The Methods of Control of Stabilized Detonation Location in a Supersonic Gas Flow in a Plane Channel

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1 Abstract

Using a detailed kinetic model of chemical interaction, detonation stabilization in a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a symmetric plane channel with constriction the outflow section of which is more than the inflow one, and possibility of control of stabilized detonation location in the flow have been studied.

In case of detonation initiation by energy input, the investigation of conditions of formation in the channel of a thrust developing flow with a stabilized detonation wave was carried out. The effect of variations of the inflow Mach number, the dustiness of the inflowing gas mixture and the width of the outflow channel cross section on stabilized detonation location was examined with the purpose of thrust increase. Several methods of controlling of detonation location in the flow have been proposed. The possibility of formation of the thrust developing flow with stabilized detonation in the channel under consideration without any energy consumption has been detected.

2 Introduction

One of the main branches of research concerned with detonation waves is the investigation of detonation combustion in a supersonic gas flow [1], in particular, the determination of conditions that guarantee detonation stabilization in the flow. 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 [2, 3]. However, the possibility of detonation stabilization in a flow without any expenditure of energy is preferable. In this

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case a specially selected channel shape can provide stabilization of a detonation wave. The overview of studies devoted to detonation stabilization in a supersonic gas flow is given in [4]. So, the conditions of detonation stabilization in a hydrogen-air mixture flowing at a supersonic velocity into a plane channel with constriction the outflow section of which is smaller than the inflow one were investigated in [2]. The stability of the formed gas flow with detonation to strong disturbances excited by an energy input has been examined in [5].

In the present research the study of conditions of formation of the thrust developing flow with the stabilized detonation wave in the channel with constriction the outflow section of which exceeds the inflow one, is carried out, and the methods of stabilized detonation location control in the flow are proposed.

3 Mathematical Model

Similarly to [2, 5], detonation combustion of a premixed stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a symmetrical plane channel with constriction (inflow cross-section and outflow one are perpendicular to the incoming flow direction) is studied. The schematic of the upper part of the channel is shown in Fig. 1. 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. As opposed to the mentioned researches a flow in the channel, the outflow section of which exceeds the inflow one, was investigated, that is $l > l_3$. The combustible gas mixture under the normal conditions (pressure $p_0 = 1$ atm and temperature $T_0 = 298$ K) is incoming into the channel at a supersonic velocity that exceeds 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 inflow Mach number, M_{J0} is the Mach number of the self-sustaining detonation wave). Flowing into the channel the combustible gas mixture is considered as the mixture of the H_2, O_2, N_2 and Ar gases in the volumetric relation 42 : 21 : 78 : 1, respectively.

As the initial condition the steady plane flow of the gas mixture obtained by the marching to steady state method is used. As the zeroth approximation for determining the initial condition the incoming gas flow is taken. It should be noted that using a series of numerical calculations the geometric parameters of the channel were chosen so that the formed in the channel steady flow was supersonic everywhere.

The initial instantaneous supercritical energy input E_0 in a domain in the shape of a thin layer, h in thickness, located near the $x = x_1$ section (shaded region in Fig. 1) with the Gaussian dependence of the energy input density on the transverse coordinate was used for detonation initiation.

A set of Euler gas dynamics equations, describing a plain two-dimensional nonstationary flow of the inviscid reactive multi-component gas mixture, coupled with detailed chemical kinetics equations [6] has been solved using a numerical method based on the Godunov's scheme [7]. The used detailed kinetic

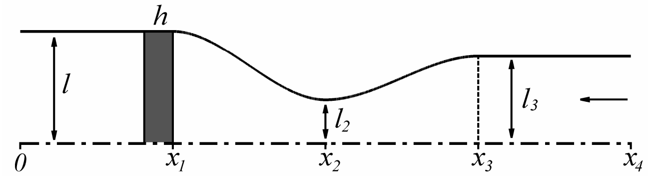

Figure 1. The schematic of the upper channel part. The arrow shows to flow direction

mechanism of hydrogen oxidation consists of twenty reversible reactions. 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 0.02 mm − 0.04 mm was used in numerical calculations. The numerical modeling was performed using the software package developed by the authors. The hybrid MPI/OpenMP parallelization of the computations was applied to reduce the time expenditures.

In this research the plane channels with constriction the geometrical parameters of which differ from channel parameters of [5] by the value of l were considered, that is $x_1 = 0.125$ m, $x_2 = 0.25$ m, $x_3 = 0.375$ m, $x_4 = 0.5$ m, $l_2 = 0.0175$ m, $l_3 = 0.035$ m, and $l > l_3$.

4 Control of Stabilized Detonation Location in a Supersonic Flow

As a result of the initial supercritical energy input E_0 two detonation waves are formed: one of which travels downstream and is carried away from the channel, whereas the other travels upstream. The conditions that provide stabilization of the latter wave, so that the formed flow develops thrust, were studied. In the case under consideration thrust T was defined as follows

$$T = 2\int_0^{x_4} p(x, y(x), t)\, ctg\alpha(x)\, dx,$$

here $y(x)$ is the function defining the form of the upper channel wall, $\alpha(x)$ is the angle between the outer normal to the upper wall and the longitudinal x axis.

It has been established that for some inflow Mach number M_0 the value of l may be selected so that the thrust developing flow with detonation stabilized in the divergent channel part is formed. In particular, it was obtained that in the $M_0 = 5$ case the sufficient condition for efficient detonation stabilization is the use of the channel with $l = 0.04$ m (Fig. 2). Let us note, for the detailed representation of the flow in Fig. 2 (and in the following figures) the pressure fields only in the channel part containing the detonation wave are plotted. In the case under consideration the detonation wave initiated by energy input near the $x = 0.125$ m section moves upstream and is stabilized with time near $x = 0.143$ m section (close to the symmetry plane).

The control of stabilized detonation location in the gas mixture flow in the channel by means of variations of the inflow Mach number, the dustiness of the inflowing gas mixture and the width of the outflow

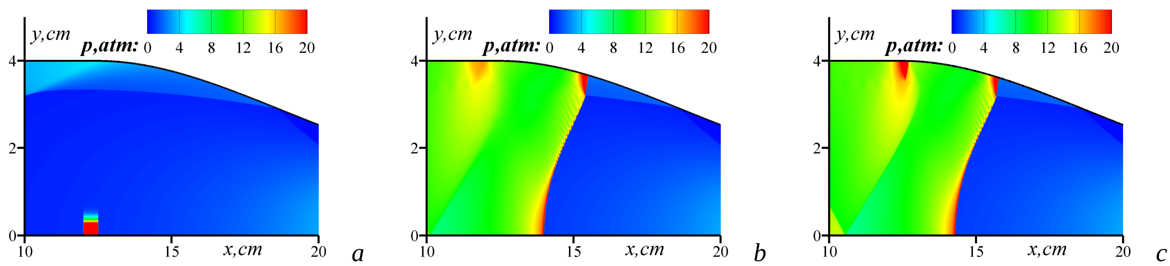

Figure 2. Formation of the flow with the stabilized detonation wave in the channel with constriction in case of $M_0 = 5$ and $l = 0.04$ m: *a* – $t = 0.0$ ms; *b* – $t = 1.0$ ms; *c* – $t = 3.1$ ms

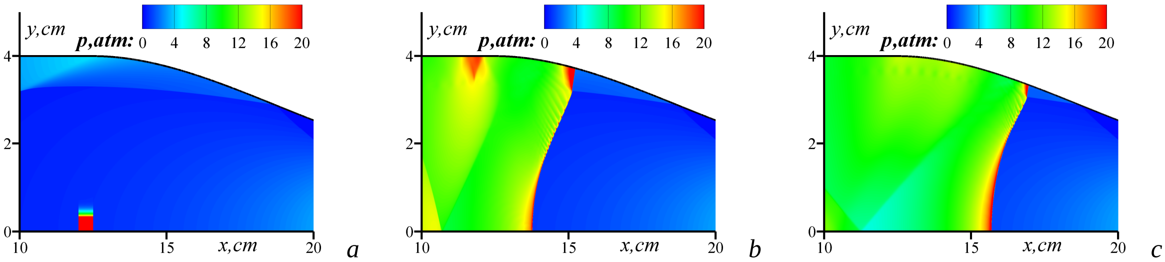

Figure 3. Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0 = 4.9, l = 0.04 m, and ρ_{s0} = 0.1 kg/m^3: *a* – t = 0.0 ms; *b* – t = 0.5 ms; *c* – t = 3.9 ms

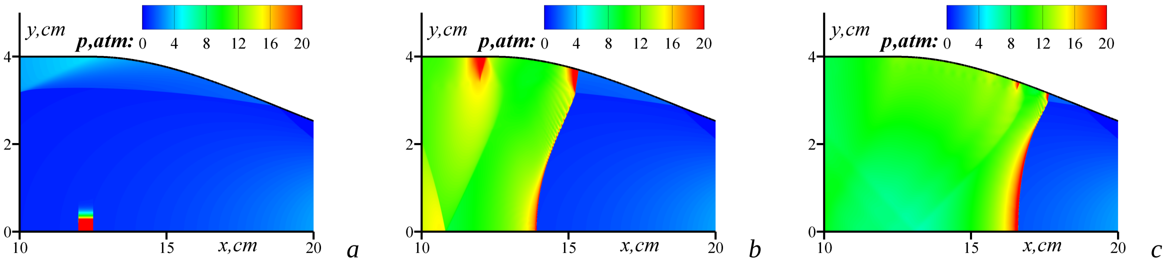

Figure 4. Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0 = 4.9, l = 0.04 m, and ρ_{s0} = 0.06 kg/m^3: *a* – t = 0.0 ms; *b* – t = 0.5 ms; *c* – t = 6.5 ms

channel section was studied with the purpose of detonation combustion efficiency increase. The adapted to multi-component mixtures [5] the one-velocity and one-temperature model [8] was used for dusty gas mixture flow simulation. This model describes the flow of gas with very small inert particles. In the investigations the dust particles with specific heat c_s = 800 J/(kg·K) were used.

So, the decrease M_0 (M_0 = 4.9) leads to the situation in which the detonation wave moves through the channel and leaves it in the counterflow direction. It has been established that the addition of fine inert dust particles into the gas flow may be used for detonation stabilization due to decrease of detonation velocity in the dusty gas mixture. Thus, in case of dust density ρ_{s0} =0.1 kg/m^3 in the incoming flow of the dust gas mixture (the flow Mach number M_0 = 4.9) the detonation wave is stabilized (Fig. 3) upstream of detonation location in the pure mixture in case of M_0 = 5 and thrust increases more than 3 times. Moreover, variation of a dust density in the incoming flow makes it possible to control the location of stabilized detonation. So, the decrease of ρ_{s0} (ρ_{s0} = 0.06 kg/m^3) leads to transfer of the stabilized detonation location in the divergent part closer to the channel throat (Fig. 4) and more than 5 times thrust increase as compared to the considered above case of M_0 = 5.

Another mechanism of detonation location control is the variation of a width of the outflow channel section. So, in case of the pure combustible mixture flowing into the channel at a velocity corresponding to M_0 = 4.9, a width of the outflow channel section may be selected so that the formed in the channel flow with the detonation wave develops thrust that exceeds the one in case of M_0 = 5. Thus, the small increase of l (l = 0.045 m) in case of M_0 = 4.9 provides more than 2.5 times increase of thrust as compared to the considered case of M_0 = 5.

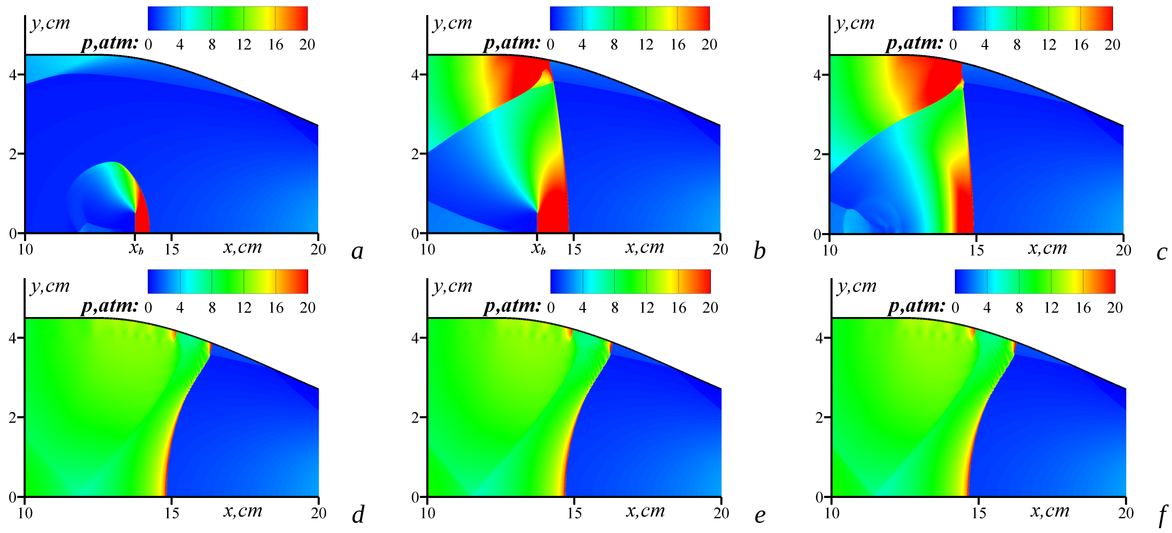

Figure 5. Formation of the flow with stabilized detonation in case of using the barrier (with height $h_b = 0.005$ m located on the plane of symmetry near the $x_b = 0.1375$ m section for a period of time $t_b = 0.05$ ms) for detonation initiation in case of $M_0 = 4.9$, $l = 0.045$ m: *a* – $t = 0.01$ ms; *b* – $t = 0.05$ ms; *c* – $t = 0.06$ ms; *d* – $t = 0.5$ ms; *e* – $t = 1.0$ ms; *f* – $t = 2.5$ ms

The possibility of detonation initiation and formation of the thrust developing flow with the stabilized detonation wave in the channel without any energy input has been detected. In these cases the obstacle (barrier) was used for detonation initiation. Thus, in the latter considered case $M_0 = 4.9$ and $l = 0.045$ m a detonation wave may be initiated by means of the barrier with height $h_b = 0.005$ m located on the plane of symmetry near the $x_b = 0.1375$ m section for a period of time $t_b = 0.05$ ms (Fig.5). The detonation wave, formed in front of the barrier (Fig.5 *a*, *b*), is stabilized with time in that particular place where detonation initiated by initial energy input was stabilized. So, in this case the thrust developing flow with detonation is formed without any energy consumption.

5 Conclusions

Using a detailed kinetic model of chemical interaction, detonation stabilization in a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a symmetric plane channel with constriction the outflow section of which exceeds the inflow one, and possibility of control of stabilized detonation location in the flow have been studied.

The possibility of formation of the thrust developing flow with a stabilized detonation wave in the channel has been established. The influence of variations of the inflow Mach number, the dustiness of the inflowing gas mixture and the width of the outflow channel cross section on the stabilized detonation location has been examined with the purpose of thrust increase. The methods of controlling of detonation location have been proposed. The possibility of detonation initiation and formation of the thrust developing flow with the stabilized detonation wave without any energy consumption in the channel with constriction has been detected.

6 Acknowledgments

This research has been supported by the Russian Foundation for Basic Research (project 16-29-01092), and by the Ministry of Education and Science of the Russian Federation (project NSh-8425.2016.1). This research has been supported by the Supercomputing Center of Lomonosov Moscow State University [9].

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