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Continuous Detonation Combustion of Hydrogen: Results of Wind Tunnel Experiments

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Abstract: Combustion tests of a ramjet model 1.05 m long and 0.31 m in diameter with an expanding annular combustor operating in the regime of detonation combustion of hydrogen are described. The tests are performed in a short-duration wind tunnel at free-stream Mach numbers of the incoming air flow from 5 to 8 and stagnation temperature of 290 K. Continuous detonation and longitudinally pulsating regimes of hydrogen combustion with characteristic frequencies of 1250 and 900 Hz, respectively, are observed. The maximum measured values of the fuel-based specific impulse and the thrust generated by the engine are 3600 s and 2200 N, respectively.

Keywords: ramjet, supersonic flow, detonation, hydrogen, specific impulse, thrust, wind tunnel.

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INTRODUCTION

Detonation combustion of fuel–air mixtures is considered as an alternative aspect in the development of advanced propulsion systems for high-velocity aerospace vehicles. The question about the energy efficiency of detonation engines was first formulated by Zel'dovich [1], and then this idea was proved experimentally [2–4]. Today the most promising schemes of detonation combustion in the flow are assumed to be those with pulse detonation in tubes and bunches of tubes [5, 6] and also schemes with continuous spin detonation in annular combustors [7–9]. Information about various aspects of engines with continuous and pulse detonation combustion operating on air, air enriched with oxygen, or oxygen as an oxidizer and various fuels (mostly, hydrogen) can be found in [5–9]. Continuous detonation combustion of hydrogen–air mixtures in annular combustors with versatile sizes and structures was experimentally studied in [7–15]. Various regimes of self-sustained detonation combustion including regimes with one or several detonation waves simultaneously rotating in the annular gap of the combustor in the same or opposite directions and also close-to-limiting regime of longitudinally pulsating detonation arising under certain conditions for the air and hydrogen flow rates were reported. In the last regime, detonation is spontaneously periodically re-initiated near the combustor exit and propagates upstream in the form of a supersonic reaction front, which covers the entire combustor cross section without regular rotation [11, 13].

The possibility of organizing continuous spin detonation of hydrogen in a ramjet engine was studied theoretically in [16–18] and experimentally in [19, 20]. Three-dimensional calculations [17] proved the possibility of its realization in a supersonic flow of a stoichiometric homogeneous hydrogen–air mixture in an annular combustor under conditions corresponding to flight

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at the Mach number M = 4. Other three-dimensional calculations [18] proved the possibility of continuous spin detonation in an axisymmetric ramjet in atmospheric flight at an altitude of 20 km at the Mach number M = 5 with separate injection of hydrogen into the annular combustor through a circular slot in the central body. Results of successful experimental investigations of continuous spin detonation of a hydrogen–air mixture in an annular combustor with an attached pipeline under conditions modeling supersonic flight at M = 4 were reported in [19]. Results of experimental investigations of detonation combustion of hydrogen in an axisymmetric model of a detonation ramjet tested in a short-duration wind tunnel at the incoming air flow Mach numbers M = 4–8 were described in [20]. Two regimes of detonation combustion of hydrogen were detected: continuous spin detonation and longitudinally pulsating detonation.

The goal of the present study is to continue the experimental investigations started in [20] with a detonation engine model in order to measure the thrust and to estimate the specific impulse.

EXPERIMENTAL SETUP AND DATA ACQUISITION SYSTEM

The Transit-M short-duration wind tunnel is designed for aerodynamic tests in the range of Mach numbers M = 4–8 at elevated Reynolds numbers [21]. The basis of the wind tunnel is the settling chamber, which serves as a source of the test gas and determines the characteristics of wind tunnel operation. The initial mass of the test gas before the experiment is accumulated simultaneously in the main chamber and in additional vessels, which yields a total of 0.11 m^3 of the gas compressed up to 200 atm. The main settling chamber contains an undestroyable fast-response valve preventing gas overflow into the auxiliary settling chamber and the axisymmetric supersonic nozzle. When the valve is opened, the compressed gas passes to the settling chamber where the total pressure decreases and the flow becomes more uniform before it enters the nozzle. The wind tunnel design includes replaceable contoured nozzles with the nozzle exit diameter of 300 mm. These nozzles generate a uniform gas flow with the Mach number ranging from 4 to 8, which impinges onto the model mounted in the wind tunnel test section. The test section is shaped as an axisymmetric Eiffel chamber and consists of two sections with optical windows for flow visualization. The gas from the test section exhausts into a vacuum tank through a diffuser, which is a cylindrical tube 400 mm in diameter. The total length of the wind tunnel including the exhaust diffuser is 7600 mm;

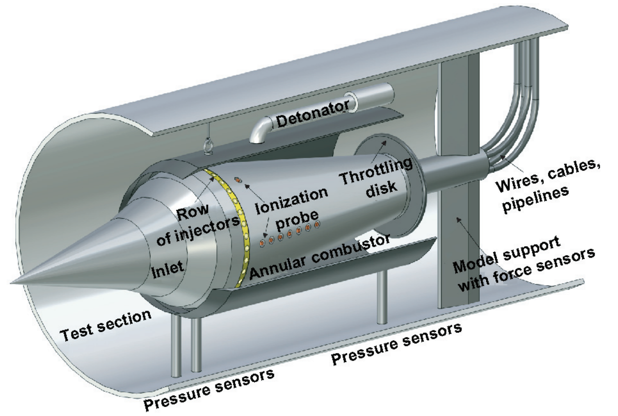

Fig. 1. Detonation ramjet model mounted in the wind tunnel.

the width and height of the wind tunnel are 870 and 1470 mm, respectively.

The detonation ramjet design is based on calculations performed by the method developed in [9] (Fig. 1). The model includes an inlet with the central body, which ensures deceleration of the impinging supersonic air flow with the Mach number M $\approx$ 5 in three oblique shocks to a supersonic flow with the maximum Mach number M$\approx$ 2.5 in the conventional inlet throat and an expanding annular combustor where the air flow is accelerated up to M $\approx$ 4. The diameter of the leading edge of the inlet cowl lip is 284 mm. This size ensures a design flow at the combustor entrance, which is unaffected by the boundary layer formed on the nozzle walls. The outer diameter of the combustor is 310 mm. The total length of the model is 1050 mm.

To ensure detonation combustion, the model implies a possibility of flow throttling in the combustor exit cross section by means of adding flat throttling disks 5 mm thick and 200, 220, or 240 mm in diameter (in what follows, D200, D220, and D240) with rounded edges to the central body; these disks cover the cross section of the annular gap of the combustor by 30, 40, and 50%, respectively (see Fig. 1). Hydrogen is injected into the combustor through an annular row of 200 uniformly distributed radial injectors 0.8 mm in diameter, which is located on the central body at a distance of 10 mm downstream from the conventional inlet throat, from a receiver with a volume of 0.08 m^3 through a pipeline with a fast-response pneumatic valve.

As was shown by preliminary three-dimensional calculations of the cold flow around the model mounted in the wind tunnel duct, to ensure starting and stable operation of the setup, the detonation ramjet model should be mounted in such a way that the distance between the nozzle exit and the leading edge of the inlet cowl lip of the model should be 70 mm or more.

The data acquisition system of the working process in the combustor includes ionization probes, static or total pressure sensors at the combustor entrance, and also static and total pressure sensors at the combustor exit. Detection of fast processes of combustion and detonation by ionization probes was tested earlier and demonstrated high efficiency [20, 22]. The ionization probe designed for measuring the conduction current in hot combustion products is placed in the combustor so that the distance between the thin uninsulated end of the probe and the combustor wall should be approximately 1 mm. Twelve ionization probes are mounted in the central body of the combustor: six probes are uniformly distributed over the circumference at a distance of 40 mm downstream from the row of hydrogen injectors, and seven probes (one of them is simultaneously one of the probes on the circumference) are uniformly distributed in the streamwise direction along the generatrix of the central body with a step of 30 mm. Such a system for data acquisition allows one to identify the regime of detonation combustion in the combustor (continuous spin or longitudinally pulsating detonation) and to measure the characteristic frequency of the working process, as well as the velocity and direction of detonation wave (DW) propagation.

In addition to the above-mentioned flow parameters, we also measure the static and total pressures at the exit of the supersonic nozzle of the wind tunnel, in the settling chamber, in the vacuum tank, in the hydrogen receiver, in the manifold for hydrogen injection, on the leading edge of the inlet cowl lip, and at the combustor entrance and exit (see Fig. 1).

The thrust force is measured by two strain-gauge sensors (T40A) with the maximum load of 2000 N each. The strain-gauge sensors are mounted behind the detonation ramjet model, as is shown in Figs. 1 and 2. Before the tests proper, the thrust measurement system is calibrated with the use of a calibrated M50 sensor with the maximum load of 5000 N. The calibration is performed by static loads ranging from −2000 to +1000 N (the positive values correspond to the load direction opposite to that of the incoming air flow).

The working process in the combustor is initiated by a specially developed hydrogen–oxygen detonator (see Fig. 1), which is an ignition chamber 20 mm in diameter and 30 mm long with an attached detonation tube 10 mm in diameter and 200 mm long. The mixture is ignited by a standard car plug. The detonator is mounted on the outer wall of the combustor at a distance of 150 mm downstream from the conventional inlet throat. Hydrogen and oxygen are injected into the combustor through tubes 4 mm in diameter. After detonation initiation, the detonation tube is first filled by the hydrogen–oxygen mixture within ≈200 ms; after that, the mixture is ignited, a deflagration-to-detonation transition occurs in the tube, and the resultant DW enters the annular gap of the combustor of the detonation ramjet model. As is seen from the recorded signals of the ionization probes, the time of the action of the detonation pulse generated by the detonator on the working process in the combustor does not exceed ≈10 ms. The time of detonator initiation is synchronized with opening of the fast-response valve of the wind tunnel and of the valve of hydrogen injection into the combustor. The process in the combustor is initiated when the air and hydrogen flow rates prescribed by the test program are reached. Hydrogen is injected into the combustor for 150 ms: this is the time period during which the working process is studied. After that, a noticeable increase in pressure in the vacuum tank is observed, resulting in distortions of the design flow in the supersonic nozzle of the wind tunnel. It should be noted that detonation combustion in the model could not be provided without the throttling disks. In fact, the throttling disk can be removed after the beginning of detonation combustion, but this was not done in the experiments described below.

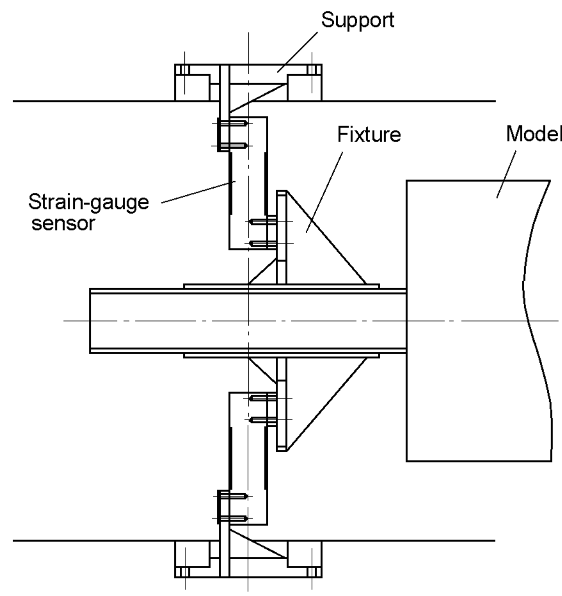

Fig. 2. System for measuring the thrust force generated by the detonation ramjet model.

EXPERIMENTAL RESULTS

Depending on the free-stream Mach number, composition of the hydrogen–air mixture, and throttling

Test conditions

M_∞	p_0, atm	p_{st}, kPa	T_{st}, K	G_a, kg/s	$G_{a,m}$, kg/s	G_{H_2}, kg/s	Throttling disk	Regime
5	17–24	4.5	50	11–16	6–8	0.06–0.2	0/D200/D220	CSD/LPD
6	30–35	2.2	37	9–10	6–7	0.03–0.2	D200/D220	CSD/LPD
8	40–54	0.6	22	3.7–5	3.3–4.5	0.02–0.17	D220/D240	LPD

Here CSD and LPD stand for continuous spin detonation and longitudinally pulsating detonation, respectively.

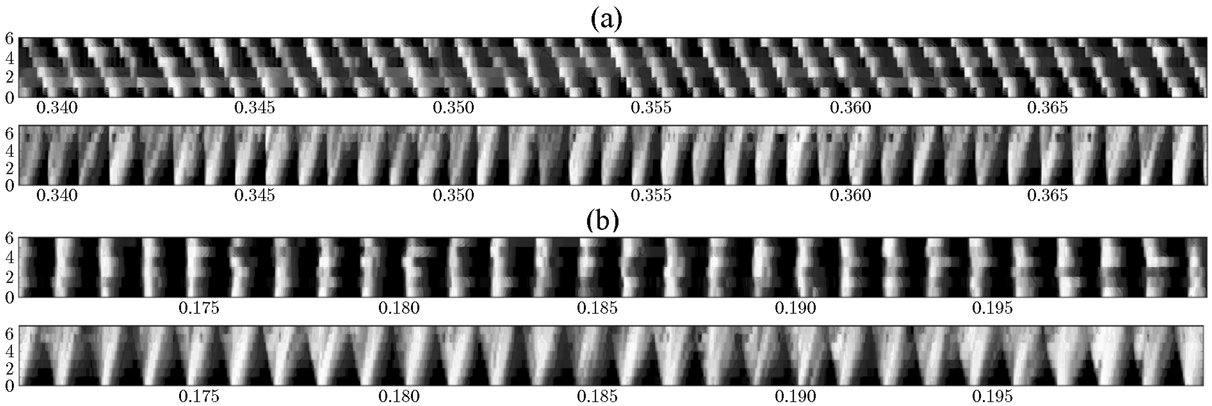

Fig. 3. Examples of "visualization" of signals recorded by the ionization probes in experiments with continuous spin detonation (a) and longitudinally pulsating detonation (b) regimes.

disk type, two regimes of hydrogen combustion were detected in combustion tests of the detonation ramjet model: continuous spin detonation (CSD) and longitudinally pulsating detonation (LPD). The experimental parameters are summarized in the table: free-stream Mach number (M_∞), stagnation pressure (p_0), static pressure (p_{st}), static temperature (T_{st}) of the incoming air flow, total mass flow rate of air through the wind tunnel duct (G_a), design value of the mass flow rate of air through the detonation ramjet model ($G_{a,m}$), mass flow rate of hydrogen (G_{H_2}), and type of the throttling disk mounted at the combustor exit. The flow rate $G_{a,m}$ was estimated on the basis of three-dimensional gas-dynamic calculations. According to these estimates, approximately 90% of the air flow at $M_\infty = 8$ passed through the model inlet.

Figure 3 shows an example of "visualization" of the signals recorded by the ionization probes within a short time period in two typical experiments: one in the CSD regime (Fig. 3a), and the other in the LPD regime (Fig. 3b). The signals recorded by the ionization probes are "visualized" in accordance with the procedure described in [22]. The upper "frames" are obtained by means of processing the signals of the probes mounted over the circumference of the central body, and the lower "frames" are those from the probes mounted along the generatrix of the central body. The white and black colors in these "frames" correspond to the maximum and minimum values of the measured conduction current in the medium, which are reached in hot detonation products and in the cold gas, respectively. In the case of continuous spin detonation, the upper "frame" shows regular light bands with an identical slope, which testifies to continuous DW propagation in one tangential direction with a constant visible velocity. The characteristic frequency of the inclined bands in the upper "frame" in Fig. 3a is close to 1250 Hz, which yields the visible velocity of DW propagation in the tangential direction approximately equal to 1200 m/s.

The analysis of the signals recorded by the probes mounted along the generatrix of the central body (lower "frame" in Fig. 3a) shows that the DW height is close to 200 mm. Calculating the time interval between the signal arrival at the last and first ionization probes mounted along the generatrix of the central body, one can estimate the angle of DW inclination with respect to the combustor axis and approximately determine the absolute velocity of DW propagation along the normal to the front: 1500–1700 m/s. Based on the slope of the rear front of the flame in the lower "frame" in Fig. 3a, one can estimate the velocity of the fresh mixture entering the combustor 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.

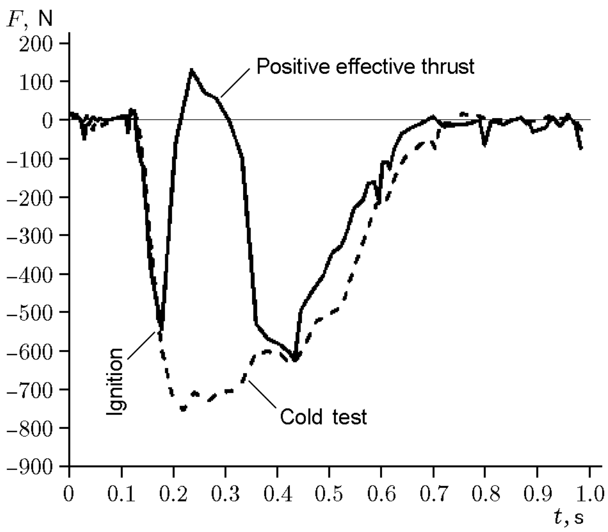

Fig. 4. Measured instantaneous force acting on the model versus time in the "hot" test (G_{H_2} = 0.034 kg/s; solid curve) and "cold" test (G_{H_2} = 0.023 kg/s; dashed curve) at M = 8 with the D220 throttling disk.

The working process with longitudinally pulsating detonation is illustrated in the upper "frame" of Fig. 3b in the form of light bands with clearly seen inflections. These inflections correspond to the advancing arrival of the DW at a particular ionization probe from the side of the combustor exit cross section. The characteristic frequency of the process in this regime is ≈900 Hz. The analysis of the signals recorded by the ionization probes mounted along the central body generatrix shows that periodic re-initiation of detonation occurs in the fresh mixture at a distance of 200–250 mm from the conventional inlet cross section, whereas the generated DW propagates upstream with a visible velocity of about 1000 m/s, i.e., the normal detonation velocity is 1550–1750 m/s.

To analyze the experimental results on the thrust force generated by the detonation ramjet model, we construct two plots on one figure: instantaneous force acting on the model in the "hot" test (with hydrogen combustion) and the force acting on the model in the "cold" test" (with no hydrogen flow at all or with hydrogen injection but without ignition of the hydrogen–air mixture). Examples of such dependences of the measured thrust force on time in the experiments with M = 8 and G_{H_2} = 0.023 kg/s in the "cold" test and G_{H_2} = 0.034 kg/s in the "hot" test are shown in Fig. 4. The fact that the total equivalence (hydrogen to air) ratio in the considered "hot" test is smaller than the limiting value of the fuel-lean limit of detonation of a homogeneous hydrogen–air mixture means that the composition of the mixture in the combustor of the detonation ramjet model is not homogeneous. It is seen in Fig. 4 that the initial (up to 0.18 s) and final (after 0.4 s) parts of both curves almost coincide, but they are significantly different in the time interval of 0.18–0.4 s. In this example, the detonation ramjet model in the "hot" test is affected by the total positive force ("effective thrust") of about 100 N in the free stream with $M_\infty = 8$. It should be noted that the positive effective thrust is obtained in this test under the conditions of an elevated drag force generated by the model due to the presence of fixtures, detonator, throttling disk, wires, cables, and pipelines for hydrogen injection (see Fig. 1).

Using the data in Fig. 4 and also the information about the mass of hydrogen used in this particular "hot" test, we can determine the fuel-based specific impulse for the detonation ramjet model by the formula

$$I_{\rm sp} = \frac{1}{g m_{\rm H_2}} \left(\int\limits_{t=0}^{t=\Delta t} F_{\rm hot}(t) dt - \int\limits_{t=0}^{t=\Delta t} F_{\rm cold}(t) dt \right), \qquad (1)$$

where $m_{\rm H_2} = G_{\rm H_2} \Delta t$ is the mass of hydrogen consumed in the "hot" test during the time $\Delta t = 1$ s, g is the acceleration due to gravity, and $F_{\rm hot}(t)$ and $F_{\rm cold}(t)$ are the instantaneous values of the force acting on the model in the "hot" and "cold" tests, respectively (see the curves in Fig. 4). It should be noted that such a definition of the specific impulse should be considered as conservative because it takes into account the amount of hydrogen injected into the model before the ignition and after the completion of the test regime after valve closing. It should be emphasized that the local thrust peaks were ignored in the analysis of the test results because of the pulse operation mode of the wind tunnel: these local peaks could be caused by impact loads of the model during transitional processes. Therefore, only the integral characteristics of forces acting on the model were taken into account in specific impulse calculations.

Using the value of $I_{\rm sp}$ calculated by Eq. (1), we can estimate the mean thrust force $\bar{F}$ generated by the detonation ramjet model by the formula

$$\bar{F} = I_{\rm sp} g m_{\rm H_2}. \qquad (2)$$

Figure 5 shows the summarized experimental dependences of the specific impulse (Fig. 5a) and mean thrust (Fig. 5b) on the mass flow rate of hydrogen $G_{\rm H_2}$ for the free-stream velocity M_∞ = 5, 6, and 8. The extreme left points in both pictures correspond to the minimum flow rate of hydrogen at which stable CSD and LPD regimes were obtained.

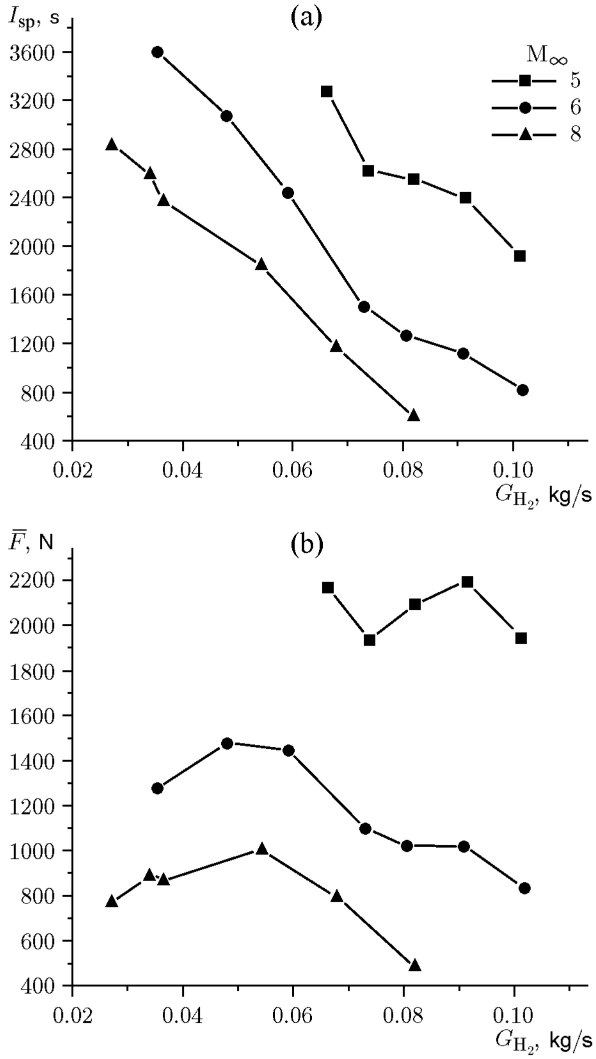

Fig. 5. Measured fuel-based specific impulse (a) and mean thrust (b) generated by the detonation ramjet model versus the mass flow rate of hydrogen for $M_\infty = 5$, 6, and 8.

CONCLUSIONS

The possibility of obtaining stable detonation combustion of hydrogen in a supersonic air flow is experimentally demonstrated by an example of an axisymmetric model of a detonation ramjet in air flows with Mach numbers ranging from 5 to 8 and stagnation temperature of 290 K in a short-duration wind tunnel. Two regimes of detonation combustion of hydrogen are obtained: continuous spin detonation and longitudinally pulsating detonation. In the CSD regime, there is one DW continuously rotating over the circumference of the annular gap of the combustor with a frequency of ≈1250 Hz corresponding to the visible wave velocity of ≈1200 m/s and its normal velocity of 1500–1700 m/s. In the LPD regime, one can observe spontaneous periodic (with a frequency of about 900 Hz) re-initiation of one or several DWs in the vicinity of the combustor exit with subsequent upstream propagation of these waves toward the row of hydrogen injectors with a visible velocity of ≈1000 m/s corresponding to the normal velocity of 1550–1750 m/s.

The measured effective thrust generated by the detonation ramjet model is either close to zero or positive (about 100 N) despite the elevated drag force of the model with attached devices for initiation and throttling disks, as well as the thrust measurement system responsible for significant blockage of the wind tunnel duct behind the model. Under these conditions, the maximum measured values of the fuel-based specific impulse and mean thrust force are 3600 s and 2200 N, respectively.

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