The Problem of Detonation Stabilization in a Supersonic Gas Flow in the Different Plane Channels

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1 Introduction

The interest in the study of detonation waves in a combustible gas mixture is closely connected with practical demands. So, the desire to use detonation in energy plants, for example, in detonation engines requires fundamental knowledge about the detonation process. In particular, the detail investigation of detonation propagation in a supersonic gas flow and determination of conditions that guarantee detonation stabilization are of great interest.

The method of detonation stabilization in a supersonic gas flow by means of weak additional discharges has been proposed in [1]. Developing the results of that research, the detonation stabilization by means of additional discharges at a large distance from the initiation place for some values of flow Mach number has been studied in [2, 3]. However the detonation stabilization without any additional energy input is of more interest. So, the conditions that guarantee detonation stabilization in supersonic flows of hydrogenous mixtures in an axisymmetric nozzle have been established in [4, 5]. Stabilization of rotating detonation in an axisymmetric combustion chamber has been studied in [6]. The formation of stationary detonation in the plane channels with a wedge-shaped part for some combustible gas mixtures has been examined [7−9]. Using quasi-one-dimensional model, the stabilization of infinity thin detonation in a supersonic flow in the channel with variable cross-section area has been studied too [10].

In the present research, the numerical investigation of detonation propagation in a stoichiometrical hydrogen-air mixture flowing with supersonic velocity into a plane channel with constant or variable cross-section area has been carried out with the purpose of determination of conditions that guarantee detonation stabilization in the gas flow. In case of the plane channel with parallel walls the cellular detonation stabilization by means of weak additional discharges has been studied. The possibility of detonation stabilization without any additional energy input in a supersonic flow of the combustible gas mixture in a plane channel of compound shape has been investigated.

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2 Mathematical Model

Detonation propagation in a premixed stoichiometrical hydrogen-air mixture flowing into a plane symmetrical channel with constant or variable cross-section area is studied. The combustible gas mixture under the normal conditions (p_0 =1atm, T_0 =298°K) is incoming into the channel with supersonic velocity that is essentially more than the velocity of self-sustaining detonation propagation in the mixture at rest with incoming flow parameters: $p = p_0$, $T = T_0$.

The initial instantaneous supercritical energy input E_0 (is sufficient for direct detonation initiation) in the narrow layer shaped domain of thickness h is used for detonation initiation. It is supposed that the dependence of energy input density E_V on transversal coordinate y (y =0 is the plane of symmetry) is exponential one (here $r_0 = h/2$ and l is the half of channel width in the energy input domain)

$$E_V(y) = A_0 \exp\left(-\frac{y^2}{r_0^2}\right), \text{ where } A_0 : \; E_0 = 2h A_0 \int_0^l \exp\left(-\frac{y^2}{r_0^2}\right) dy .$$

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

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

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

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

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

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

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 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, O, OH,* H_2, O_2, H_2O, HO_2, H_2O_2, N_2 and *Ar*.

The equations of state for the mixture have the usual form

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

Here, T is the temperature, R_0 is the universal gas constant. The values of partial enthalpies $h_i(T)$ were taken from [11].

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 conditions are imposed at the channel surface.

A set of gas dynamics equations coupled with detailed chemical kinetics equations [12] (in case of the channel with variable cross-section area) or [13] (in case of the channel with parallel walls) has been solved using a finite-difference method based on the classical Godunov's scheme [14] with use the exact solution of the Riemann Problem. The code has been validated on some standard test cases.

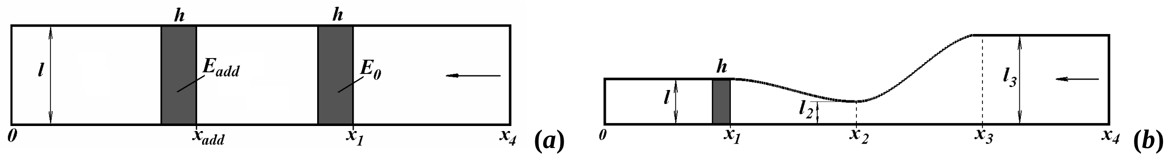

Figure 1. The schemes of the plane channel with parallel walls (***a***) and of the plane channel with variable cross-section area (***b***).

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 0.14mm − 0.012mm was used in numerical calculations. The dependence of numerical solution on grid resolution was verified. So, halving decrease of the mesh size did not lead to the qualitative change of the numerical solution.

3 Stabilization of the cellular detonation in the plane channel with parallel walls

The examination of cellular detonation stabilization by means of weak additional discharges in a supersonic flow of a stoichiometrical hydrogen-air mixture in the plane channel with parallel walls has been carried out. The scheme of upper half channel is depicted on fig. 1*a* (the arrow shows to flow direction): the inflow boundary is $x = x_4$, the outflow boundary is $x = 0$.

Two detonation waves are formed as a result of the initial energy input E_0 (h =0.001m): the one propagates downstream (this wave is transferred by flow) and the other one propagates upstream. Without any perturbations, the latter wave is transferred by gas flow too. Due to instability of the initiated detonation wave and due to numerical noise the detonation wave is modified and the steady cellular detonation is formed eventually [15, 16]. In the present research the location of additional discharges has been selected so that the cellular detonation approaches to the ones. Similarly to [2, 3] the additional discharges with exponential (Gauss) distribution of energy input density is used. Energy input by additional discharge $E_{add} = \alpha E_0$ (where α <<1) occurs at that moment when the front of the detonation wave is transferred by flow to the middle of the additional discharges domain. The discharge intensifies the leading shock and prevents thus the detonation transference by flow.

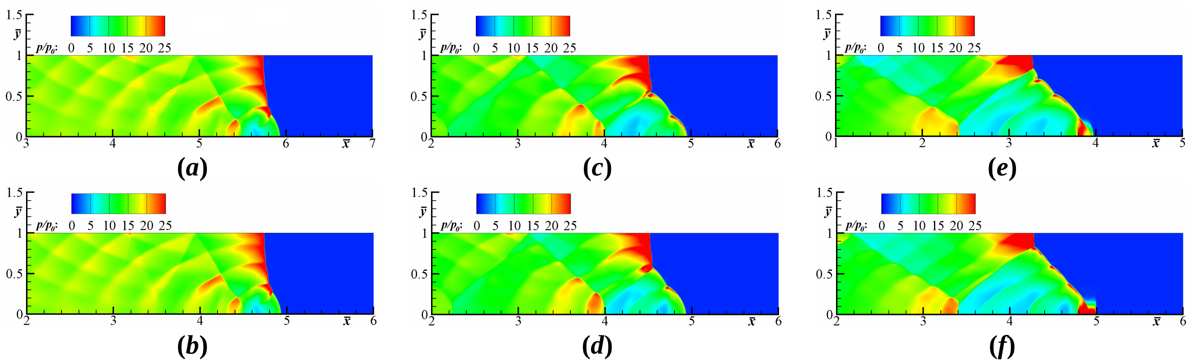

Figure 2. Detonation stabilization by means of weak additional discharges (x_1 / l =10): M_0 =5.2, α =0.05, L / l =4 (***a***); M_0 =5.2, α =0.15, L / l =5 (***b***); M_0 =5.5, α =0.05, L / l =5 (***c***); M_0 =5.5, α =0.15, L / l =5 (***d***); M_0 =6.0, α =0.05, L / l =6 (***e***); M_0 =6.0, α =0.15, L / l =5 (***f***) (here and then $\bar{y} = y / l$, $\bar{x} = x / l$).

However, the wave velocity gradually decreases and the detonation is again transferred by flow to the middle of the additional discharges domain, which leads to the actuation of the next discharge (to the input of energy E_{add}).

It has been established that for fixed incoming flow Mach number M_0 and for fixed additional discharges location $L = x_1 - x_{add}$ the detonation wave is stabilized in the flow if additional discharges energy E_{add} is more than some critical one (E^*_{add}). It has been detected that the critical energy E^*_{add} depends on discharges location very weakly and is determined by the flow Mach number substantially. It was obtained that in case of subcritical energy of discharges the detonation wave is transferred by flow and the detonation cellular structure modified by the additional discharges is reestablished after some time. This fact conforms to results of [17].

In case of supercritical energy of additional discharges the detonation combustion is stabilized in the flow and the wave is transformed to the stationary pulsating detonation eventually (fig. 2). Let us note that the shape of stabilized detonation wave is determined by the flow Mach number substantially. So, with the increase of the Mach number M_0 the detonation shape is more stretched along the flow and the straight part of the detonation front becomes smaller.

The influence of the flow Mach number M_0, of the energy of discharges E_{add} and of their location L on the process of detonation stabilization has been also studied. In particular, it was established that the frequency of the stabilized detonation additional energy input decreases with increase of the additional discharges energy or with decrease of the incoming flow Mach number.

4 Detonation stabilization in the plane channels of compound shape

The possibility of detonation stabilization without any additional energy input in a stoichiometrical hydrogen-air mixture flowing with supersonic velocity into the plane channel with variable cross-section area (the channel width is a continuously differentiable function of longitudinal coordinate) has been investigated. The scheme of upper half channel is depicted on fig. 1*b* (the arrow shows to flow direction): the inflow boundary is $x = x_4$, the outflow boundary is $x = 0$.

Two detonation waves are formed as a result of the initial energy input in the domain of thickness

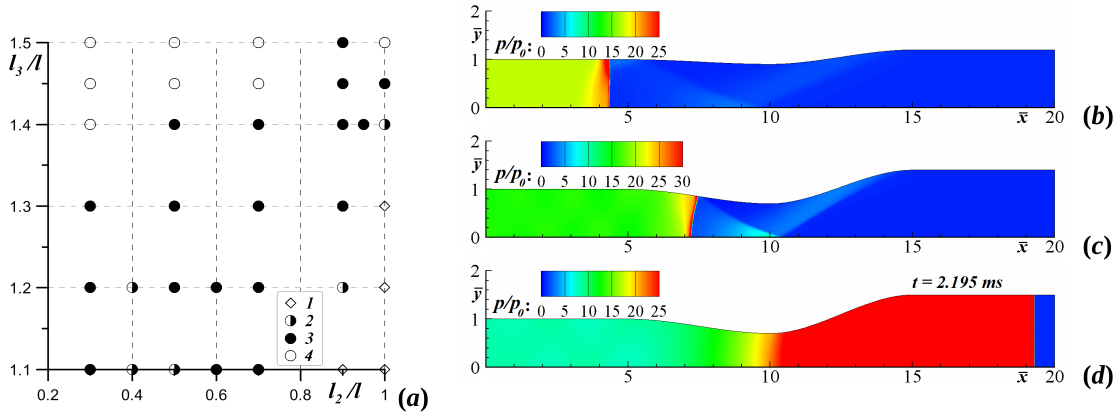

Figure 3. Detonation (DW) propagation in the channel with variable cross-section area in case of M_0 =5.2: ***a*** – the regimes of detonation propagation: *1* − DW is transferred by flow, *2* − DW is stabilized near the outflow boundary, *3* − DW is stabilized in the divergent part of the channel, 4 − DW comes out upstream from the channel; ***b*** – DW is stabilized near the outflow boundary in case of l_2/l =0.9, l_3/l =1.2; ***c*** – DW is stabilized in the divergent channel part in case of l_2/l =0.7, l_3/l =1.4; ***d*** – DW comes out upstream from the channel in case of l_2/l =0.7, l_3/l =1.5.

h =0.005m placed near the cross-section $x = x_1$: the one propagates downstream (this wave is transferred by flow) and the other one propagates upstream. The influence of geometrical parameters of the channel on propagation of the latter detonation wave has been studied for different values of the incoming flow Mach number M_0. Numerical calculations, the results of which are discussed below, were carried out with the following geometrical characteristics of the channel: l =0.025m, x_1/l =5, x_2/l =10, x_3/l =15, x_4/l =20.

So, for M_0 =5.2 the influence of geometrical channel parameters l_2/l and l_3/l on the detonation propagation has been considered. Let us note that if the channel width is constant ($l_2/l = l_3/l = 1$) the considered detonation wave is transferred by flow. It has been established that the different regimes of flow are realized according to values of these geometrical parameters (fig. 3*a*): the detonation wave is transferred by flow (*1*); the detonation is stabilized near the outflow boundary (*2*); the detonation is stabilized in the divergent (in the line of flow) part of the channel (*3*) and the detonation passing through opposed flow comes out from the channel (*4*). The pressure fields corresponding to the regimes 2–4 are represented on fig. 3*b*,*c*,*d*, respectively. The incoming flow Mach number influence on the propagation of detonation under others conditions being equal has been examined too.

For M_0 = 6 and 7, the flow in the channel with double-stage convergent part was considered. In case of M_0 =7, it has been obtained that there exist such values of the intermediate channel shrinkage at which the stationary detonation is formed in the convergent part of the channel without any energy input (fig. 4).

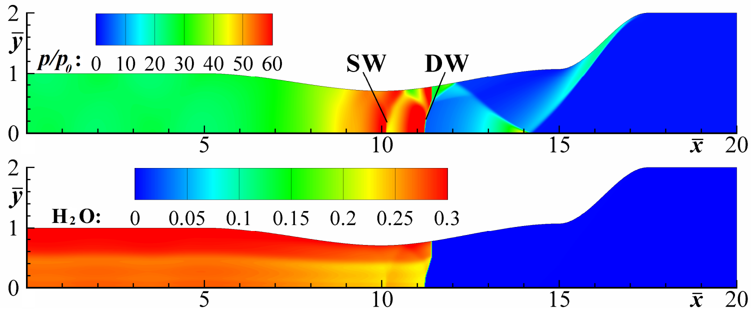

Figure 4. The formation of stationary detonation (DW) in the convergent part of the channel in case of M_0 =7, l_2/l =0.7, l_3/l =2.0 (SW is the attendant shock wave).

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