$, is estimated based on the CFD calculations rather than based on measurements. Most probably, the realistic value of $G_{Am}$ is smaller than its estimated value due to various effects not included in the CFD calculations (boundary layers, finite dimensions of model edges, etc.).

Fig. 14 shows the dependence of the fuel-based specific impulse $I_{sp}$ on the mass flow rate of hydrogen $G_{H2}$ supplied to the combustor. The maximum value (3600 s) of the fuel-based specific impulse defined by Eq. (1) is attained at $M = 6$. The extreme points on the left correspond to the minimum hydrogen mass flow rates at which a stable operation mode with CSD or LPD was detected. As could be expected, the fuel-based specific impulse increases with the decrease in $G_{H2}$ and decreases with the Mach number at a given value of $G_{H2}$.

Finally, Fig. 15 shows the total thrust produced by the detonation ramjet model vs. hydrogen mass flow rate at $M = 5$.

**Fig. 15 – The total thrust of the detonation ramjet model vs. mass flow rate of hydrogen in “hot” experiments with $M = 5$, 6 and 8.**

6 and 8. The total thrust is defined by Eq. (2). The maximum value (2200 N) of the total thrust is attained at $M = 5$.

**Conclusions**

We have demonstrated experimentally the possibility of organizing stable detonative combustion of hydrogen in a supersonic air flow using the axisymmetric detonation ramjet model with an expanding annular combustor under conditions of approaching air stream Mach number ranging from 4 to 8 in a pulsed wind tunnel at a total temperature of 290 K. The air intake of the ramjet model is designed for the conditions of $M = 5$. At $M = 5$, the approaching air stream is decelerated in the air intake to a local Mach number ~2.5 before entering the expanding annular combustor. Hydrogen is fed to the combustor through the set of multiple equidistant radial nozzles in the conical center body of the combustor. Detonation is initiated by a hydrogen – oxygen detonator attached to the combustor of the ramjet model. The duration of tests is usually 150–200 ms which allows reliable detection of about hundred rotations or longitudinal pulsations of a DW.

Two detonation modes in the annular combustor of the ramjet model, CSD and LPD, are registered in the experiments. In the first, continuous spinning mode, a single DW is rotating in the combustor annular gap in the tangential direction with the apparent velocity of ~1200 m/s giving the rotation frequency of 1250 Hz and the normal detonation velocity of 1500–1700 m/s. In the second, longitudinally pulsating mode, one or several DWs are spontaneously re-initiated in the rear part of the combustor and propagate upstream towards the hydrogen supply nozzles at the apparent velocity of ~1000 m/s giving the longitudinal pulsation frequency of 900 Hz and the normal detonation velocity of 1550–1750 m/s.

The detonative combustion once initiated in the ramjet model with the attached throttling disk appears to be self-sustained in both modes, CSD and LPD, and the throttling
disk seems to exert no influence on the operation process. It stands to reason that the throttling disk is required only for detonation initiation and can be removed afterwards.

At approaching air stream Mach numbers exceeding 5 the air flow in the air intake of the ramjet model is not affected by the combustion process: it remains supersonic during firing tests. At approaching air stream Mach numbers less than or equal to 5 the air flow in the air intake of the ramjet model can be shortly affected by the combustion process during detonation initiation. Video recording shows that the start of the operation process in this case can be accompanied by a short-term emanation of combustion products upstream through the air intake, but after the establishment of the steady operation process no luminosity of detonation products is observed at the intake.

Detonative combustion of hydrogen provides a significant increase in the static pressure in the combustor, which persists during the test time. Thrust measurements show that the thrust produced by the detonation ramjet model can be equal to or even exceed the aerodynamic drag of the model by about 100 N despite the aerodynamic drag of the realistic ramjet model together with the throttling disk and thrust measuring system is about twice larger than the calculated aerodynamic drag of the model without regard for mechanical support, throttling disk and thrust measuring system. The maximum measured values of the fuel-based specific impulse and the total thrust are 3600 s and 2200 N, respectively.

Thus, the possibility of creating a compact ramjet with detonative combustion of hydrogen has been substantiated experimentally. Further studies will be focused on the experiments with the air total temperature corresponding to the conditions of atmospheric flight at M = 5 to 8. Also, attempts will be made to apply removable/destroyable throttling disks.

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