RAMJET WITH CONTINUOUS-DETONATION COMBUSTION OF HYDROGEN: FORMATION OF A CONCEPTUAL DESIGN BASED ON MULTIDIMENSIONAL NUMERICAL SIMULATIONS AND TEST FIRES

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Abstract: Using the computational technology of the Federal Research Center for Chemical Physics of the Russian Academy of Sciences, multivariant three-dimensional numerical calculations of the operation process in a hydrogen-fueled detonation ramjet at flight conditions with Mach number $\mathrm{M} = 2.0$ at sea level were performed. The possibility of organizing the continuous-detonation combustion of hydrogen in an expanding annular combustor has been proved. The conceptual design of the hydrogen-fueled detonation ramjet for the cruising flight speed of $\mathrm{M} = 2.0$ at sea level is developed. 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 are performed. The calculated effective thrust of such a ramjet is shown to become positive at $\mathrm{M} = 1.3$, i. e., the start-up Mach number for such a ramjet can be very low: below $\mathrm{M} = 2.0$ which is typical for ramjets operating on deflagrative combustion. A detonative ramjet demonstrator has been designed and manufactured. Its test fires are performed in a pulsed wind tunnel at Mach numbers $\mathrm{M} = 2.0$ and 1.5. The most important result of test fires at Mach 2.0 is the experimental proof of the possibility of organizing stable continuous-detonation combustion of hydrogen in the detonation ramjet of the developed design. The most important result of test fires at $\mathrm{M} = 1.5$ is the experimental proof of the possibility of organizing stable continuous-detonation combustion of hydrogen in the detonation ramjet of the developed design at an off-design flight speed. Thus, it has been experimentally proved that the start-up Mach number for the detonation ramjet can be about or less than $\mathrm{M} = 1.5$, which confirms the calculations qualitatively. For both Mach numbers, the thrust and economic performances of the detonation ramjet are obtained.

Keywords: detonation ramjet; hydrogen; three-dimensional gasdynamic calculations; start-up Mach number; wind tunnel; test fires

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Figure Captions

Figure 1 Schematic of the computational domain

Figure 2 Conceptual design of the detonation ramjet (left to right: air intake, bypass channel, combustor). Dimensions are in millimeters

Figure 3 Calculated distributions of local flow Mach number M (*a*) and static pressure P_{st} in the longitudinal section and at the combustor surfaces under conditions of detonation ramjet flight with Mach 2 (*b*)

Figure 4 Calculated time histories of the mean static pressure in the combustor volume P_{CC} (*1*) and in the outlet sections of the combustor (*2*) and bypass channel (*3*) under conditions of detonation ramjet flight with Mach 2

Figure 5 Calculated dependence of the detonation ramjet effective thrust on the flight Mach number

Figure 6 Three-dimensional model of the detonation ramjet: (*a*) general view; and (*b*) longitudinal section (left to right, top to bottom: (*a*) forward cone, air intake, forward support, fuel supply, gauges lines, detonation initiator, rare support; and (*b*) forward cone, air intake, fuel manifold, combustor, isolator)

Figure 7 Demonstrator of the detonation ramjet

Figure 8 Test rig with the pulse wind tunnel: (*a*) three-dimensional model; and (*b*) photograph (left to right, top to bottom: thrust table, ramjet, supersonic nozzle, high-pressure chamber, air manifolds, outlet of air receiver (16 atm, 10.4 m^3), air valves, valve for gaseous fuel supply, cylinder for pressure control)

Figure 9 Measured time histories of pressure in the air receiver (P_r), in the high-pressure chamber (P_0), and at the nozzle exit ($P_{\mathrm{st,noz}}$) in the test with M = 2.0

Figure 10 Example of primary records of all gauges measuring flow parameters in one of test fires: (*a*) pressure in hydrogen manifold P_{H_2}; (*b*) $P_{\mathrm{st,noz}}$, (*c*) measured force F; (*d*) mean static pressure in the combustor volume $\bar{P}_{\mathrm{CC}}$; and (*e*) pulsating pressure in the combustor P'_{CC}

Figure 11 Fragments of records of a pressure pulsation gauge in the combustor for longitudinally pulsed detonation (LPD) mode in test fire No. 2 (*a*) and combined mode of LPD and continuous spinning detonation in test fire No. 4 (*b*)

Figure 12 Frames of video records of test fires Nos. 1 to 4 at M = 2.0: (*a*) No. 1, $\alpha = 0.80$; (*b*) No. 2, $\alpha = 0.97$; (*c*) No. 3, $\alpha = 1.19$; and (*d*) No. 4, $\alpha = 1.65$

Figure 13 Frames of video records of test fires Nos. 1, 3, 5–8 at M = 1.5: (*a*) No. 1, $\alpha = 0.77$; (*b*) No. 3, $\alpha = 0.83$; (*c*) No. 5, $\alpha = 1.05$; (*d*) No. 6, $\alpha = 1.19$; (*e*) No. 7, $\alpha = 1.41$; and (*f*) No. 8, $\alpha = 1.60$

Table Captions

Table 1 Calculated thrust performance of detonation ramjet under flight conditions with $\mathrm{M} = 2.0$

Table 2 Flow parameters in the supersonic nozzles

Table 3 Main parameters and results of detonation ramjet test fires at $\mathrm{M} = 2.0$

Table 4 Main parameters and results of detonation ramjet test fires at $\mathrm{M} = 1.5$

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