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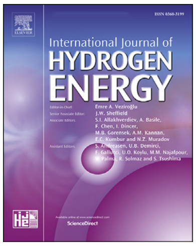

Control of detonation combustion of rarefied hydrogen-air mixture in a laval nozzle

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ABSTRACT

The possibility of stabilizing the detonative combustion of hydrogen-air mixtures coming into an axisymmetric Laval nozzle with a high supersonic velocity under conditions of atmosphere at altitudes up to 24 km is being studied. The appropriate parameters for the composition of the mixture and the nozzle channel are determined. Used mathematical model is based on the non-stationary two-dimensional equations of an axisymmetric flow of an inviscid multi-component gas with non-equilibrium chemical reactions. A detailed kinetic model is used to describe the detonative combustion of hydrogen-air mixtures. The heat capacity and enthalpy of the mixture are calculated from the reduced Gibbs energy of the gas components. Numerical simulation is performed on the basis of Godunov's finite-difference scheme and its modification of a higher order of accuracy.

Most of the calculations are performed on a supercomputer "Lomonosov" of Lomonosov Moscow State University using OpenMp technology of parallel calculations.

Introduction

The study of detonation as a special physical process is carried out since the beginning of the last century. However, active research on the use of detonation in power machines has a relatively short history. The thermodynamic advantages of detonation combustion are shown theoretically [1] and confirmed experimentally (see, for example [2]). In direct-flow supersonic combustion chambers, detonation combustion can be more efficient than turbulent combustion, also because it does not require slowing the flow down to subsonic or low supersonic speeds. At the same time, in its dynamics, detonation is an explosive process, the uncontrolled development of which can lead to undesirable consequences.

Researches in this area are aimed at finding effective ways to control detonation combustion in ramjet combustion chambers. At present, several ways of detonative combustion of fuel-air mixtures in supersonic streams are considered:

1. Continuous combustion of fuel in a transverse rotating detonation wave. The initial information can be found in Refs. [3,4].
2. Fuel combustion in a detonation wave pulsating longitudinally in a combustion chamber of constant cross section (see, for example [5–8]).
3. Stationary detonative combustion in a flat channel with a complex shock-wave structure of the flow [9–12].
4. Stationary detonative combustion in an axisymmetric convergent-divergent nozzle [13–16].

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5. The detonation combustion in three-dimensional channels with complex geometry and composition [17–19].

The most advanced is a project with a detonation wave rotating continually in the annular channel transversely to the incoming supersonic flow of combustible mixture (see, for example [20–24]). However, this scheme can lead to regimes with unwanted instabilities [25].

In a scheme with longitudinally pulsating detonation, the periodic movement of the wave is caused by a change in the composition of the mixture entering the channel. Excessive enrichment or depletion of the mixture poses a risk of the detonation decay [26]. In addition, any pulsations increase loses of energy and impulse. Therefore now it is still difficult to talk about the effectiveness and reliability of this scheme. Studies on the stabilization of detonation combustion in planar and three-dimensional channels have so far, as a rule, are limited by solving the problems of initiating stationary detonation and transforming the shock-wave structures appearing in the flows.

In Refs. [13–16] the possibility to generate the thrust as a result of stable detonation combustion of hydrogen in an air stream coming into an axisymmetric convergent-divergent nozzle with Mach number from 7 to 9 at altitudes up to 16 km is numerically established. Decrease of the flow velocity in the convergent part of the nozzle reduces the probability of detonation removing downstream when the velocity of the incoming gas is higher than the Chapman-Jouguet detonation velocity. Expansion of the combustion products in the divergent part of the nozzle contributes to the stabilization of detonation combustion at a lower velocity of coming flow. In this respect, axisymmetric and three-dimensional nozzle is much more efficient than flat. The main idea in Ref. [16] is to determine the maximum altitude at which the nozzle under investigation provides traction as a result of stable detonation combustion of hydrogen for given Mach number of the incoming flow. The choice of hydrogen as fuel is due to its relatively high specific energy content, ecological purity and the availability of tested combustion kinetics.

The main goal of this work is to propose and test the method of designing a convergent-divergent nozzle that would ensure the stabilization of detonation combustion of hydrogen and the generation of thrust upon transition to the conditions of a more rarefied atmosphere for given values of Mach of the coming flow. We will be interested in the altitudes 20 and 24 km and Mach numbers of the oncoming flows 7 and 9.

The problem statement and solution method

The initiation and stabilization of detonation combustion under conditions of a rarefied atmosphere is a common problem for the aforementioned detonation combustion schemes for fuel-air mixtures. At altitudes up to 16 km, stationary detonation combustion and thrust are produced in the axisymmetric convergent-divergent nozzle with a coaxial central body, when the ratio of the entrance radius to a minimum η is about 1.63 [16]. At more high altitudes, the detonation initiation is hampered by a drop in the density and temperature of the atmospheric air. One can hope that a strong compression of the supersonic flow within the converging section of Laval nozzle can sufficiently increase the gas density to initiate detonation combustion. Such compression of the supersonic flow in the diffuser can be realized by increasing the ratio η. In Ref. [15] it is shown that a supersonic flow in a tapering axisymmetric channel is characterized by the presence of an inclined shock wave that interacts with the axis of symmetry to form a Mach disk. An increase in the ratio η at a constant length of the convergent part of the nozzle increases the radius of the Mach disk. This increases the probability of uncontrolled initiation of the detonation wave and reduces the probability of stabilization of detonation combustion. Therefore, in order to exclude such a development of the process, it is necessary to increase the length of the diffuser.

The one-dimensional theory makes it possible to estimate the compression ratio of the diffuser, which will provide the necessary gas density near the minimum nozzle cross section at high altitudes. At an altitude of 20 km, the nozzle radius at the inlet should be 2.5 times larger than the minimum and 3.5 times at an altitude of 24 km. In addition, nozzles, whose contours are in some sense similar to the contour of the nozzle in Ref. [16], may be of interest.

In this article we consider nozzles whose length of convergent part is equal to 15, and the radius at input $R_1 = 2.6$. Here and below, all distances and lengths refer to the radius of the nozzle throat $r_0 = 10$ cm. The radius of the cross-section at the outlet $R_2 = R_1$. The shapes of the diffuser AB and the divergent section CD (Fig. 1) are given by the power function of the sinusoid with the exponent α_1 and α_2, respectively. In general, these contours have inflection points: x_{z1} and x_{z2}. The values of α_1 and α_2 determine the position of these points along the abscissa. Between the nozzle diffuser and the expanding section is a cylindrical insert BC, the length of which equals 0.5. Since $\alpha_i > 1$, the contours of the diffuser and the divergent nozzle smoothly mate with the cylindrical part of the channel. The tangent lines at the outermost points of the contour are parallel to the axis of symmetry.

The nozzle is built into an outer coaxial cylindrical body with a generatrix AD parallel to the axis of symmetry. Therefore, its resistance in the external flow is absent. As a rule, a central coaxial body "cylinder-cone" is inserted into the nozzle. Below in the calculations, the radius of this body is 0.1. Its front end wall is in a point X_d.

The calculations are carried out in a region that is divided by a straight line AD into two parts corresponding to the internal and external flows (Fig. 1). The upper boundary of this region is given by the straight line EF, parallel to AD. The lower boundary coincides with the axis of symmetry of the nozzle and the surface of the central body. On the left, the computation area is

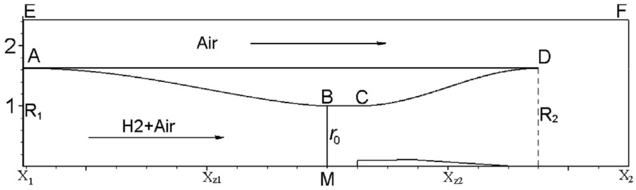

Fig. 1 – Schematic presentation of the computation region and nozzle contour (ABCD).

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