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Rocket and Air-Breathing Detonation Engines

Keynote Lecture

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Abstract

At present, aerospace propulsion engineering addresses several promising areas of development. One of them is the use of detonative rather than deflagrative combustion of the reactive mixture in liquid rocket engines, ramjets and turbojets. The expediency of transition to the detonative combustion is mainly due to the higher efficiency of the thermodynamic cycle with detonative combustion as compared with the conventional cycle using relatively slow combustion at constant pressure. The lecture outlines the current accomplishments and challenges in theoretical and experimental studies of detonative combustion of hydrogen and hydrocarbon fuels as applied to the aerospace propulsion. Various demonstrators of propulsion devices operating on continuous detonations are presented and their thrust performances are discussed.

1 Introduction

At present, aerospace propulsion engineering addresses several promising areas of development. These are the use of liquefied natural gas (LNG) as a propellant, the use of continuous-detonation rather than conventional combustion in liquid rocket engines (LREs) and ramjets, etc. The expediency of the transition to LNG – oxygen fuel couple is mainly due to (a) an increased specific impulse compared to kerosene – oxygen LRE; (b) the availability and low cost of LNG; (c) significantly less soot formation during combustion; and (d) high environmental characteristics compared with kerosene. The expediency of transition to a continuous-detonation combustion is mainly due to higher efficiency of the thermodynamic cycle with detonative combustion as compared with the conventional cycle using relatively slow combustion at constant pressure. Other advantages of continuous-detonation engines are: (a) a compact combustion chamber with an increase in the total pressure; (b) short nozzle; (c) high combustion efficiency; and (d) low concentrations of harmful substances in the exhaust gas. In theory, the replacement of kerosene by LNG in a traditional LRE promises the gain in the specific impulse of 3%–4%, and the transition from a traditional LRE to the engine with detonative combustion promises the theoretical gain of 13%–15%. The energy efficiency of the detonative LRE was recently proved experimentally for the hydrogen–oxygen fuel couple. In ramjets, continuous-detonation combustion provides a very powerful means of mixing enhancement: fuel and air are forced to mix by the lead shock wave continuously circulating across the mean flow.

The purpose of the research outlined in this lecture is to investigate both computationally and experimentally the impact of the detonation engine configuration and fuel supply parameters on the operation process and thrust performance of LREs and ramjets.

2 Computational studies

For simulating three-dimensional physical and chemical processes in the engines and for determining the operational and geometrical conditions required for continuous-detonation combustion, the object-oriented computational technology has been developed at the Semenov Institute of Chemical Physics (ICP), Moscow, Russia.
Institute of Chemical Physics (ICP). The main features of the technology are briefly described below.

The flow of viscous compressible gas is described by the Reynolds-averaged unsteady Navier-Stokes equations supplemented by energy equation and continuity equations for all chemical species in a multicomponent mixture. Molecular and turbulent fluxes of mass, momentum, and energy are modeled using the transported probability density function approach realized through the lagrangian Monte-Carlo based Particle Method in which the ensemble-averaged rates of chemical reactions in a turbulent flow are calculated with due regard for the effect of turbulent fluctuations of temperature and species concentrations (the effect of “turbulence – chemistry interaction”). The governing equations are closed with the caloric and thermal equations of state of an ideal gas mixture with variable specific heats, as well as with initial and boundary conditions. All other thermal parameters of the gas are also considered variable. Fuel and oxidizer are supplied to the combustor separately and, before reacting, exhibit turbulent and molecular mixing.

Fig. 1: Predicted quasi-stationary fields of static pressure in Pa (a, b) and static temperature in K (c) in the continuous-detonation LRE operating on methane and oxygen.

Fig. 2: Predicted quasi-stationary fields of static temperature (a) and static pressure (b) in the continuous-detonation ramjet operating on hydrogen.

Fig. 3: Experimental model of continuous-detonation LRE.

Fig. 4: Experimental model of continuous-detonation ramjet.
As the first example of computational results, Fig. 1 shows the predicted quasi-stationary fields of static pressure at the outer wall of the annular (outer diameter 100 mm, annular gap 5 mm) methane-oxygen continuous-detonation LRE (a) and in the combustor cross-section slightly downstream from the bottom (b), as well as a static temperature at the outer wall (c) at the mass flow rate of fuel components equal to 0.37 kg/s and the overall fuel-to-oxygen equivalence ratio equal to 1.1. The calculation predicts the operation process with three equidistant detonation waves circulating in the same direction at a velocity of 2270 ± 20 m/s. The predicted frequency of detonation rotation is 22 kHz.

As the second example, Fig. 2 shows the predicted quasi-stationary fields of static temperature and pressure at the outer wall of the hydrogen-fueled ramjet (outer diameter 400 mm, 1.5 m long, variable annular gap) at atmospheric flight conditions with Mach 5 at altitude 20 km. In this case, a single detonation wave inclined by about 60° to the engine axis is continuously rotating in the annular gap at a frequency of about 1.3 kHz.

3 Experimental studies

The objective of experimental studies is to explore the predictive capability of the computational technology in terms of operation modes and thrust performances of continuous-detonation engines. Figures 3 and 4 show the experimental models of continuous-detonation LRE (Fig. 3) and ramjet (Fig. 4) designed using this technology. Experiments with the LRE are performed at the ICP test stand, whereas experiments with the continuous-detonation ramjet are performed in the “Transit-M” pulse wind tunnel of the Institute for Theoretical and Applied Mechanics (ITAM) in Novosibirsk.

![Graph](image)

**Fig. 5:** Experimental dependence of the sea-level specific impulse on the mean pressure in the combustor for the continuous-detonation LRE.

**Fig. 6:** Experimental dependences of the fuel-based specific impulse on hydrogen mass flow rate for the continuous-detonation ramjet at approach stream Mach numbers 5, 6, and 8.

For the continuous-detonation LRE, comparison of the predicted results with measurements proved that the calculations accurately predict the operation mode in terms of the number of detonation waves circulating in the tangential direction of the annular combustor and even the chaotic near-limiting operation mode resembling the mode with longitudinally pulsating detonations. Calculations predict with reasonable accuracy both the detonation propagation velocity and detonation rotation frequency. In addition, calculations correctly predict the trends in the variation of continuous-detonation operation parameters with decreasing the mass flow rate of reactive mixture in an engine of a particular design: as in the experiment, the number of
detonation waves, detonation velocity and thrust decrease. The maximum measured values of the LRE specific impulse and the thrust are 270 s (Fig. 5) and 3000 N, respectively. It is noteworthy that the specific impulse of 270 s has been attained at a very low pressure in the combustor (about 30 atm).

For the continuous-detonation ramjet, the possibility of organizing stable detonative combustion of hydrogen in a supersonic air flow using the axisymmetric detonation ramjet model with an expanding annular combustor under conditions of approach air stream Mach number ranging from 4 to 8 at a stagnation temperature of 290 K has been demonstrated both computationally and experimentally. Two detonation modes in the annular combustor of the ramjet model are registered in the calculations and experiments. In the first, continuous spinning mode, a single detonation wave is rotating in the combustor annular gap with the rotation frequency of 1250 Hz and the normal detonation velocity of 1500–1700 m/s. In the second, longitudinally pulsating mode, one or several detonation waves are spontaneously re-initiated in the rear part of the combustor and propagate upstream towards the hydrogen supply nozzles at the normal detonation velocity of 1550–1750 m/s with the longitudinal pulsation frequency of 900 Hz. Detonative combustion of hydrogen provides a significant increase in the static pressure in the combustor, which persists during the test time (150 – 200 ms). 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. The maximum measured values of the fuel-based specific impulse and the total thrust are 3600 s (Fig. 6) and 2200 N, respectively. Experiments in another ITAM wind tunnel (AT-303) at elevated stagnation temperatures (1400 K) confirmed the existence of the self-sustained continuous spinning detonation mode of hydrogen in the ramjet model at approach stream Mach number 6.

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