The Possibility of Detonation Stabilization in a Supersonic Flow of a Combustible Gas Mixture without Any Expenditure of Energy

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1 Abstracts

The numerical investigation of detonation propagation in a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a plane channel has been carried out with the purpose of determination of conditions that guarantee detonation stabilization in the flow without any expenditure of energy.

The possibility of stabilization of a formed detonation wave without energy input in the combustible gas mixture flowing at a supersonic velocity into the plane channel with narrowing cross-section has been determined. The stability of the flow with stabilized detonation in the channel with narrowing has been examined.

In addition for some Mach numbers of the incoming flow the method of determination of the channel shape which gives detonation initiation and its stabilization in the flow without any energy input is proposed.

2 Introduction

The interest in the study of detonation wave in a combustible gas mixture is closely connected with practical demands. So the intention to use detonation in energy plants, for example, in detonation engines requires fundamental knowledge about the detonation combustion of high-velocity flows. In particular the investigation of a possibility of a control of detonation propagation in a supersonic gas flow and determination of conditions that guarantee detonation stabilization are of great interest. So the method of detonation stabilization in a supersonic gas flow by means of weak discharges has been proposed in [1-2]. However detonation stabilization without any energy input is of more interest. So, the conditions that guarantee detonation stabilization in supersonic flows of hydrogenous mixtures in an axisymmetric nozzle were investigated (see, for example, [3]). Stabilization of rotating detonation

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in an axisymmetric combustion chamber was studied in [4]. The formation of stationary detonation in plane channels with a wedge-shaped part for some combustible gas mixtures was examined in [5-6]. Using quasi-one-dimensional model detonation stabilization in a supersonic flow in a channel with variable cross-section area was studied too [7].
In the present research the possibility of stabilization of detonation combustion of a supersonic flow a stoichiometrical hydrogen-air mixture due to use special form plane channels (without any energy input) was investigated.

3 Mathematical Model

Detonation propagation in a premixed stoichiometrical hydrogen-air mixture flowing into a plane channel (inflow cross-section and outflow one are perpendicular to the incoming flow direction) is studied. The combustible gas mixture under the normal conditions (p_0 =1 atm, T_0 =298K) is incoming into the channel at a supersonic velocity that is essentially larger than the velocity of self-sustaining detonation propagation in the quiescent mixture with incoming flow parameters: that is $M_0 > M_{J0}$ (here, M_0 is the flow Mach number, M_{J0} is the Mach number of self-sustaining detonation).

The set of gas dynamics equations describing a plain two-dimensional nonstationary flow of the inviscid reactive multi-component gas mixture is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} + \frac{\partial (\upsilon\rho)}{\partial y} = 0$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} + \frac{\partial (\rho u \upsilon)}{\partial y} = 0$$

$$\frac{\partial (\rho \upsilon)}{\partial t} + \frac{\partial (\rho \upsilon u)}{\partial x} + \frac{\partial (\rho \upsilon^2 + p)}{\partial y} = 0$$

$$\frac{\partial (\rho (u^2 + \upsilon^2)/2 + \rho h - p)}{\partial t} + \frac{\partial (u\rho ((u^2 + \upsilon^2)/2 + h))}{\partial x} + \frac{\partial (\upsilon\rho ((u^2 + \upsilon^2)/2 + h))}{\partial y} = 0$$

$$\frac{\partial (\rho n_i)}{\partial t} + \frac{\partial (u\rho n_i)}{\partial x} + \frac{\partial (\upsilon\rho n_i)}{\partial y} = \rho \omega_i$$

where x and y are the Cartesian coordinates; u and υ are the corresponding velocity components; t is the time; ρ , p and h are the density, the pressure and the enthalpy, respectively; n_i is the molar concentration of the i th species in the mixture; and ω_i is the rate of formation/depletion of the i th component. The examined mixture consists of 10 species: H_2 , O_2 , H , O , OH , HO_2 , H_2O , H_2O_2 , N_2 and Ar .
The equations of state for the mixture have the usual form

$$p = \rho R_0 T \sum_i n_i , \quad h = \sum_i n_i h_i(T) .$$

Here T is the temperature, R_0 is the universal gas constant. The values of partial enthalpies $h_i(T)$ were taken from [8].

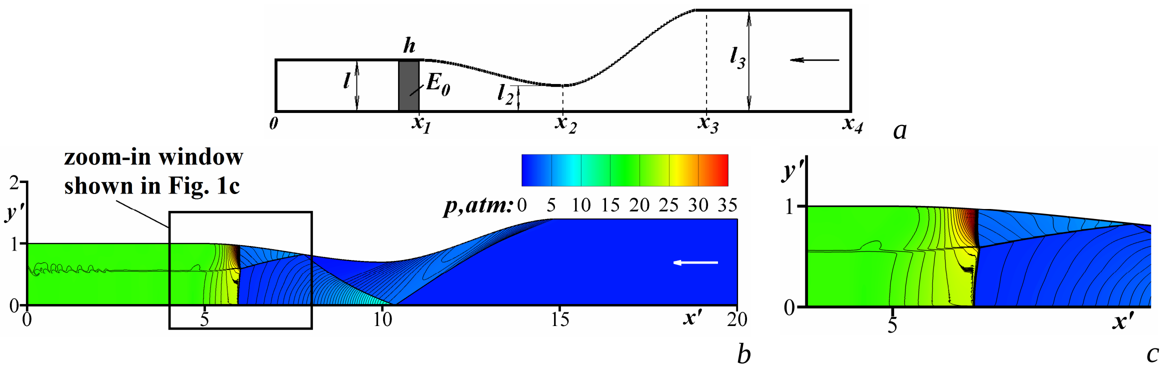

Figure 1. Detonation stabilization in the symmetrical plane channel with narrowing cross-section: *a* – the schematic of the upper part of the plane channel; *b* – the pressure field and the density contours in case of detonation stabilization in the divergent part of the channel for M_0 =5.2; *c* – zoom-in window showing the stabilized detonation. Here and further $x' = x / l$, $y' = y / l$, where l is the half of the outflow section width; the arrow shows to flow direction.

The inflow boundary conditions are the incoming flow parameters, the outflow boundary condition is necessary only in boundary points with the subsonic velocity of gas outflow (in this case, the boundary condition is $p_{out} = p_0$). Slip condition is imposed at the channel surface.

A set of Euler gas dynamics equations coupled with detailed chemical kinetics equations [9] (in case of symmetrical channels with narrowing cross-section) and [10] (for channels of special shape) has been solved using a finite-difference method based on the Godunov's scheme. The adaptive computational mesh was used for numerical simulation of studied flows with detonation waves. The size of mesh was selected so that the flow behind the detonation front (in particular, the flow in the induction zone) was represented correctly. Thus the computational mesh with cell size 0.03mm − 0.01mm was used in numerical calculations.

4 Stabilization of a formed detonation wave in the symmetrical plane channel with narrowing cross-section

The possibility of stabilization of formed detonation without any energy input in the combustible gas mixture flowing at a supersonic velocity into the symmetrical plane channel with narrowing cross-section was investigated. The schematic of the upper part of the channel is shown in Fig. 1*a*. The initial condition is the steady supersonic plane two-dimensional flow of the gas mixture in this channel obtained by the stabilization method without account for the chemical interaction. The initial instantaneous supercritical energy input E_0 in the narrow layer shaped domain located near $x = x_1$ section (shaded region in Fig. 1*a*) was used for detonation initiation. Two detonation waves are formed as a result of the energy input: the first one propagates downstream (this wave is transferred by the flow) and the other propagates upstream. The influence of geometrical parameters of the channel on propagation of the latter detonation wave has been studied. It has been established that for some values of the incoming flow Mach number M_0 the geometrical channel parameters may be selected so that the detonation wave is stabilized in the flow without any energy input.

So, the pressure field and the density contours in case of detonation stabilization in the divergent (in the line of flow) part of the channel for M_0 =5.2 are presented in Fig. 1*b* and Fig. 1*c*. In the case under consideration the detonation wave initiated in the channel part with parallel walls (x_1' =5) moves upstream and is stabilized with time at a short distance from $x' = 6$ section. Decrease of a wave velocity and subsequent detonation stabilization are determined by the presence of transversely-extended flow region with a large value of the longitudinal velocity in front of the wave in the

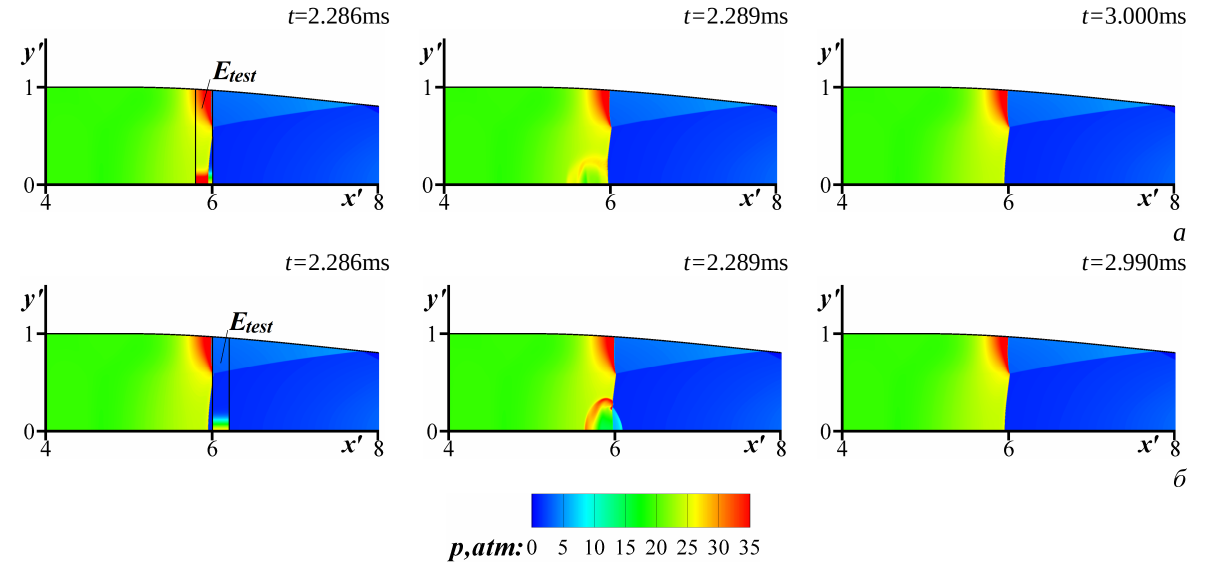

Figure 2. The stabilized detonation wave in case of energy input E_{test} (at the moment of time *t*=2.286ms) with the exponential dependence of energy input density on transversal coordinate: *a* – the energy input domain contains stabilized detonation; *b* – the energy input domain is located in front of the detonation wave.

divergent part of the channel. The stabilized detonation wave and the oblique shock wave of the initial steady flow form a Mach configuration; the formed flow with stabilized detonation is unsteady.

In case of detonation stabilization for M_0=5.2 the energy input in a narrow layer shaped domain was used for testing the stability of this flow with the stabilized wave. The energy input E_{test} (E_{test}=100 J/m) with the exponential dependence of energy input density on transversal coordinate and with uniform density in the domain containing the stabilized detonation front and in a domain placed in front of detonation was considered. It has been established that in spite of a disturbance of the stabilized detonation after energy release the energy input under consideration does not break the wave stabilization and does not change the location of the stabilized detonation wave (Fig. 2). Moreover the flow disturbance by the energy input E_{test} with the exponential dependence of energy input density on transversal coordinate in the domain located near the $x'=7$ section was considered. In this case energy supply E_{test} leads to formation of a new detonation wave upstream. However this

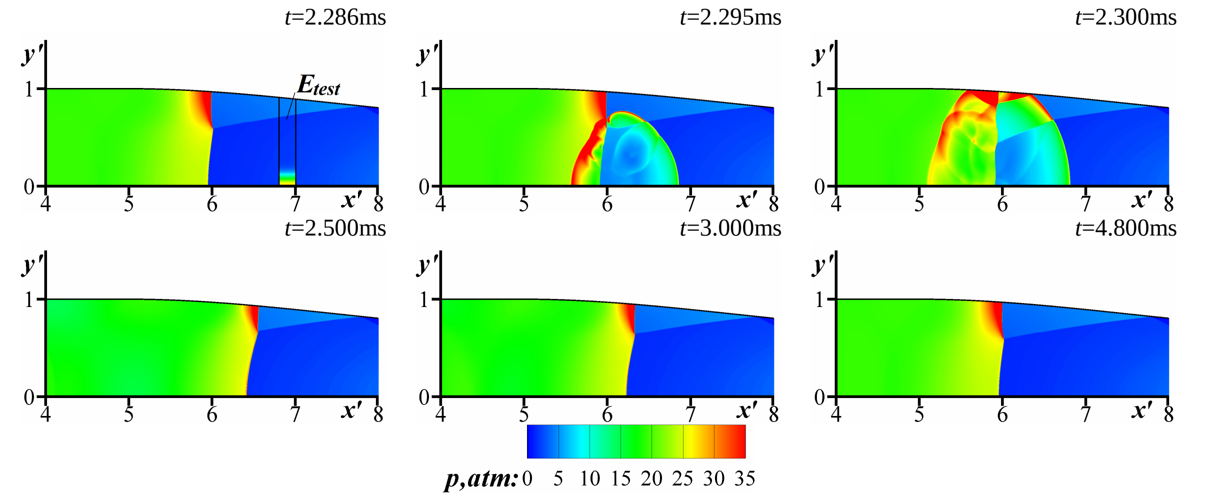

Figure 3. Restoration of the flow with stabilized detonation in case of energy input E_{test} (at the moment of time *t*=2.286ms) in the domain near the x'=7 section.

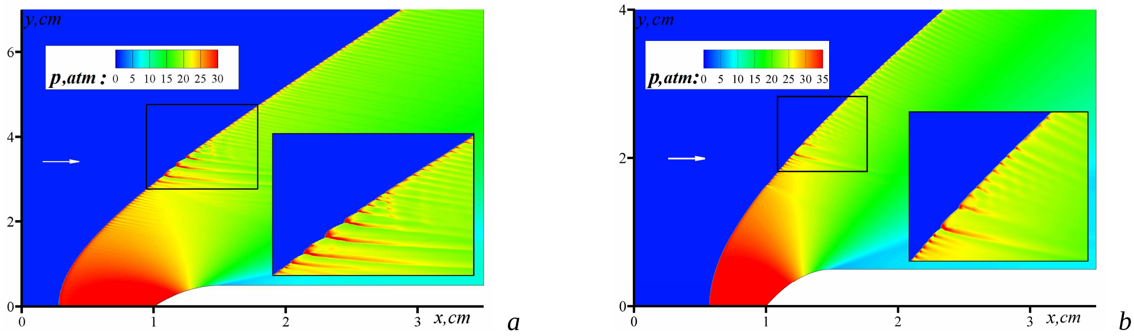

Figure 4. The detonation wave stabilized ahead of the obstacle: *a* – M_0 =5.5; *b* – M_0 =6.

wave is transferred by the flow and is stabilized with time in that place where the initial stabilized detonation was located (Fig. 3). These results indicate the stability the flow under consideration with the stabilized detonation wave in the channel with narrowing.

5 Formation of stabilized detonation in the plane channel of special shape

In case of channel with narrowing cross-section the initial energy input was used for detonation initiation. For determination of a channel shape which gives detonation initiation and its stabilization in the flow without any expenditure of energy a plane two-dimensional supersonic flow of the combustible gas mixture with Mach number M_0 =5.5 and 6 about the symmetrical semi-infinite plane obstacle placed along the stream was considered. The obstacle configuration was chosen so that the flow with detonation was formed. There is formation of a detonation wave stabilized near the obstacle due to a flow velocity which is more than a detonation one ($M_0 > M_{J0}$). In cases under consideration the flow with the stabilized detonation is unsteady due to transverse waves propagating along the detonation front (Fig. 4).

In case of M_0 =5.5 the structure of the stabilized ahead of the obstacle detonation wave was considered. It has been established that the detonation wave is divided into three sections with different structures. So a part of the wave near the symmetry plane is overdriven detonation; with the increase of the distance from the plane of symmetry the left-running transverse waves (facing upstream) propagate along the detonation front; with the further distance increase the transverse waves of both sets (left-running and the right-running) are formed and define a cellular structure that is qualitatively similar to a plane detonation wave structure [11]. The detected structure of the detonation wave stabilized ahead of the obstacle is conformed with a structure of a wedge-induced oblique detonation wave [12 – 13].

Then detonation combustion of the gas mixture flowing at the same velocity into plane channels (the

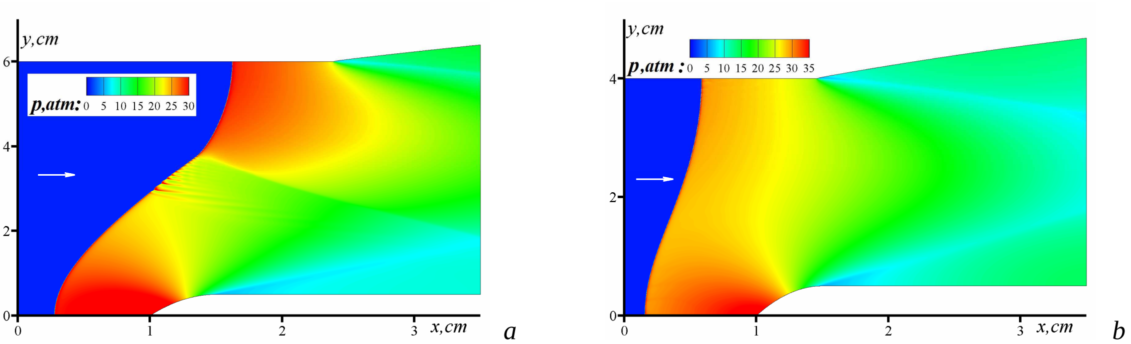

Figure 5. Flow in the channel of the special shape in case of M_0 =5.5: *a* – formation of stabilized detonation in the channel with supercritical width of the inflow cross-section; *b* – the detonation wave moves upstream from the channel in case of subcritical width of the inflow cross-section (t =0.985ms).

top walls of which are determined by streamlines of the flow under consideration, the bottom one is determined by the plane of symmetry and by the obstacle surface) was studied. The initial condition is the incoming gas flow. It has been established that for fixed incoming flow Mach number M_0 the detonation wave is stabilized in the channel, the shape of which is defined in this way, if the width of the inflow cross-section is more than some critical one (Fig. 5*a*). In case of subcritical width of the inflow cross-section the detonation wave moves upstream from the channel (Fig. 5*b*).

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