WIND TUNNEL TESTS OF A HYDROGEN-FUELED DETONATION RAMJET MODEL AT APPROACH AIR STREAM MACH NUMBERS FROM 4 TO 8

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Abstract. Experimental studies of an axisymmetric hydrogen-fueled detonation ramjet model 1.05-meter 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 stagnation temperature of 293 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 are 3600 s and 2200 N.

Keywords: air-breathing detonation propulsion, supersonic airflow, ramjet, hydrogen, specific impulse, thrust, wind tunnel

Introduction

The use of detonation 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 was recently proved experimentally in [2–4]. The most promising schemes for the organization of detonation combustion in the flow include schemes with pulse detonation in tubes and tube bundles [5, 6] and continuous spin detonation (CSD) in annual combustors [7–9]. References [5–9] contain information on various aspects of continuous- and pulse-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 elsewhere [7–15] in annular combustors of different scale and design. Various modes of self-sustained detonative combustion are reported including modes with one and several DW(s) simultaneously rotating in the combustor annulus in the same or opposite circumferential directions, as well as the longitudinal pulse-detonation (LPD) mode arising at certain limiting conditions of hydrogen and air supply. In the LPD mode, the detonation is reinitiated in a position close to the combustor outlet and propagates upstream as a supersonic reaction front occupying the entire cross section of the combustor without regular rotation [11, 13].

The possibility of organizing the CSD of hydrogen in a ramjet was studied theoretically in [16–18] and experimentally in [19, 20]. Three-dimensional calculations in [17] proved the possibility of the realization of the CSD in the supersonic flow of the premixed hydrogen–air mixture in a ramjet combustor under conditions corresponding to the flight with the Mach number M = 4. Three-dimensional calculations in [18] proved the possibility of realizing the CSD in the hydrogen-fueled axisymmetric ramjet with an annular combustor at atmospheric flight at the altitude of 20 km with a Mach number M = 5 with hydrogen injection into the annular combustor through the circumferential slit in the central body. In [19], the results of successful experimental studies of the CSD of a hydrogen – air mixture in an annular combustor with an attached air conduit are reported for conditions simulating a supersonic flight with Mach number M = 4. Reported in [20] are the results of experimental investigations of the detonation combustion of hydrogen in a demonstrator of ramjet in a pulse wind tunnel at the approaching air stream Mach number ranging from 4 to 8. Two modes of detonation combustion of hydrogen were obtained, namely the CSD and the LPD mode.

The objective of this work is to study experimentally the detonation combustion of hydrogen in a detonation ramjet model of scheme suggested in [18, 20] under conditions of airflow with a Mach number from 4 to 8 in a pulsed wind tunnel of ITAM SB RAS "Transit-M".

Experimental setup and data acquisition system

Pulsed wind tunnel "Transit-M" [21] is designed for aerodynamic tests in the range of Mach numbers from 4 to 8 at elevated values of Reynolds number. The base of the wind tunnel is the prechamber, the source of the working gas which determines the characteristics of the operation mode. Before the experiment, the initial mass of the working gas is accumulated simultaneously in the main prechamber and in additional tanks yielding in total 0.11 m^3 of compressed gas under a pressure of up to 200 atm. The main prechamber is equipped with a fast-response non-destructible shutter that blocks the gas outlet into the auxiliary prechamber and an axisymmetric supersonic nozzle. After the shutter opens, the compressed gas flows into the prechamber where the total pressure decreases and the flow is getting more uniform across section 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 from 4 to 8 is created, which 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. Gas from the test section flows into the vacuum tank through a diffuser, a cylindrical tube with a diameter of 400 mm. 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 on the basis of the results of calculations in [18]. The detonation ramjet model includes an air intake with a central body that ensures the 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 ~ 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 ~ 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 to the 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.

To control detonation combustion in the detonation ramjet model, a provision is made for throttling the flow in the outlet section of the combustor by connecting flat throttle discs 5 mm thick and 200, 220 and 240 mm in diameter (hereinafter D200, D220 and D240) with rounded edges to the central body. These discs block the cross section of the annular gap of the combustor by 30%, 40% and 50%, respectively. Hydrogen is fed to the combustor through an annular belt of 200 uniformly distributed radial holes 0.8 mm in diameter located on the central body 10 mm downstream from the conditional critical section of the intake. Hydrogen is supplied from a receiver with a volume of 0.08 m^3 along a manifold equipped with a high-speed pneumatic valve.

Preliminary three-dimensional calculations of cold flow in the flow path of the wind tunnel with installed detonation ramjet model showed that for the successful starting of the operation process in the model the latter should be installed in such a way that the distance between the nozzle edge and the leading edge of the outer cowl of the model intake exceeds 70 mm. Figure 1 shows the schematic and photograph of the flow path of the wind tunnel with the installed detonation ramjet model as well as the calculated distribution of the local Mach number in the cold flow (without combustion) with the approach stream Mach number M = 5. Also shown in Fig. 1 are the main elements of the installation, namely, the prechamber (1), an axisymmetric supersonic nozzle (2), test section (3), diffuser (4), intake (5) and combustor (6) of the detonation ramjet model.

The data acquisition system for recording the parameters of the operation process in the installation includes ionization probes, low-frequency (~1 kHz) static and total pressure sensors at the combustor inlet and outlet, strain gauges for thrust

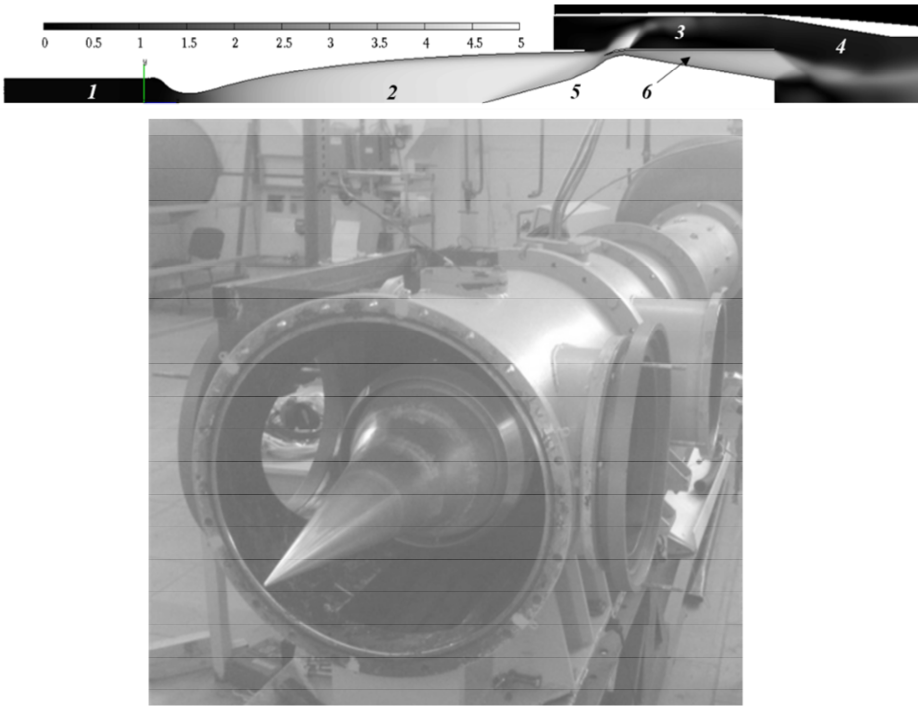
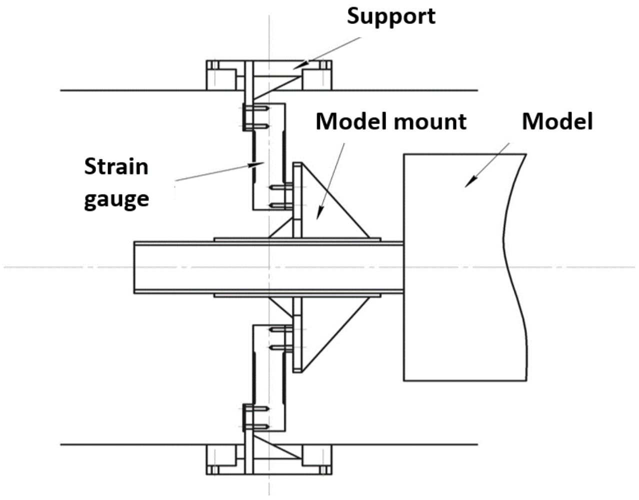


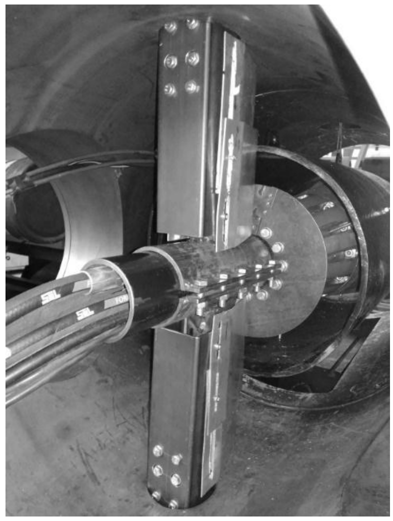
Fig. 1. Top: The flow path of the wind tunnel with the installed detonation ramjet model and with the calculated distribution of the local flow Mach number for cold flow conditions at the approach air stream Mach number of 5. Bottom: The photograph of the detonation ramjet model installed in the wind tunnel.

measurements, and high-speed digital video cameras. Registration of combustion and detonation processes by ionization probes was tested earlier and showed high efficiency [20, 22]. Twelve ionization probes are installed in the central body of the combustor: 6 probes are placed evenly around the circumference at a distance of 40 mm downstream from the hydrogen supply belt, and 7 probes (1 probe is common with the probes located in a circumferential direction) are placed evenly along the generatrix of the central body with a pitch of 30 mm. Such a measuring system makes it possible to identify the mode of detonative combustion (CSD or LPD) and to measure the characteristic frequency of the operation process, as well as the velocity and direction of DW propagation.

Static and total pressure are measured at the edge of the supersonic nozzle of the wind tunnel, in the prechamber, in the vacuum tank, in the hydrogen receiver, in the hydrogen supply manifold, at the edge of the intake cowl, as well as at the combustor inlet and outlet.



(a)



(b)

Fig. 2. Arrangement of strain gauges in the tail part of the detonation ramjet model for thrust measurements.

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 Fig. 2. Prior to the tests in the wind tunnel, the thrust measurement system was calibrated using a calibrated load cell M50 with a maximum load of 5000 N was used. 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).

To initiate the operation process in the combustor, a specially developed hydrogen-oxygen detonator is used. 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 of the detonation ramjet model at a distance of 150 mm downstream from the conditional critical section of the intake. The time of triggering the detonator is synchronized with the opening of the fast-response shutter of the wind tunnel and with 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 this interval. After this interval, the pressure in the vacuum tank increases noticeably, which leads to a violation of the design flow in the supersonic nozzle of the wind tunnel.

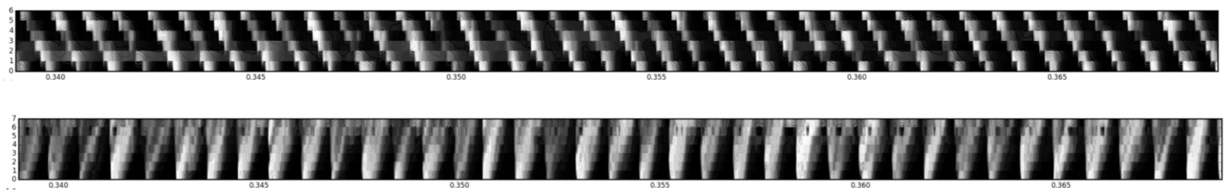
Experimental results

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 types of the operation process were recorded in the experiments reported herein: with CSD and LPD of hydrogen. Table 1 shows the parameters of the experiments: the Mach number (M), the stagnation pressure (P_0) and stagnation temperature (T_0), as well as the static pressure (P_{st}) and the static temperature (T_{st}) of the approaching air stream, the estimated value of the mass flow rate of air through the flow path of the model (G_A), mass flow rate of hydrogen (G_{H2}) and the type of the throttle disk installed at the combustor outlet. The value of the mass flow rate of air through the flow path of the model was estimated on the basis of three-dimensional gas-dynamic calculations (see Fig. 1).

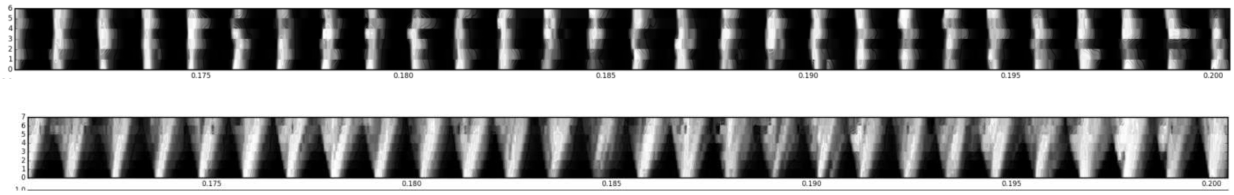
Figure 3 presents the "visualization" of the records of ionization probes over a short time interval for two typical experiments: one with the CSD mode (Fig. 3a) and another for LPD mode (Fig. 3b). The records of ionization probes were “visualized” according to the procedure of [22]. The records in the top frames are obtained by processing the signals of probes mounted along the circumference of the central body. The records in the bottom frames correspond to the signals of probes installed along the generatrix of the central body. White and black colors in these records correspond to the largest and smallest values of the measured conductivity current in the medium (the conductivity current is maximal in hot detonation products). In the case of CSD, characteristic light bands of the same 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. 3a is close to 1250 Hz, which gives the apparent propagation velocity of the DW in the tangential direction of about 1200 m/s.

Table 1. Parameters of experiments

M	P_0, atm	T_0, K	P_{st}, kPa	T_{st}, K	G_A, kg/s	G_{H2}, kg/s	Throt. disc	Operation process
4	8	290	5,2	71	4,8	0,12	D200/D220	CSD
5	20-24		4,5	50	7-8	0,06-0,2	0/D200 /D220	CSD/LPD
6	30-35		2,2	37	7	0,12-0,2	D200/D220	CSD/LPD
8	54		0,6	22	5	0,05-0,17	D220/D240	LPD



(a)



(b)

Fig. 3. Visualization of the records of ionization probes in the circumferential (top) and longitudinal (bottom) lines for the CSD (a) and LPD (b) modes of hydrogen combustion in the detonation ramjet model.

The corresponding signals of the probes installed along the generatrix of the central body (the bottom frame in Fig. 3a) indicates that the height of the DW is close to 200 mm. Calculating the time difference between the signals at the last and first (downstream) ionization probes along the generatrix of the central body, one can readily estimate the angle of inclination of the DW to the combustor axis and determine the approximate value of the absolute normal propagation velocity of the DW for the CSD: 1500–1700 m/s. From the value of white-band inclination angle in the bottom frame of Fig. 3a it is possible to estimate the filling rate of the combustor by a fresh mixture in the near-wall region ahead of the detonation front: 550–750 m/s, which corresponds to the local Mach number of 1.5–2.0.

The operation process with LPD is visualized in the top frame of Fig. 3b in the form of light bands with pronounced fractures. These fractures correspond to the advancing arrivals of DWs at a particular ionization probe from the side of the outlet section of the combustor. The characteristic frequency of the operation process in the LPD mode is ~900 Hz. Examination of the records of ionization probes installed along the generatrix of the central body for such a regime indicates that the periodic re-initiation of detonation takes place in the fresh mixture at a distance of 200–250 mm from the conditional critical section of the air intake, and the generated DW propagates upstream with an apparent velocity of about 1000 m/s, i.e. the absolute normal detonation velocity is 1550–1750 m/s.

When analyzing the experimental results in terms of the thrust produced by the detonation ramjet model, we plotted 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. 4 for the experiment with M = 8, G_{H2} = 0.023 kg/s and throttle disk D220. It is seen from Fig. 4 that the initial (before 0.18 c) 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 8.

Using the data like those depicted in Fig. 4 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:

$$I_{SP} = \frac{\int_{t=0s}^{t=1s} F_{hot}(t)dt - \int_{t=0s}^{t=1s} F_{cold}(t)dt}{m_{H_2}} \quad (1)$$

where m_{H_2} is the mass flow rate of hydrogen (the mass of hydrogen consumed in a "hot" test during 1-second interval), and $F_{hot}(t)$ and $F_{cold}(t)$ are the instantaneous cumulative thrust values in "hot" and "cold" tests, taken from the cumulative thrust

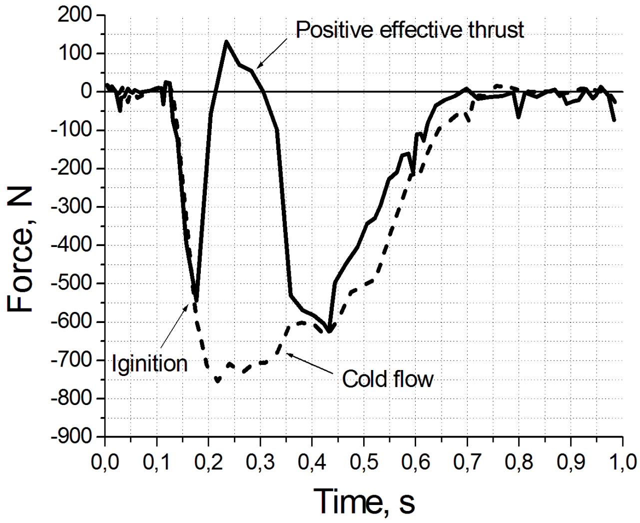


Fig. 4. The cumulative thrust curve for cold and hot flow for the experiment with M = 8, G_{H2} = 0.023 kg/s and throttle disk D220.

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 I_{SP} defined by Eq. (1) one can evaluate the total thrust produced by the detonation ramjet model as:

$$\overline{F} = I_{SP} m_{H_2} \quad (2)$$

Figures 5 and 6 show the dependences of the fuel-based specific impulse and thrust on the mass flow rate of hydrogen supplied to the combustor. 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.

Conclusions

We have demonstrated experimentally the possibility of organizing a stable detonation combustion of hydrogen in a supersonic air flow using an axisymmetric detonation ramjet model under conditions of approaching air stream Mach number ranging from 4 to 8 in a pulsed wind tunnel at a stagnation temperature of 290 K.

Two detonation modes in the ramjet model, CSD and LPD, are obtained in the experiments. In the first, continuous rotation mode, a single detonation wave is rotating in the combustor annulus in the tangential direction with the apparent

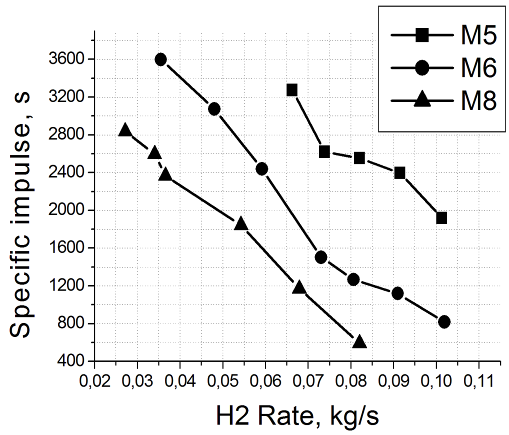


Fig. 5. Dependences of the fuel based specific impulse on the mass flow rate of hydrogen for M = 5, 6 and 8.

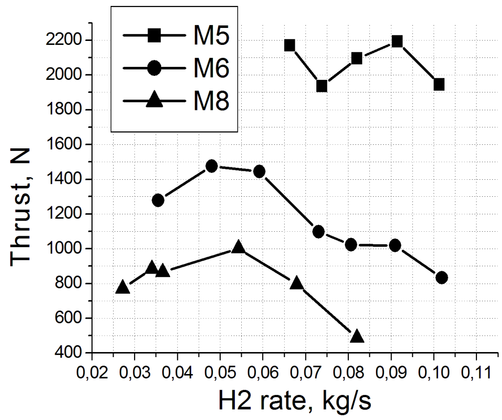


Fig. 6. The total thrust of the detonation ramjet model vs. mass flow rate of hydrogen in "hot" experiments with M = 5, 6 and 8.

velocity of ~1200 m/s giving the rotation frequency of 1250 Hz and the absolute normal detonation velocity of 1500–1700 m/s. In the second, pulsating mode, one or several detonation waves are spontaneously reinitiated in the rear part of the combustor and propagate upstream towards the hydrogen supply holes at the apparent velocity of ~1000 m/s giving the longitudinal pulsation frequency of 900 Hz and the absolute normal detonation velocity of 1550–1750 m/s.

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 thrust measuring system is considerably larger than the calculated aerodynamic drag of the model without regard for mechanical support and thrust measuring system. The maximum measured values of fuel-based specific impulse and total thrust are 3600 s and 2200 N.

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