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COMBUSTION, EXPLOSION, AND SHOCK WAVES

Breakthrough in the Theory of Ramjets

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Abstract—The paper considers the possibilities of increasing the thrust and economic characteristics of a hydrogen-fueled ramjet through the use of detonation combustion of fuel. The computational and experimental work carried out at the Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences proves that the use of continuous-detonation combustion makes it possible to expand the range of the stable and effective operation of the ramjet to the range of flight Mach numbers significantly below 2.0 (up to 1.3–1.5) and significantly above 5.0 (at least up to $M_0 = 8$) due to the transition from deflagration combustion of hydrogen to more energy efficient continuous-detonation combustion.

Keywords: detonation combustion, ramjet, hydrogen, three-dimensional gas-dynamic calculations, wind tunnel, test fires

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INTRODUCTION

The theory of chain reactions, developed by N.N. Semenov [1] forms the foundation of the theory of combustion and detonation. Combustion refers to the rapid course of exothermic chemical reactions with progressive self-acceleration, generally complicated by the processes of diffusion of the initial materials and products, release of reaction heat, and heat propagation through the medium, as well as convective flows. Combustion studies are important for science and technology, and in particular for the creation of high-speed aircraft (AC) with ramjets.

A classical ramjet consists of the following main units [2]: an air intake device (AID), a diffuser, a combustion chamber (CC), and a nozzle. In a ramjet, the supersonic flow decelerates at the inlet to the AID in oblique shock waves, and the geometric parameters of the diffuser, the CC, and the nozzle are selected so that the normal shock wave during fuel combustion in the CC comes as close as possible to the throat of the AID, creating a positive force on the inner surfaces' flow path. Fuel combustion in the CC is stabilized by a flame holder. The flame holder creates recirculating flow zones in the CC, in which hot combustion products circulate, serving as an ignition source for the newly supplied fuel-air mixture (FAM). The rate of fuel combustion in a ramjet is controlled by the turbulent-molecular mixing of fuel with air and is 10–12 m/s [3], i.e., much slower than the speed of sound. According to the existing classification of stationary reaction fronts, such combustion is called deflagration.

The ramjet has a number of advantages over other types of engines. The design of the ramjet is much simpler than that of a turbojet. With the Mach number of the flight of the aircraft (AC) $M_0 > 2.5$, the specific thrust characteristics of a ramjet are comparable to or exceed those for a turbojet. Compared to solid-propellant rocket engines, the ramjet has significantly higher specific thrust characteristics due to the use of atmospheric air as an oxidizer.

Like other engines, ramjets also have certain disadvantages. Modern ramjets begin to work effectively starting from the flight Mach number $M_0 \approx 2.0$ (the start-up Mach number). The maximum efficiency of the ramjet is achieved when flying an AC at $M_0 = 3–4$, and then as M_0 increases, the efficiency declines. The limiting Mach number at which the ramjet is still effective is close to the value $M_0 = 5$. Thus, the range of stable and effective operation of the ramjet engine in relation to the AC's flight speed is rather narrow. Currently, ways to improve the thrust and cost performances and expand the range of stable and efficient operation of the ramjet are being sought.

The problem of creating a ramjet for a flight at $M_0 < 2.0$ is related to the low stagnation pressure in the incoming air flow. When flying at $M_0 = 2$, the total pressure ratio R_0 to the static pressure R_{st} is $R_0/R_{st} = 8$, while at $M_0 = 4$, it reaches the value $R_0/R_{st} = 150$. As a consequence, the deceleration of the air flow in the normal shock wave leads to a slight increase in pressure in the flow path, which is insufficient to create a positive effective thrust, which ensures further acceleration of the AC. In addition, in these conditions it is difficult to ensure stable operation of the AID. That is why, to accelerate an AC with a ramjet to the start-up Mach number $M_0 \approx 2.0$, usually accelerating solid propellants rocket engines with relatively low specific thrust characteristics are used. The installation of solid-propellant rocket engines significantly increases the launch weight and dimensions of the AC.

When flying an AC at $M_0 > 4$, the ramjet's efficiency decreases due to the increase in the total pressure loss in the normal shock wave and increase in the stagnation temperature of the incoming air flow. The latter reduces the thermodynamic efficiency of the cycle with deflagration combustion due to the decrease in the temperature difference between the combustion products flowing from the CC and the air entering the CC. The possibility of increasing the efficiency of the ramjet when flying an AC at $M_0 > 5$ is mainly related to the organization of combustion in a supersonic flow. In this case, the incoming air flow does not decelerate to a subsonic speed, but remains at a supersonic speed throughout the ramjet's flow path. With such an organization of the flow, the gas temperature at the inlet to the CC can be significantly reduced and, therefore, the thermodynamic efficiency of the operation cycle can be increased. However, in order to ensure complete molecular mixing of the fuel with the oxidizer and stable combustion of the FAM in the supersonic flow, the CC must be long and have special devices for aerodynamic stabilization of the reaction front, which greatly complicates the practical implementation of an effective ramjet in this scheme.

One of the possibilities for increasing the efficiency of a ramjet when an AC flies at $M_0 < 2$ and $M_0 > 5$ is by the organization of spinning detonation combustion of the FAM in the CC [4]. For this, the CC is implemented in the form of an axisymmetric annular channel with smooth walls [5]. Air enters such a CC in the axial direction, and the fuel is supplied in the form of distributed radial jets in one of the cross sections of the CC. Fuel combustion occurs in one or more detonation waves (DWs), continuously circulating at a high supersonic speed in the annular gap of the CC downstream of the fuel supply belt. Such combustion is called continuous-detonation, and a ramjet with this type of combustion is called a detonation ramjet. It is important to note that the flow velocity at the inlet to the CC of the detonation ramjet can be significantly supersonic.

Continuous detonation combustion in a CC has a number of advantages over deflagration combustion. First, the thermodynamic efficiency of a cycle with detonation combustion is much higher [6, 7]. Second, in contrast to deflagration combustion, in which the energy release zone is distributed over the entire cross section of the ramjet, the energy release in a traveling DW is localized in a narrow reaction zone. In the works [8, 9], it is shown that such localization of the energy release makes it possible to organize a stable operation process at low flight speeds of an AC with a detonation ramjet without disrupting the operation of the AID. Third, due to the high supersonic velocity of the reaction front, continuous-detonation combustion provides a significantly higher power of energy release. Fourth, the shock wave leading the detonation has an extremely high destructive force, which contributes to the turbulent-molecular mixing of liquid sprays or gas jets of fuel with air. The ability of DWs to intensify the mixing of fuel sprays and jets with an air flow and the high power of energy release make it possible to create compact CCs with high combustion efficiency. The disadvantages of CCs with continuous-detonation combustion include the following points: the need to work with FAMs close to stoichiometric; the need for the partial preliminary evaporation of liquid fuel to ensure a sufficient concentration of the vapor phase ahead of the front of the traveling DW; large thermal loads on the structural elements of the CC of the detonation ramjet caused by the high temperature of the detonation products; intense vibration loads on the structural elements of the detonation ramjet during detonation combustion with one spinning DW or with longitudinaly pulsating detonation in the CC [10].

In our works [8–17], we performed computational and experimental studies of the possibility of expanding the domain of stable and efficient operation of a hydrogen detonation ramjet both in the direction of decreasing the flight Mach number and in the direction of increasing it in comparison with the classical ramjet. The aim of this study is to generalize the results obtained. We note that this is a new direction in the combustion science, in which commonly accepted concepts have not yet been formed.

REDUCING THE START-UP MACH NUMBER

In [8], based on the computational and experimental studies, the possibility of reducing the start-up Mach number for a hydrogen detonation ramjet was studied in detail. The task was to form conceptual design of the detonation ramjet for a cruising speed of $M_0 = 2.0$ at sea level, carrying out three-dimensional numerical calculations of the operation process in the detonation ramjet in flight conditions with a Mach number ranging from 1.1 to 2.3, determining the start-up Mach number, and experimentally checking the results obtained on a demonstrator model in a pulsed wind tunnel (WT).

Computational Studies

Figure 1 shows conceptual design of a detonation ramjet engine obtained using multivariate gas-dynamic calculations. The detonation ramjet consists of a central body (CB) with a front cone, a cylindrical part and a rear cone, an AID and an annular CC with a gas-dynamic isolator made in the form of a bypass channel located between the CC and the outer wall of the CC. In flight conditions, the approaching supersonic gas flow first partially decelerates in the oblique shock wave attached to the front cone of the CB and in the near-wall boundary layer, and then accelerates in a fan of rarefaction waves with the partial recovery of its parameters and enters the AID. The length of the cylindrical part of the CB is selected so that the fan of rarefaction waves does not enter the AID. The local Mach number of the flow at the inlet to the AID is $M \approx 1.1M_0$, the local static pressure is approximately $0.9R_{st}$, and the gas flow rate through the AID reaches 94% of the gas flow rate calculated from the velocity and density of the undisturbed approaching flow, as well as from the area of the inlet cross section of the AID.

After entering the AID, the gas flow is divided into two parts: one part enters the CC and the other part enters the bypass channel. In the calculations, after ignition in the CC, continuous-detonation combustion of the combustible mixture is established, which accelerates the detonation products downstream with the formation of a quasi-stationary exhaust jet and the creation of thrust. The continuous-detonation combustion in the CC is organized so that neither the combustible mixture nor the detonation products penetrate the AID upstream. For the flight conditions at $M_0 = 2.0$, in the calculations, a stable operation process is observed with one DW continuously rotating in the annular gap of the CC. The tangential and axial components of the DW velocity vector are about 1900 and 520 m/s, respectively, which gives the value of the normal detonation velocity ≈1970 m/s. The DW length in the axial direction is about 70 mm, i.e., half the length of the CC.

The gas flow entering the bypass channel includes a near-wall boundary layer formed when flowing around the CB. This eliminates the negative effect of the boundary layer on filling the CC with a combustible mixture. Also, the gas flow directed into the bypass channel bypassing the CC, on the one hand, cools the inner wall of the CC, and on the other hand, prevents the gas-dynamic effect of continuous detonation combustion of the combustible mixture in the CC on the gas flow at the inlet to the AID. The detonation combustion of a combustible mixture in the CC is accompanied by the generation of gas-dynamic disturbances in the form of shock waves traveling towards the inlet, which cause an increase in pressure in the inlet section of the AID. This can lead to disruption of the operation of the AID and disruption of continuous-detonation combustion in the CC. Since the leading edge of the wall separating the CC from the bypass channel is displaced into the depth of the AID, when leaving the CC, such shock waves are effectively weakened and transformed into weak acoustic disturbances that do not disrupt the operation of the AID but contribute to the creation of additional thrust when the jet flows out from the bypass channel.

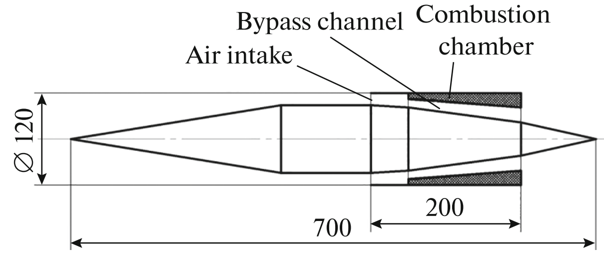

Fig. 1. The conceptual design of the ramjet for the cruising flight Mach number $M = 2.0$. Dimensions are in mm.

Numerical optimization of the geometrical parameters of the detonation ramjet was aimed at selecting the cross-sectional areas of the AID, CC, and bypass channel. The areas are selected so as to ensure the stable operation of the detonation ramjet with at least one DW and the stable operation of the AID without unstart. The outlet's cross sections are selected so as to ensure almost complete expansion of the detonation products and gas flowing through the bypass channel to atmospheric pressure. The calculations showed that the thrust of the ramjet is created during the detonation combustion of hydrogen with about 35% of the air entering the detonation ramjet, while about 65% of the air passes through the bypass channel.

The calculations of the operation process with a change in the Mach number of the approaching flow, all other things being equal, showed that the calculated effective ramjet thrust becomes positive at $M_0 \geq 1.3$, the maximum value of the effective thrust (510 N) is achieved at $M_0 = 2$, and for $M_0 \geq 2.8$ the continuous-detonation operation process is unstable: it breaks down irreversibly without any residual hydrogen combustion.

Experimental Research

Based on the conceptual design of the ramjet obtained by calculation, a mock-up demonstrator with a length of 730 mm with a CC with a diameter of 120 mm, operating on hydrogen, was developed and manufactured. Hydrogen is supplied to the CC from a collector on the outer wall through a belt of equidistant holes with a diameter of 0.8 mm (120 pieces) with a supply pressure less than 3 MPa. To initiate a continuous-detonation operation process, a detonation initiator operating on a hydrogen-oxygen mixture was used.

The test fires of the mock-up demonstrator were carried out in a pulsed WT of the Federal Research Center for Chemical Physics, Russian Academy of Sciences with the Mach number of the approaching air flow ranging from $M_0 = 0.9$ to $M_0 = 2.5$ and normal atmospheric pressure. The mock-up demonstrator was installed on a thrust table along the axis of a supersonic nozzle with a zero angle of attack. With the help of preliminary three-dimensional gas-dynamic calculations, the location of the demonstrator was deter-

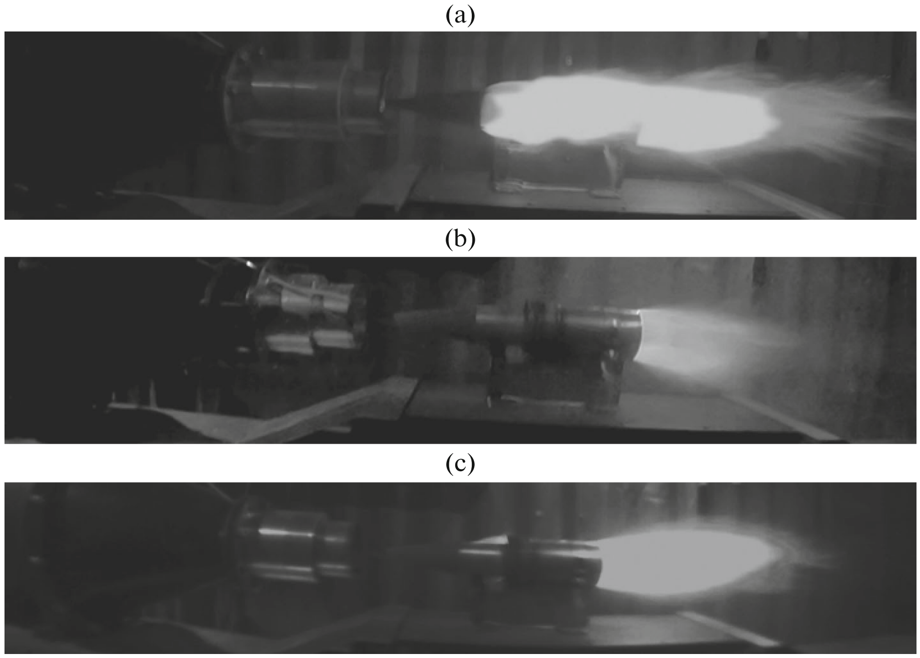

Fig. 2. Video frames of an operation process in a ramjet at $M = 0.9$ (a), 1.5 (b), and 2.0 (c) with the air-to-fuel equivalence ratio α close to 1.0.

mined in relation to the nozzle exit, at which the supersonic air flow around the demonstrator was as close as possible to its unconfined supersonic flow around it. In addition, the calculations of the supersonic air flow around the detonation ramjet demonstrator installed on the thrust table were carried out. The calculated values of the aerodynamic drag force of the detonation ramjet, F_d, in the approaching air flow at $M_0 = 2.0$ and 1.5 were –700 and –450 N, respectively.

The system for measuring the parameters of the operation process in the CC of the detonation ramjet included a low-frequency static pressure sensor and a high-frequency pressure pulsation sensor. In addition, the force acting on the demonstrator was measured by the load cell. The tests also measured the parameters of the test rig: static pressure in the air receiver, in the high-pressure chamber, and at the exit of the supersonic nozzle of the WT.

The results of the test fires confirmed the possibility of organizing stable continuous-detonation combustion of hydrogen in a detonation ramjet of the developed design. In the experiments, the recordings of the pressure pulsation sensor with regular triangular pulsations having a steep front and a constant frequency were obtained, characteristic of continuous-detonation combustion. With a change in the air-to-fuel equivalence ratio (α), the operation process in the CC and its characteristic frequency changed from ~800 to 2000 Hz.

Figure 2 shows the video frames of the operation process in the detonation ramjet at $M_0 = 0.9$, 1.5, and 2.0 with α close to 1.0. When $M_0 = 0.9$, continuous-detonation combustion transitions to the deflagration combustion mode in the flow separation zones in the region of the forward cone of the inlet. When $M_0 = 1.5$, the detonation ramjet worked normally: no signs of off-design operation of the AID were observed. When $M_0 = 2.0$ the AID device of the mock-up demonstrator operated in the off-design mode. Violation of the operation of the AID in test fires at $M_0 = 2.0$ is related to the formation of flow separation zones on the front cone of the detonation ramjet due to the turbulence of the approaching air flow. When $M_0 = 2.5$, the operation process was disrupted due to an increase in the Mach number at the inlet to the CC and its short length. In order for the detonation ramjet of the selected configuration to operate effectively at $M_0 \geq 2.5$, it is necessary to reduce the area of the inlet cross section in the CC, which reduces the flow rate.

In all the test fires, the measured value of the force acting on the mock-up demonstrator was negative. This is due to the high aerodynamic resistance of the model's attachment system on the thrust table (see above). If we exclude the latter from the aerodynamic balance, the effective thrust is positive: ≈200 N at $M_0 = 1.5$ and ≈160 N at $M_0 = 2.0$. The decrease in the effective thrust when $M_0 = 2.0$ is caused by the losses arising from the off-design operation of the AID.

The depletion of the composition of the FAMs with hydrogen to $\alpha > 1.6$ led to the breakdown of continuous-detonation combustion, and the effective thrust of the detonation ramjet remained positive up to $\alpha = 1.5$ at $M_0 = 1.5$ and up to $\alpha = 1.3$ at $M_0 = 2.0$. The maximum measured fuel-based specific impulse was $I_{sp} \approx 1600$ s and was reached at the maximum value of α, at which stable continuous-detonation combustion was observed in the CC of the detonation ramjet engine. The specific impulse for the operating modes of the detonation ramjet on a stoichiometric FAM with the maximum thrust was $I_{sp} \approx 1200–1400$ s.

Thus, we have experimentally proved that the use of continuous-detonation combustion makes it possible to expand the range of stable and efficient operation of the ramjet to the range of flight Mach numbers significantly below 2.0: the start-up Mach number for a hydrogen fueled detonation ramjet can take values at the level of $M_0 = 1.5$ (theoretically, at the level $M_0 = 1.3$).

INCREASE IN A FLIGHT MACH NUMBER

In [9–17], based on the computational and experimental studies, the possibility of expanding the range of the stable and efficient operation of a ramjet to $M_0 \geq 5$ due to the transition from deflagration combustion of hydrogen to continuous-detonation combustion is studied in detail.

Computational Studies

In [9, 10], with the help of multivariate three-dimensional numerical calculations, the conceptual design of a detonation ramjet for an atmospheric flight with the Mach number $M_0 = 5.0$ at an altitude of 20 km (Fig. 3) was developed. The detonation ramjet includes a supersonic AID with a CB and an expanding annular CC. The supersonic air flow decelerates in three oblique shock waves to a certain supersonic speed in the throat of the AID. Gaseous hydrogen is supplied through a belt of radial holes on the outer and/or inner walls of the flow path close to the throat of the AID. The total length of the detonation ramjet, including the AID, was about four CC diameters. The calculations have shown the possibility of stable continuous-detonation combustion of hydrogen in such an detonation ramjet and obtaining a significant positive effective thrust of the power plant with a fuel-based specific impulse up to 2600 s.

In a steady operation process with one DW continuously rotating in the annular gap of the CC, the DW front is strongly inclined towards the approaching air flow. The angle of inclination of the DW front is determined by the Mach number at the inlet to the CC and the Mach number of the DW. The calculation results showed that at $M_0 = 5$ the optimal speed in the throat of the AID, which is the inlet to the CC, is $M_{\text{th. (throat)}} \approx 2.0–2.5$ and depends on the composition of the FAM.

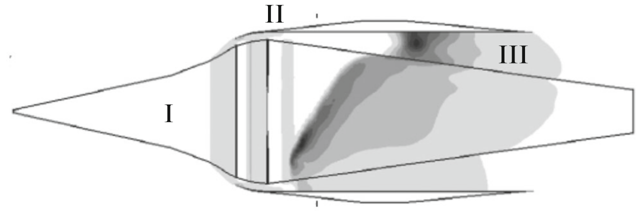

Fig. 3. The conceptual design of a ramjet with a continuous detonation CC for flight conditions with Mach number $M = 5$ at altitude $H = 20$ km: *I*, AID; *II*, throat of AID; *III*, CC.

Experimental Research

For the experimental verification of the results obtained, we have developed and manufactured a mock-up demonstrator of a detonation ramjet with a CC with a diameter of 310 mm and a length of 1050 mm, corresponding to the conceptual design in Fig. 3. The diameter of the front edge of the cowl of the AID is 284 mm. Hydrogen is supplied to the CC through an annular belt of 200 uniformly distributed radial holes 0.8 mm in diameter located on the CB at a distance of 10 mm downstream from the throat of the AID. To control detonation combustion in the mock-up demonstrator, the possibility of throttling the flow in the outlet section of the CC is provided by a connection to the CB of flat throttle discs with a diameter of 200, 220, and 240 mm with the sharp edges overlapping the section of the annular gap of the CC by 30%, 40%, and 50%, respectively.

The mock-up demonstrator was tested in the WTs, Transit-M and AT-303, of the Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences (ITAM SB RAS). Two series of test fires were carried out. The first series was performed in WT Transit-M with the Mach numbers of the approaching air flow ranging from $M_0 = 4$ to $M_0 = 8$ and stagnation air temperature $T_0 = 300$ K [11–13]. The second series was carried out in WT, AT-303, at the Mach number $M_0 = 5.7$ and the actual stagnation temperature of air flow $T_0 = 1500$ K [14–17] (stagnation pressure $R_0 = 1.6$ MPa).

It should be noted that in all test fires for the successful initiation of detonation of FAMs, it was required to use throttle discs. However, in contrast to the first series of experiments, in which it was necessary to use external ignition using a hydrogen-oxygen detonator, in the second series of test fires detonation was initiated spontaneously, without a detonator.

Depending on the Mach number of the approaching air flow and the composition of the FAMs, two types of operation process were recorded in the experiments: with continuous spinning detonation (CSD) and with longitudinally pulsating detonation (LPD) of hydrogen, the limiting mode of continuous-detonation combustion [18]. Figure 4 shows examples of the

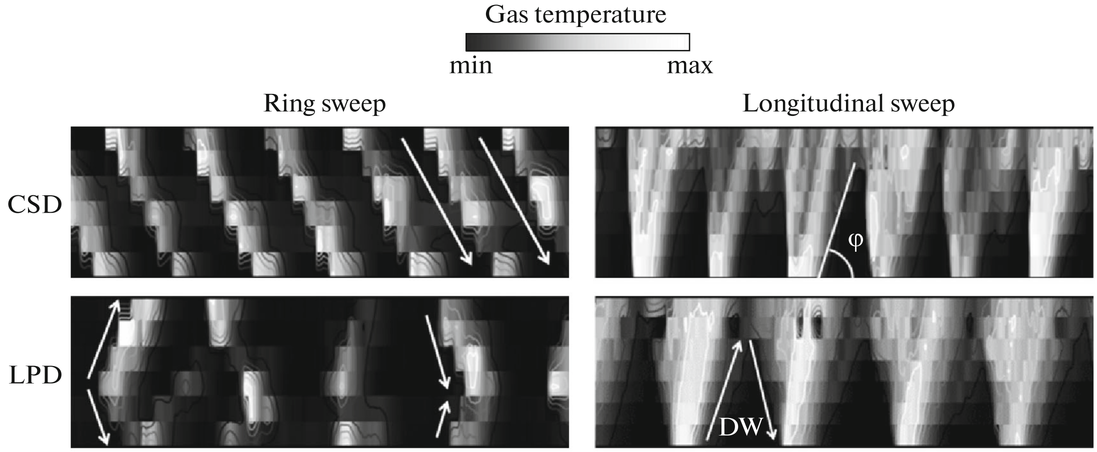

Fig. 4. Examples of visualization of the operation process with the CSD and LPD of hydrogen in the form of annular and longitudinal scans of ionization probe records.

visualization of these modes in the form of longitudinal and ring time sweeps of the recordings of ionization probes installed in the CC. The CSD mode is characterized by a constant speed of rotation of the DW in the annular gap of the CC, which is visible on the ring sweep in the form of light lines with a constant angle of inclination. The frequency of rotation of the DW in Fig. 4 is ≈1250 Hz, which corresponds to the apparent velocity of DW propagation in the tangential direction ≈1200 m/s. The corresponding longitudinal scanning of the signals shows that the DW length is close to 200 mm. By calculating the time difference between the signals on the last and the first (downstream) ionization probes located along the axis of the CC, it is possible to estimate the angle of inclination of the DW to the axis of the CC and to estimate the normal velocity of propagation of the DW during CSD: 1500–1700 m/s. Angle φ (see Fig. 4) can be used to estimate the velocity of the new mixture ahead of the DW front: 550–750 m/s, which corresponds to the local Mach number M = 1.5–2.0. The DW's shape and velocity calculated based on the experimental data are in good agreement with the data obtained using multidimensional numerical calculations.

The operation process with the LPD on the ring sweep of the signals of the ionization probes is recorded in the form of light bands with pronounced kinks: the leading points corresponding to the advance arrival of the DW to one of the probes from the side of the outlet section of the CC. In this case, the bands extending in both directions from the leading point correspond to the propagation of the DW along the CC's circumference at a speed of about 1800 m/s. The characteristic frequency of the operation process in the LPD mode is 900 Hz. From the longitudinal sweep of the signals for such a mode, it can be concluded that the periodic reinitiation of detonation occurs in the new mixture at a distance of 200 to 250 mm from the throat of the AID, and the generated DW propagates upstream with an apparent velocity of about 1000 m/s; i.e., the detonation velocity is 1550–1750 m/s. Records of the total and static pressure sensors installed in the throat of the AID, and the video recording of the flow in the area of the AID, including using shadow devices, showed that there were no violations of the flow at the entrance to the AID of the detonation ramjet.

Figure 5 shows the experimental dependences of the fuel-based specific impulse on the hydrogen consumption. These dependences are obtained from the values of the measured thrust of the detonation ramjet and the measured hydrogen consumption. The data processing showed that for all velocities of the approaching air flow, the specific impulse increases with a decrease in the hydrogen flow rate and reaches its maximum value at its minimum flow rate at which detonation combustion in the CC was still registered. The specific impulse for FAMs with a near-stoichiometric composition was 2400–2800 s, which is in good agreement with the results of a three-dimensional numerical calculation (2600 s). The maximum specific impulse values were obtained for modes with the Mach number $M_0 = 5$ and 6. For $M_0 = 8$ the maximum specific impulse is lower by 200–300 s due to the decrease in pressure in the CC.

The main difference between the second series of test fires and the first is the use of an approaching supersonic air flow with a real stagnation temperature, i.e., modeling the conditions of an atmospheric flight of an AC with a detonation ramjet. The increase in the stagnation temperature led to a more stable operation process with CSD, and the characteristic frequency of rotation of the DW increased to 1300 Hz. An increase in the air-to-fuel equivalence ratio to $\alpha = 1.4$ led to the disruption of the operation process with CSD: an

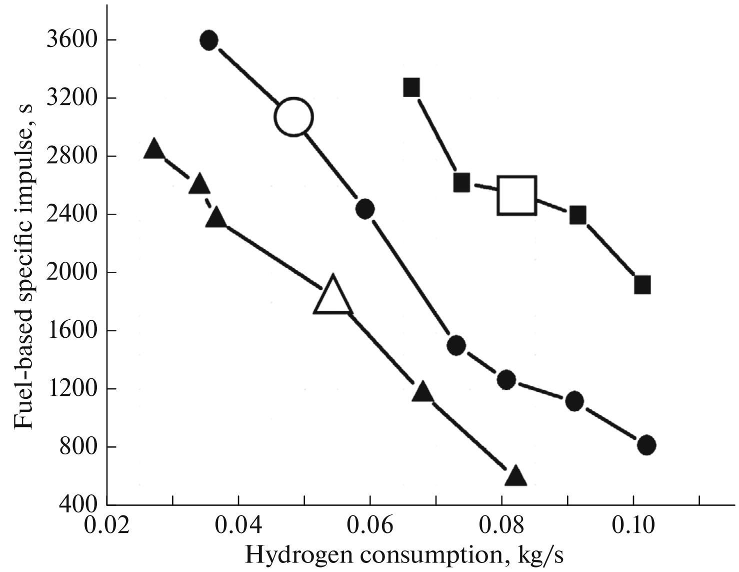

Fig. 5. Experimental dependences of fuel-based specific impulse on hydrogen consumption for $M = 5$ (■), 6 (●), and 8 (▲). Light points correspond to combustion modes with the air-to-fuel equivalence ratio α close to 1.0.

operation process with LPD was observed. A further increase in α to 1.6 led to the breakdown of detonation combustion in the CC. The results of measurements of the thrust of the detonation ramjet showed a decrease in the measured fuel-based specific impulse by ~200 s in comparison with experiments with a cold flow. At $\alpha = 1.2$, the fuel-based specific impulse was 3300 s.

Thus, we have experimentally proved that the use of continuous-detonation combustion makes it possible to expand the range of stable and effective operation of the ramjet to the range of a flight Mach numbers that are significantly higher than 5.0 due to the transition from the deflagration mode of hydrogen combustion to the continuous-detonation mode.

CONCLUSIONS

The computational and experimental work carried out at the Federal Research Center for Chemical Physics, Russian Academy of Sciences proved that the use of continuous-detonation combustion makes it possible to expand the range of stable and efficient operation of the ramjet to the range of the flight Mach numbers significantly below 2.0 (up to 1.3–1.5) and significantly above 5.0 (at least up to $M_0 = 8$) due to the transition from the deflagration mode of hydrogen combustion to a more energy efficient continuous-detonation mode. In fact, these works laid the foundations for designing a ramjet of a new type that is the detonation ramjet.

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