Detonation combustion in a supersonic gas flow in a plane channel

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Abstract

Using a detailed chemical kinetics the possibility of a control of detonation propagation in a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a plane channel was investigated. The conditions that provide detonation stabilization in the flow (without any energy input) were studied. The possibility of controlling a stabilized detonation wave location in the high-velocity gas mixture flow is examined.

1 Introduction

The study of detonation combustion in high-velocity gas flows is the one of the main branches of detonation investigation. In particular, detection of the technique of controlling detonation propagation in a supersonic gas flow and determination of conditions that provide detonation stabilization in a flow are of great interest. So, the method of detonation stabilization in a supersonic gas flow in a plane channel with parallel walls by means of weak discharges has been proposed in [1]. However, the detonation stabilization without any expenditure of energy is more preferable. So, the formation of stabilized detonation in supersonic flows of hydrogenous mixtures in an axisymmetric nozzle was investigated (see, for example, [2]). Stabilization of rotating detonation in an axisymmetric combustion chamber was studied in [3]. The formation of stationary detonation in plane channels with a wedge-shaped part for some combustible gas mixtures was examined in [4], [5]. In [1] the possibility of stabilization of formed detonation in a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into the symmetrical plane channel with narrowing cross-section was ascertained. However, the stability of the formed flow with a stabilized detonation wave was not studied.

In this work advancing the research [1] the stability of the flow with stabilized detonation in the channel with narrowing to strong disturbances was examined. In addition, the capability of a control of a stabilized detonation wave location in the high-velocity flow of a stoichiometrical hydrogen-air mixture in the channel with narrowing is investigated. The possibility of initiation and stabilization detonation combustion in the supersonic flow of the gas mixture due to using the special form plane channels (without any energy input) is studied.

2 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=1atm, T_0=298K) is incoming into the channel at a supersonic velocity that exceeds a 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 incoming flow Mach number, M_{J0} is the Mach number of self-sustaining detonation). A stoichiometrical hydrogen-air mixture flowing into the channel is considered as the mixture of the H_2, O_2, N_2 and Ar gases in the volumetric relation 42 : 21 : 78 : 1. The set of gas dynamics equations describing a plain two-dimensional nonstationary flow of the inviscid reactive multi-component gas mixture is:

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

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

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

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

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

where x and y are the Cartesian coordinates; u and v 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 ith species in the mixture; and ω_i is the rate of formation/depletion of the ith component.
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 partial enthalpy $h_i(T)$ of the ith mixture component is determined by the Gibbs reduced energy of this component [6].
The inflow boundary conditions are the incoming flow parameters, the outflow boundary condition is necessary only in the 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 [7] (in case of symmetrical channels with narrowing cross-section) or [8] (for channels of special shape) has been solved using a finite-difference method based on the Godunov's scheme [9]. 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.

3 A gas flow with a stabilized detonation wave in a 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 a symmetrical plane channel with narrowing cross-section has been investigated in [1]. The schematic of the upper part of the channel is shown in Fig. 1a: the inflow boundary is $x = x_4$, the outflow boundary is $x = 0$; the channel width is a continuously differentiable function of a longitudinal coordinate. The initial condition is the steady supersonic plane two-dimensional flow of the gas mixture in this channel obtained by the stabilization method. The initial instantaneous supercritical energy input E_0 in the narrow layer shaped domain located near the $x = x_1$ section (shaded region in Fig. 1a) 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. In [1] numerical calculations were carried out with the fixed geometrical characteristics l =0.025m, x_1/l =5, x_2/l=10, x_3/l=15, x_4/l=20 and with different values of M_0, l_2 and l_3. 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. In particular, in case of M_0=5.2 the using of the channel with parameters l_2/l=0.7 and l_3/l=1.4 is the sufficient condition for stabilization of the detonation wave in the flow.
The numerical modeling of this research that performed with the use of a finer computational grid (the mesh size is reduced more than 6 times as compared with a modeling of [1]) has confirmed the formation of the flow with the stabilized detonation wave in the channel under consideration in case of M_0=5.2. The pressure field and the density contours for this gas flow with the stabilized detonation wave are presented in Fig. 1b. In the case under consideration the detonation wave initiated by energy input near the $x' = 5$ section moves upstream and is stabilized with time in the divergent (in the line of flow) part of the channel at a short distance from the $x' = 6$ section. 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 due to instability of the contact surface.
The stability of this flow with the stabilized detonation wave in the channel to strong disturbances excited by energy input has been studied. The input of energy E_{test} ($E_{test} = E_0/3$ and $E_{test} = 5E_0/3$) with an exponential dependence of energy input density on transversal coordinate (or uniform energy input) in the narrow layer located in other parts of channel has been considered.
In case of the energy input in a domain placed in front of the stabilized detonation wave it has been established that in spite of a disturbance of stabilized detonation

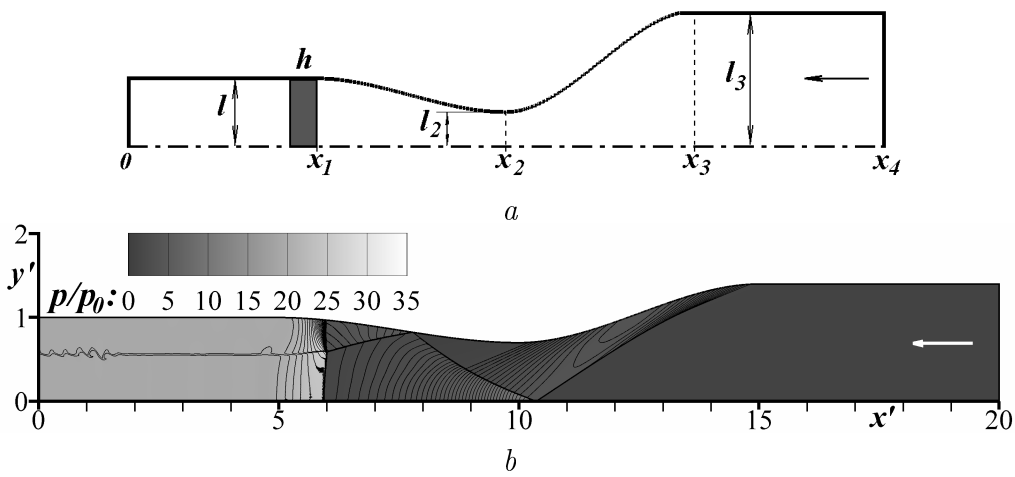

Figure 1: Detonation stabilization in the symmetrical plane channel with narrowing cross-section: a – the scheme of the plane channel; b – stabilization of the detonation wave in the divergent channel part in case of M_0 =5.2. Here and further $y' = y/l$, $x' = x/l$, where l is the half of the outflow section width; the arrows show the flow direction.

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. 2a). In case of the energy input in the domain located near the $x' = 7$ section, energy supply E_{test} leads to formation of a new detonation wave upstream (DW). The initial wave transforms to a shock wave (SW). However, new detonation wave is transferred by the flow and is stabilized with time in that particular place where the initial stabilized detonation wave was located (Fig. 2b).

In case of the disturbing energy input $E_{test} = 5E_0/3$ near the narrowest part of the channel (either in the convergent part or in the part of the constant width near the inflow section) a formed new detonation wave moves upstream from the channel. Thus, these disturbances destroy the detonation stabilization in the flow.

As a result of the detailed analysis it has been established that the flow under consideration with stabilized detonation in the channel with narrowing cross-section is stable to those disturbances (excited by energy input) that do not initiate a new detonation wave upstream some critical cross section of the channel. At such disturbances detonation wave remains in the divergent part of the channel and the flow with stabilized detonation restores with time. Otherwise, the detonation wave appears in the convergent channel part and wave moves upstream from the channel.

The possibility of controlling a stabilized detonation wave location in the high-velocity gas mixture flow in the plane channel with narrowing was investigated. So, the influence of increase of the incoming flow Mach number and of dustiness of the incoming combustible gas mixture to detonation stabilization in the flow was studied. In particular, it has been obtained that in the channel the form of which provides detonation stabilization in case of incoming flow Mach number M_0=5.2 (Fig. 1b), dustiness of the incoming combustible gas mixture leads to transferring of a stabilized detonation wave location in the downstream direction (Fig. 3).

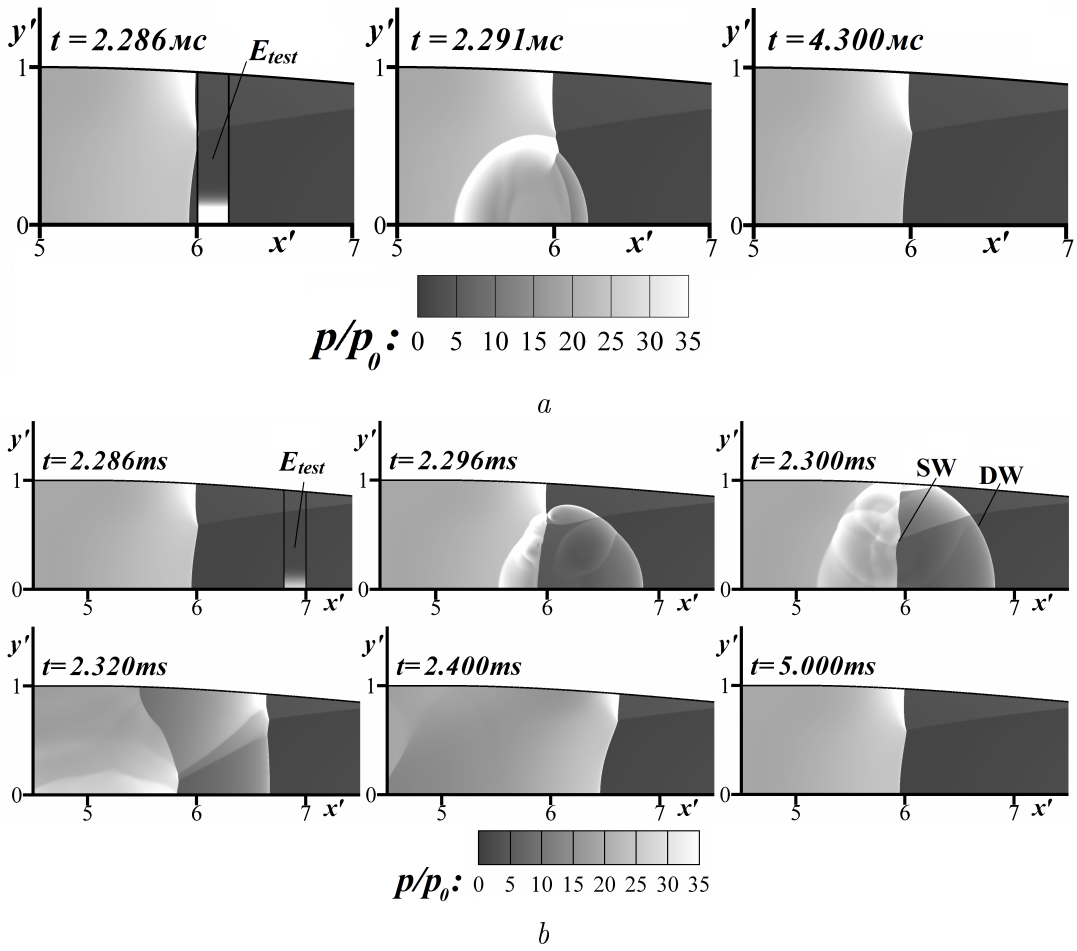

Figure 2: The conservation of stabilized detonation in case of energy input at the moment of time t=2.286ms for M_0=5.2: a - the energy input domain is located in front of the detonation wave ($E_{test} = 5E_0/3$); b - the energy input domain is located near the $x' = 7$ section ($E_{test} = E_0/3$). The channel part containing the stabilized detonation wave and a domain of energy input E_{test} is depicted.

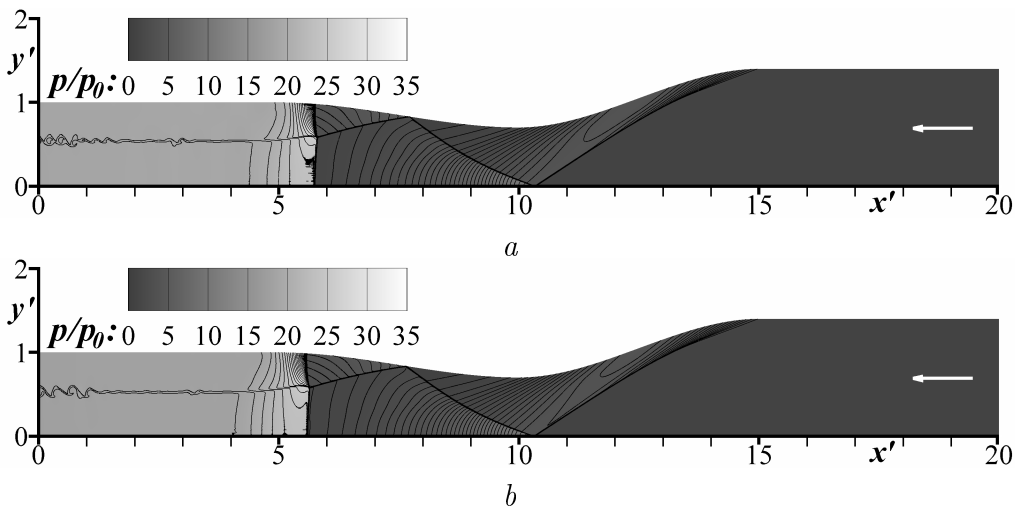

Figure 3: Stabilization of detonation combustion of the dusty gas mixture in the channel with narrowing cross-section for M_0=5.2: a – ρ_{so}=0.1kg/m^3, b – ρ_{so}=0.2kg/m^3. Here ρ_{so} is a dust density in the incoming flow.

4 Detonation wave stabilization in the supersonic flow in a plane channel of special shape

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 M_0=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 stabilized detonation is unsteady due to transverse waves propagating along the detonation front (Fig. 4a).

The structure of the stabilized ahead of the obstacle detonation wave in case of M_0=5.5 was considered in [10]. 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. The detected structure of the detonation wave stabilized ahead of the obstacle is conformed with a structure of a wedge-induced oblique detonation wave [11], [12].

Then detonation combustion of the gas mixture flowing at the same velocity into plane channels (the 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. The flow in the channel was investigated under different values of width of the inflow

cross-section. It has been established that for a fixed value of M_0 there is the critical value of inflow cross-section width such that detonation is stabilized in the channel if width of the inflow cross-section is more than critical one. A configuration of the stabilized detonation wave is the Mach one and the flow in the channel is qualitative identical to represented in Fig. 4*b*. In case of subcritical width of the inflow cross-section the overdriven detonation wave moves upstream from the channel.

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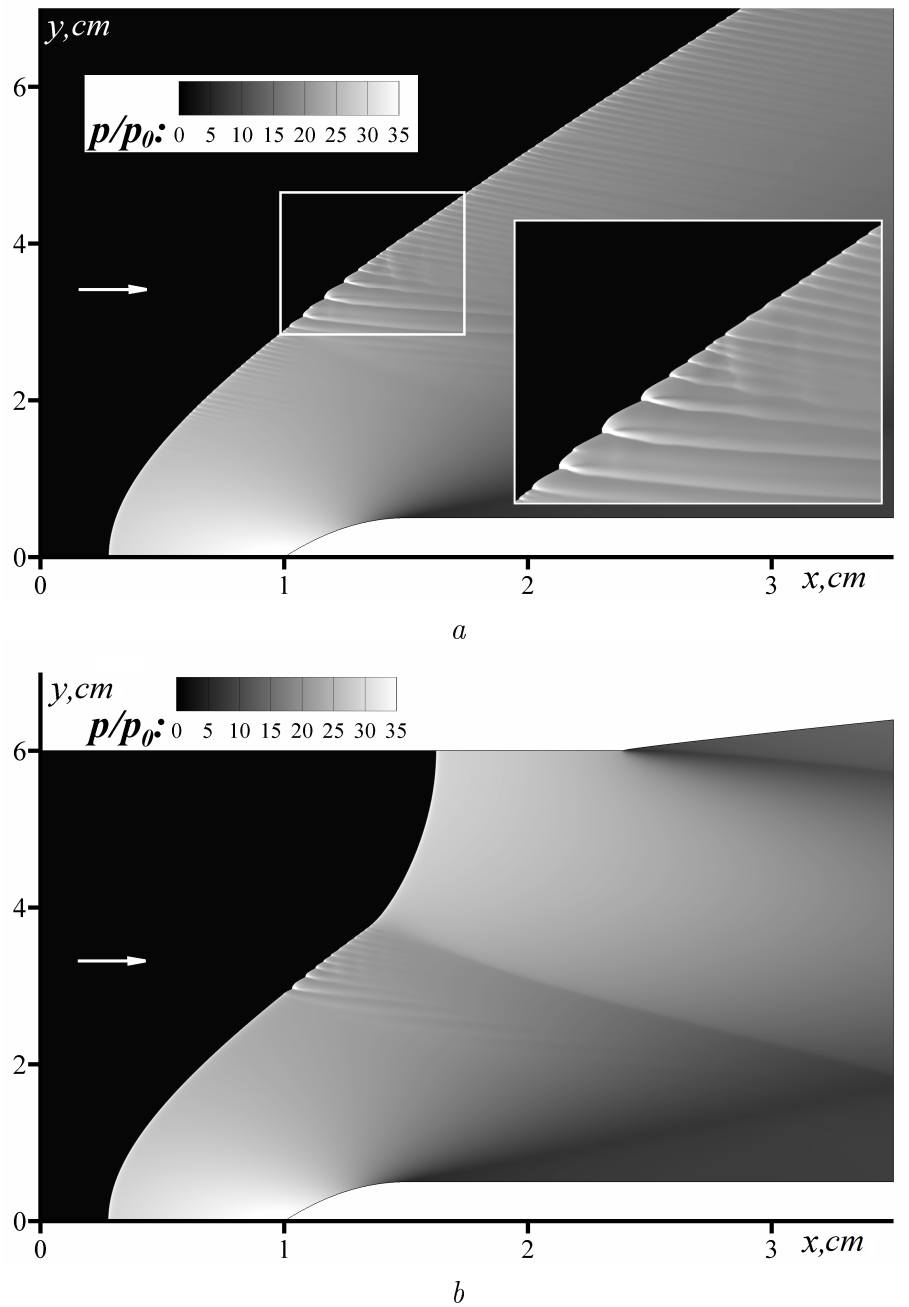

Figure 4: The flow in case of M_0=5.5: *a* – the detonation wave stabilized ahead of the obstacle; *b* – formation of stabilized detonation in the channel of the special shape with supercritical width of the inflow cross-section.

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