HYDROGEN-FUELED RAMJET WITH AN ANNULAR DETONATIVE COMBUSTOR

V. S. Ivanov, A. E. Zangiev, and S. M. Frolov

N. N. Semenov Federal Research Center for Chemical Physics
of the Russian Academy of Sciences (ICP)
4 Kosygin Str., Moscow 119991, Russian Federation
e-mail: smfrol@chph.ras.ru

Modern high-speed unmanned aerial vehicles are powered with small-size turbojets or ramjets. It is known that the efficiency of small-size turbojets during the flight at a speed exceeding the speed of sound decreases sharply. Thus, one of the most important characteristics of the efficiency of turbojets, the fuel-based specific impulse which is equal to the ratio of thrust to the rate of fuel consumption, is approximately 1300 s at a flight Mach number of 1 and decreases to $\sim$800 s at a flight Mach number of 1.25.

Existing ramjets operating on a thermodynamic cycle with the deflagrative combustion of fuel at constant pressure are efficient at flight Mach numbers ranging approximately from 2 to 6. One of the most important characteristics of a ramjet-powered aircraft is the minimum Mach number (start-up Mach number) at which an autonomous flight of an aircraft becomes possible after a launch boost provided by auxiliary boosters such as rocket engines. The start-up Mach number for existing ramjet-powered aircraft is approximately 2. The rocket boosters have relatively low specific thrust which leads to a considerable increase in the starting mass and dimensions of the aircraft. Thus, there is a need in reducing the ramjet start-up Mach number.

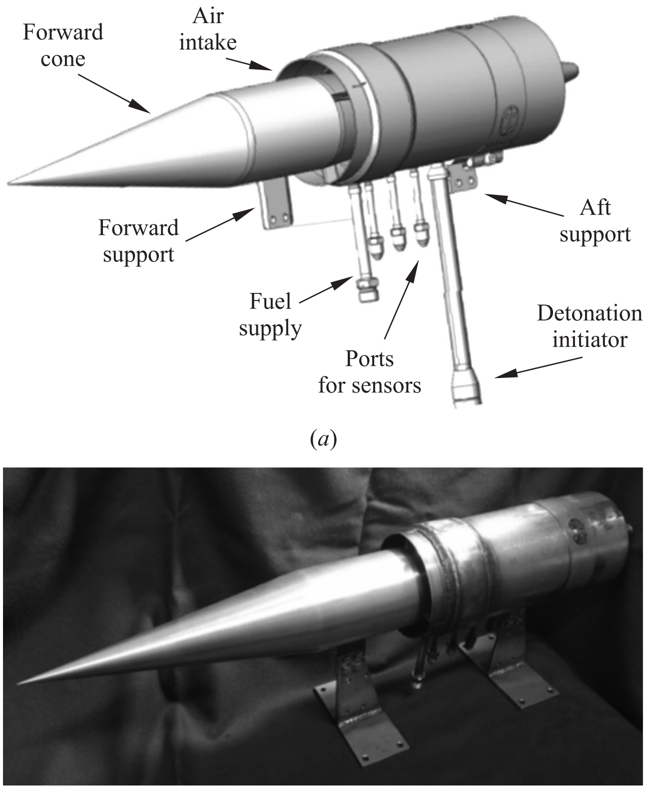
The thrust performances of ramjets have reached the upper limit and their further improvements are problematic. Therefore, to obtain a significant increase in the ramjet efficiency, the possibility of utilizing a thermodynamic cycle with continuous detonative combustion of

DOI: 10.30826/IWDP201923

fuel in an annular combustor (Zel'dovich cycle) is considered (see, for example, [1]). As compared with deflagrative combustion, continuous detonative combustion of a fuel has a number of advantages. Firstly, the Zel'dovich cycle has a higher efficiency [2]. Secondly, during continuous detonative combustion, energy is released in a narrow reaction zone in a single or several detonation waves continuously circulating in the annular combustor, thus creating only a localized backpressure to the incoming air flow, rather than in the entire cross section of the combustor, thus creating a bulk backpressure to the incoming air flow and leading to the unstart of the air intake. Thirdly, it allows organizing the operation process with high combustion efficiency in a combustor of a relatively small longitudinal size corresponding to the height of the self-sustaining detonation wave, thus reducing the loss of total pressure in the engine duct. In view of all these advantages, the ramjet start-up Mach number could be reduced if deflagrative combustion is replaced by detonative combustion. The objective of the work presented in this paper is to explore the possibility of such a reduction.

Figure 1*a* shows the three-dimensional (3D) model of a hydrogen-fueled ramjet with an annular detonative combustor located in the rare of the engine. The diameter of the outer combustor wall is 120 mm. This configuration has been chosen based on the multivariant parametric 3D numerical simulations fulfilled at the ICP using the computational technology reported elsewhere [3]. Figure 1*b* shows the photograph of the ramjet model manufactured for test fires in a wind tunnel. The ramjet is designed for the approaching air flow Mach number $\mathrm{M} = 2$ at the sea level and is currently under preparation for testing in the wind tunnel at $\mathrm{M} = 1 \ldots 2.5$.

Figure 2 shows the calculated dependencies of the effective thrust and fuel-based specific impulse of the hydrogen-fueled ramjet in the range of the approaching flow Mach number $\mathrm{M} = 1.1$–2.7 at the sea level conditions. The effective thrust is determined as the integral of pressure and friction forces over all solid surfaces of the model, i. e., it includes the aerodynamic drag of the model. The specific impulse is determined as the ratio of the total thrust to the rate of fuel consumption. In all simulations, for the sake of simplicity, the ramjet was placed in the supersonic flow of the homogeneous stoichiometric hydrogen–air mixture and mixture reactivity was artificially deacti-



(*a*)

(*b*)

Figure 1 Hydrogen-fueled ramjet with an annular detonative combustor: (*a*) 3D-model; and (*b*) the photograph of the experimental sample

vated upstream from the entrance to the annular combustor. This way, the formation of fuel–air mixture was avoided from consideration. In these conditions, the operation mode with a single rotating detonation wave was always obtained after the forced ignition of the reactive mixture in the combustor.

It is seen from Fig. 2 that the start-up Mach number of the ramjet with detonative combustion is as low as $M = 1.3$ when the effective

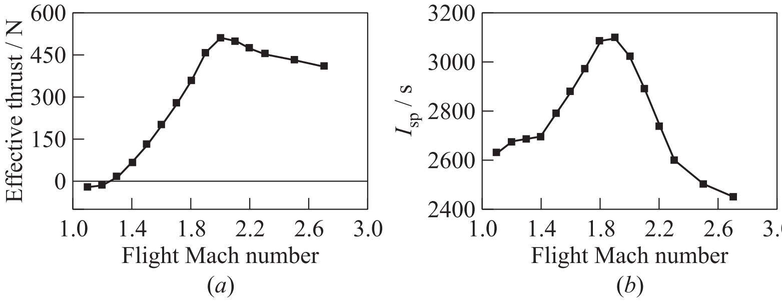


Figure 2 Calculated dependencies of the effective thrust (*a*) and fuel-based specific impulse (*b*) on the flight Mach number

thrust becomes positive. This result will be further verified by numerical simulations with separate delivery of air and hydrogen in the combustor as well as by test fires of the experimental sample of Fig. 1*b* in the wind tunnel.

This work is supported by the Russian Science Foundation (project 18-73-10196).

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