HiSST: International Conference on
High-Speed Vehicle Science Technology
26–29 November 2018, Moscow, Russia

Stabilization and Control of Detonation in Supersonic Gas Flow in Plane Channel

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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 exceeds 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. Several methods of control of stabilized detonation location in the flow with purpose of thrust increase 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.

Keywords: *supersonic flow, plane channel, detonation stabilization, detonation control, thrust.*

Nomenclature

D – Detonation wave velocity
E_0 – Energy input
L – Width of a plane channel with gas at rest
M – Mach number
R_0 – Universal gas constant
T – Temperature
Y – Mass fraction
h – Specific enthalpy
$\tilde{h}$ – Partial enthalpy
h_b – Height of a barrier
l – Channel width
n – Specific concentration of species of a mixture
p – Pressure
t – Time
u – Velocity component
v – Velocity component
x – Longitudinal coordinate
y – Transversal coordinate

Greek
α – Geometrical channel parameter
ρ – Density
ω – rate of formation/depletion of species of a mixture
τ – existence time

Subscripts
0 – Inflow parameters
J – Self-sustained
$J0$ – Self-sustaining under incoming flow condition
1, 2, 3, 4 – Denotation of different channel geometrical parameters
S – Particles
i – Denotation of species of the mixture
b – Barrier

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1. 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 [1] requires fundamental knowledge about the detonation combustion in 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 in a plane channel with parallel walls by means of weak discharges has been proposed in [2]. However, the possibility of detonation stabilization in a flow without any expenditure of energy is preferred. In this case a specially selected channel shape can provide stabilization of a detonation wave. There have been many studies devoted to an investigation of detonation stabilization in a supersonic gas flow. The overview is given in [3]. In particular, 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 was examined in [4]. However, in the considered in [2, 4] cases combustion of gas mixture in the detonation wave turned out to be ineffective, as the flow did not produce thrust.

In the present research the study of conditions of formation of the thrust developing flow with the stabilized detonation wave in the plane symmetrical channel with constriction is carried out, and the methods of stabilized detonation location control in the flow are proposed.

2. Mathematical Model

As in researches [2, 4], we study detonation combustion of a premixed stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a symmetrical plane channel with constriction. The schematic of the upper part of the channel is shown in Fig. 1. As opposed to the mentioned researches a flow in the channel, the outflow section of which exceeds the inflow one, is 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 parallel to its plane of symmetry. 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.

The system of equations describing the plane two dimensional (2D) nonstationary flow of inviscid nonheat-conducting reactive multi-component gas mixture is as follows:

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

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

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

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

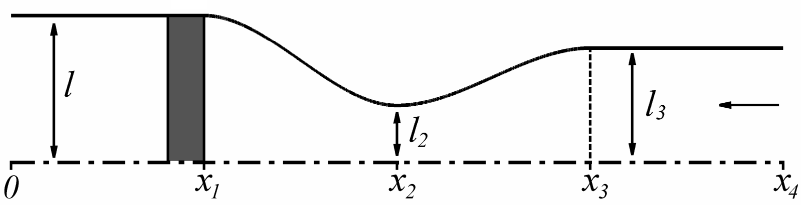

Fig 1. The schematic of the upper channel part. The arrow shows to flow direction

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

The equations of state of the combustible mixture considered as a perfect gas are as follows:

$$p=\rho R_0 T\sum_i n_i\ ,\quad h=\sum_i n_i\tilde{h}_i(T)\,.$$

Temperature dependences of the partial enthalpies $\tilde{h}_i(T)$ are determined from the reduced Gibbs energies of the corresponding mixture components [5].

As the initial condition the steady plane flow of the gas mixture obtained by the marching to steady state method is used. Note that 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 located near the $x=x_1$ section (shaded region in Fig. 1) was used for detonation initiation.

A set of Euler gas dynamics equations coupled with detailed chemical kinetics equations [6] has been solved using the classical Godunov's scheme [7]. 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 – 0.03 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 computations was applied to reduce time expenditures.

In this research gas flows in plane channels with the following geometrical parameters: $x_1=0.125$ m, $x_3=0.375$ m, $x_4=0.5$ m, $l_2=0.0175$ m, $l_3=0.035$ m, $l>l_3$ and variable value $\alpha=(x_2-x_1)/(x_3-x_1)$ were considered.

3. Numerical Results

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 one travels upstream. The conditions that provide stabilization of the latter wave, so that the formed flow develops thrust, were studied.

First, the case when an inflow velocity 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 inflow Mach number, M_{J0} is the Mach number of the self-sustaining detonation wave) has been studied. It has been established that for some inflow Mach number M_0 ($\alpha=0.5$) the value of l may be selected so that the thrust developing flow with detonation stabilized in the divergent part of the channel 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). For the detailed representation of the flow near the detonation wave in Fig. 2 (and in the following figures) the flow parameters only in the channel part containing the detonation wave are represented. In the case under consideration the detonation wave initiated by energy input near the x = 0.125 m section moves upstream (Fig. 2 *a*) and is stabilized with time in the divergent part of the channel (Fig. 2 *b*, *c*). The stabilized wave (*1*) forms a three-shock Mach configuration with the oblique shock wave (*2*) of the stationary flow. The flow with stabilized detonation combustion is unsteady owing to instability of the contact discontinuity (*3*) and propagation of transverse waves (*4*).

The control of stabilized detonation location in the gas mixture flow in the channel by means of variations of the inflow Mach number, addition of fine inert particles into the inflowing gas mixture and the channel geometrical parameters was studied with the purpose of detonation combustion efficiency increase. Adapted to multi-component mixtures [4] one-velocity and one-temperature

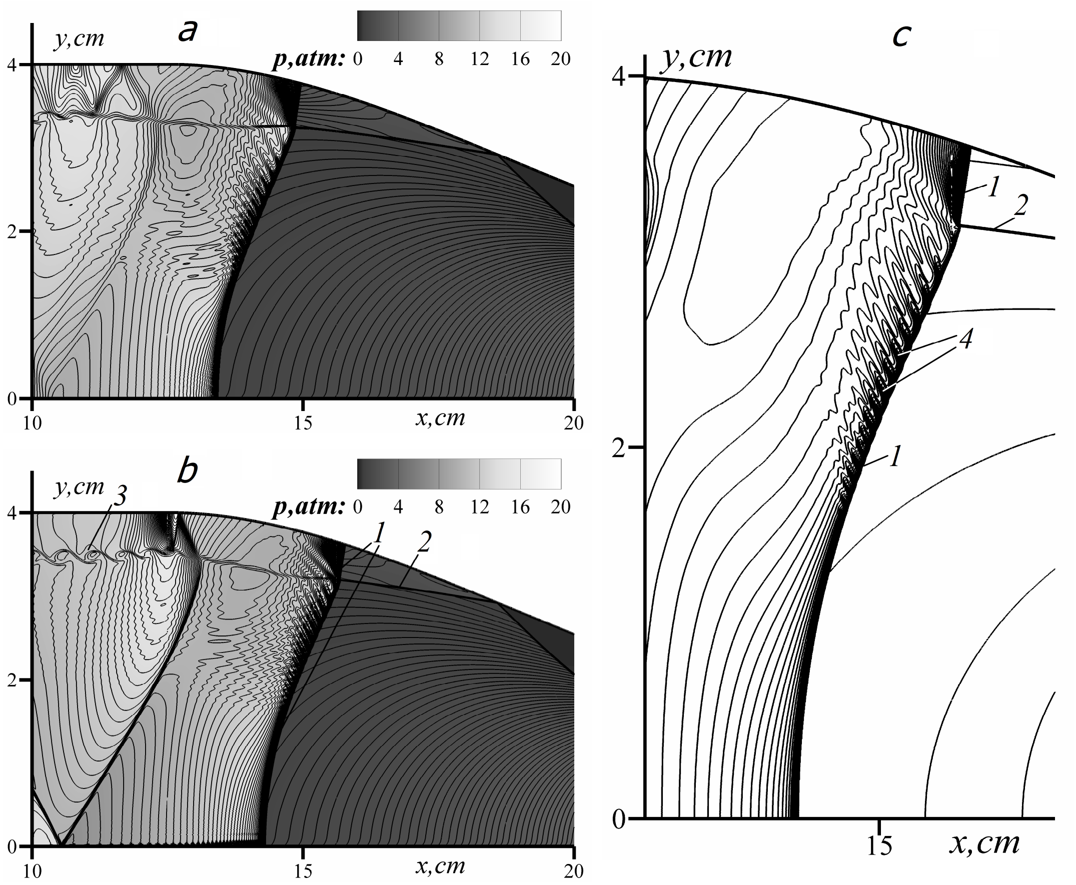

Fig 2. Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0 = 5, α =0.5, l = 0.04 m: *a* – t = 0.5 ms, *b, c* – t = 3.1 ms; *a, b* – pressure field and density contours, *c* – pressure contours; *1* – stabilized detonation wave, *2* – oblique shock wave of the stationary flow, *3* – contact discontinuity, *4* – transverse waves

model [8] was used for dusty gas mixture flow simulation. This model describes the flow of gas with very small inert particles.

It is well known that the velocity of detonation waves in gas mixtures depends strongly on the mixture composition, the concentrations of the fuel and oxidant, and the presence of various additions in the mixture [9, 10]. This allows one to control the propagation of a detonation wave and, if necessary, to guarantee the quenching of detonation combustion. In [11], it was found numerically that when one increases the volume fraction of quiescent inert particles in a gas mixture, the cell of the detonation wave passing through the particles enlarges; and a further increase in the fraction of particles leads to detonation failure. In [12], it was established experimentally that detonation combustion in a gas mixture can be completely quenched by the veil of inert dust particles. Contrariwise, a means of conservation of detonation combustion are of interest.

We investigated detonation propagation in a quiescent gas mixture under the normal condition in a plane channel of constant width L. This way, the modelling of detonation propagation in a stoichiometrical hydrogen-air mixture with inert particles in case of particles mass fraction Y_S = 0.104 indicated that the addition of fine inert particles into the gas mixture results in decrease of the detonation propagation velocity D_J ($D_J \approx$ 1840 m/s) and increase of the detonation cell rate. It should be noted, that in case of a pure stoichiometrical hydrogen-air mixture $D_J \approx$ 1975 m/s. Contrariwise, preliminary decomposition of some volume of the molecular hydrogen and molecular oxygen gases into atomic gases in the pure combustible mixture leads to increase of detonation propagation velocity and decrease of detonation cell size. So in case of detonation combustion of the

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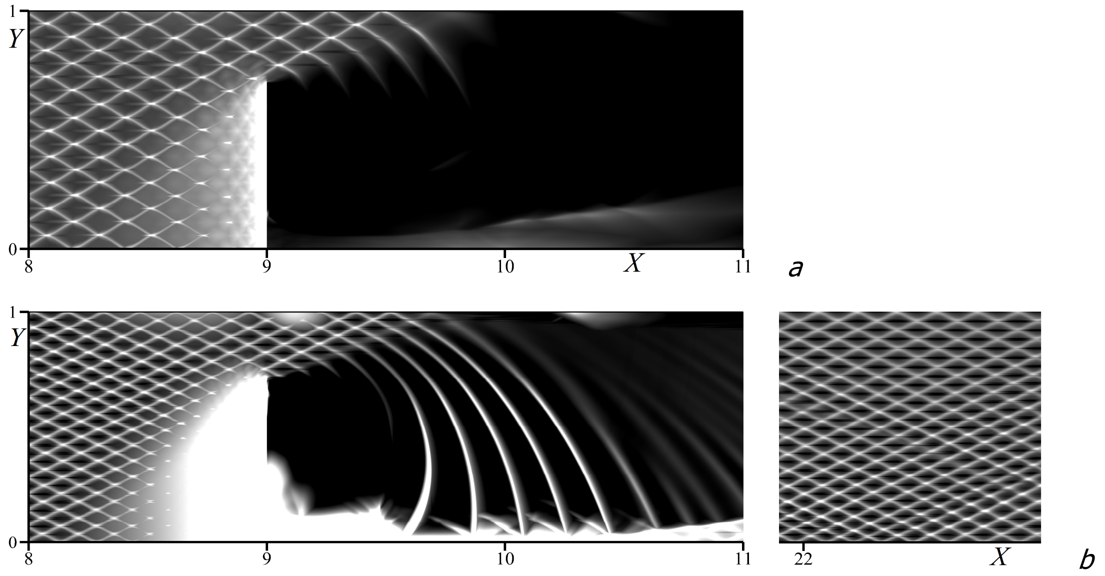

Fig 3. Numerical soot foil in case of detonation propagation in a plane channel of width L with a barrier ($h_b = 0.7L$, $x_b = 9L$): *a* – detonation destruction in case of the stoichiometrical hydrogen-air mixture, *b* – detonation conservation in case of the preliminary prepared mixture. Here $X = x/L$, $Y = y/L$. Detonation propagates from left to right

mixture H_2, H, O_2, O, N_2, Ar gases in the volumetric relation 41.16 : 1.68 : 20.58 : 0.84 : 78 : 1, respectively, the detonation propagation velocity $D_J \approx 2010$ m/s.

We examined influence of preliminary preparation of the gas mixture to detonation propagation in a quiescent gas in a channel of width L with a nondestructing infinitely-thin transverse obstacle (barrier) of height h_b smaller than the channel width L. The barrier located at a distance x_b from the closed channel end. The distance x_b was so chosen that a detonation wave with a formed cellular structure approaches the barrier. It is known, that there is a critical obstacle height, dependent on the channel width, such that the detonation wave is destructed after the interaction with the barrier if its height exceeds the critical value [13]. It was established that the critical height of the barrier for the prepared mixture exceeds the critical height for the unprepared under other conditions being equal (Fig. 3). This fact allows the use of preliminary conversion of the mixture to prevent destruction of the detonation wave by the obstacle (barrier) located in the channel. It should be noted that in case of conservation of detonation combustion after passing the obstacle the detonation wave structure is temporarily modified and then the previous flow pattern is restored (Fig. 3*b*).

The established ability to detonation velocity control by means of inert particles was used to stabilization of detonation combustion in the supersonic gas mixture flow in a symmetrical plane channel with a constriction. It has been established that in some cases when the geometric parameters of the channel do not ensure detonation stabilization in the supersonic flow, the addition of fine inert particles into the gas mixture flowing into the channel leads to formation of thrust developing flow with a stabilized detonation wave. So in case of decrease M_0 (M_0 = 4.9) under other conditions been equal (α = 0.5, l = 0.04 m) the detonation wave moves through the channel and leaves it in the counterflow direction. It has been established that the addition of particles (mass fraction Y_S = 0.104) in the incoming flow (inflow Mach number M_0 = 4.9) leads to detonation stabilization (Fig. 4*a*) upstream of detonation location in the pure mixture in case of M_0 = 5 and thrust increases over 3 times. Moreover, variation of particles mass fraction in the incoming flow makes it possible to control of location of stabilized detonation. So, the decrease of Y_S (Y_S = 0.065) leads to transfer of the stabilized detonation location in the divergent part closer to the channel throat

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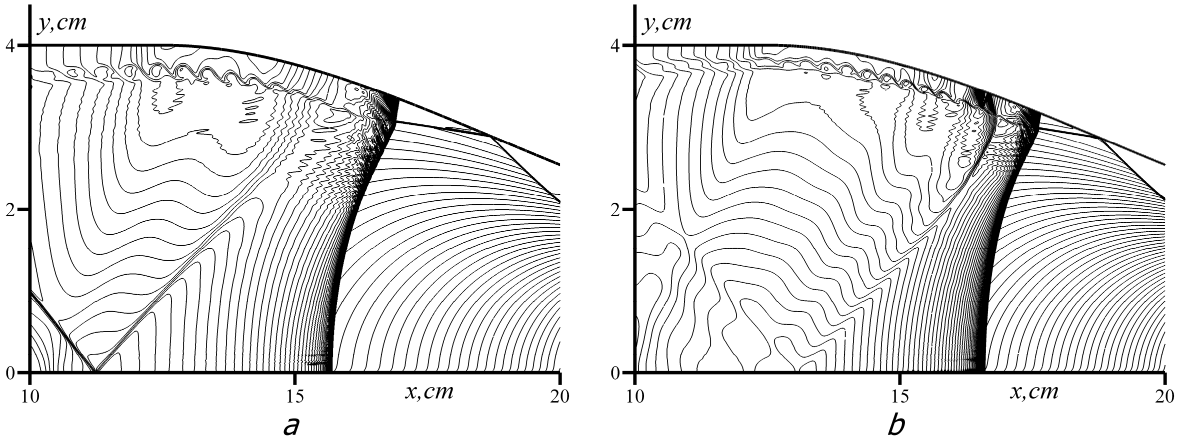

Fig 4. Stabilization of a detonation wave in the channel with constriction in case of the dusty gas mixture, M_0 = 4.9, α =0.5, and l = 0.04 m (density contours): *a* – dust mass fraction Y_S = 0.104, *b* – dust mass fraction Y_S = 0.065

(Fig. 4*b*) 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 variation of 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, small extension of the outflow channel part l = 0.045 m in case of M_0 = 4.9, α =0.5 provides more than 2.5 times increase of thrust.

In channels that provide stabilization of detonation initiated by energy input the possibility of formation of the thrust developing flow with a stabilized wave without any energy expenditure has been detected. In these cases, an obstacle (barrier) was used to initiate detonation. Thus, in the latter considered case M_0 = 4.9, α = 0.5, l = 0.045 m a detonation wave may be initiated by means of a 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 τ_b = 0.1 ms (Fig. 5). The detonation wave in this case is formed in front of the barrier (Fig. 5*a*). When the barrier vanishes the wave moves in the divergent channel part (Fig. 5 *b*, *c*) and is stabilized with time (Fig. 5*d*) 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.

The effect of variations of barrier height, its location, and existence time on detonation stabilization in the flow has been studied. It has been established that in order to achieve detonation stabilization a barrier height h_b, its location x_b and time τ_b must be selected so that the initiated detonation wave does not travel upstream of a certain (critical) channel section. If the condition is granted the detonation combustion of a mixture continues to proceed in the divergent part of the channel and the flow with a stabilized detonation wave is formed with time. Otherwise, the detonation wave turns out to be located in the convergent part and leaves the channel counter the flow with time.

In addition, conditions that guarantee formation of the thrust developing flow with stabilized detonation in case when a velocity of the inflow is less than a velocity of propagation of the self-sustaining detonation wave have been detected. As a result of numerical calculations it has been established that for inflow Mach number M_0 = 4.8 ($M_0 < M_{J0}$) the values of l and α may be selected so that the thrust developing flow with detonation stabilized in the divergent channel part is formed. Specifically, in case of l = 0.07 m and α = 0.65 the detonation wave initiated by energy input moves upstream and is stabilized with time in the divergent part of the channel (Fig. 6). The

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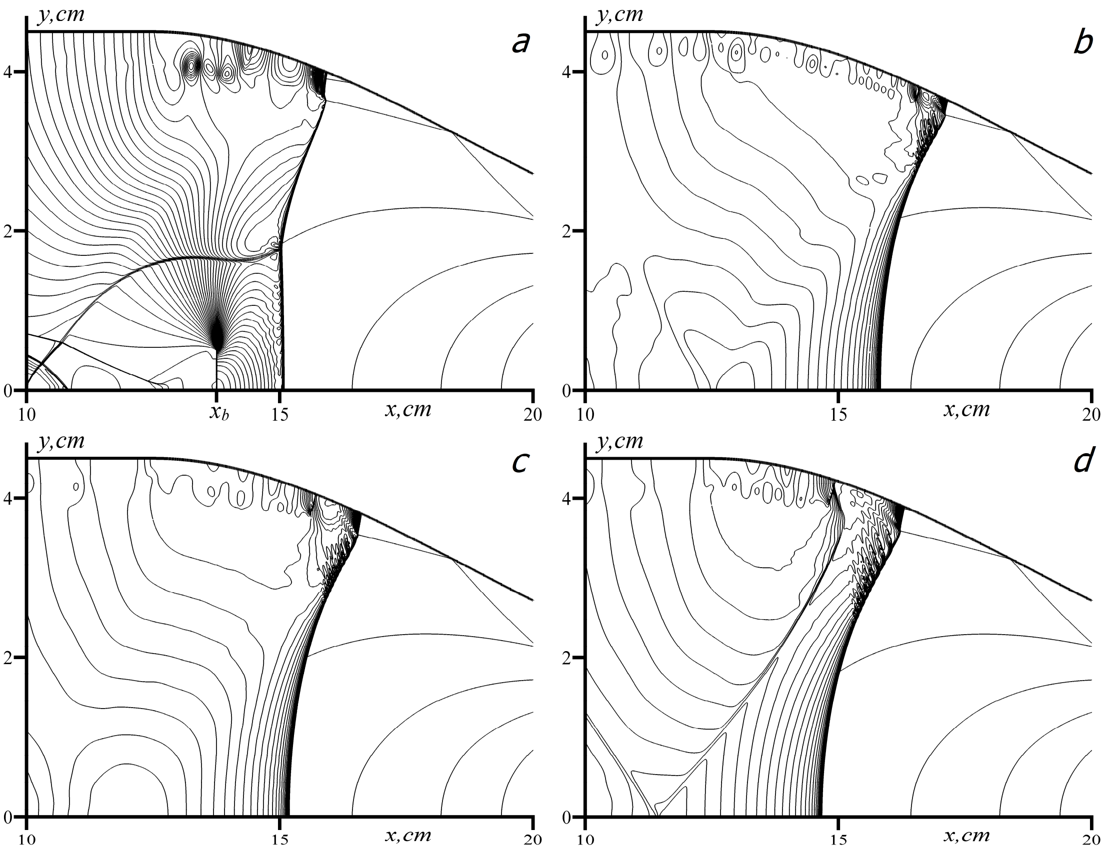

Fig 5. Formation of the flow with stabilized detonation in case of using the barrier (with height h_b = 0.005 m located on the plane of symmetry near the x_b = 0.1375 m section for a period of time τ_b = 0.1 ms) for detonation initiation in case of M_0 = 4.9, α =0.5, l = 0.045 m (pressure contours): $a - t$ = 0.1 ms; $b - t$ = 0.3 ms; $c - t$ = 1.0 ms; $d - t$ = 2.3 ms

flow formed in this case develops thrust that is 2 times greater than that in the considered case of M_0 = 5. Moreover, the variation of l and coordinated variation α make it possible to control the location of stabilized detonation with the purpose of thrust increase. This way, the decrease of l and α (l = 0.06 m and α = 0.6) leads to transfer of the stabilized detonation location in the divergent part closer to the channel throat and over 2 times thrust increase as compared to the considered case of l =0.07m and α =0.65.

4. Conclusion

Using a detailed kinetic model of chemical interaction, detonation combustion of a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a symmetric plane channel with constriction has been studied with purpose of determination of conditions of formation in the channel of a thrust developing flow with a stabilized detonation wave.

In case when an inflow velocity exceeds a velocity of propagation of the self-sustained detonation wave, conditions that provide formation in the channel of a thrust developing flow with stabilized detonation initiated by energy input have been determined. The effect of variations of the inflow Mach number, the concentration of fine inert dust particles added into the inflowing gas mixture, and the width of the outflow channel cross section on stabilized detonation location was examined. Several methods of control of stabilized detonation location in the flow with purpose of thrust increase have been proposed.

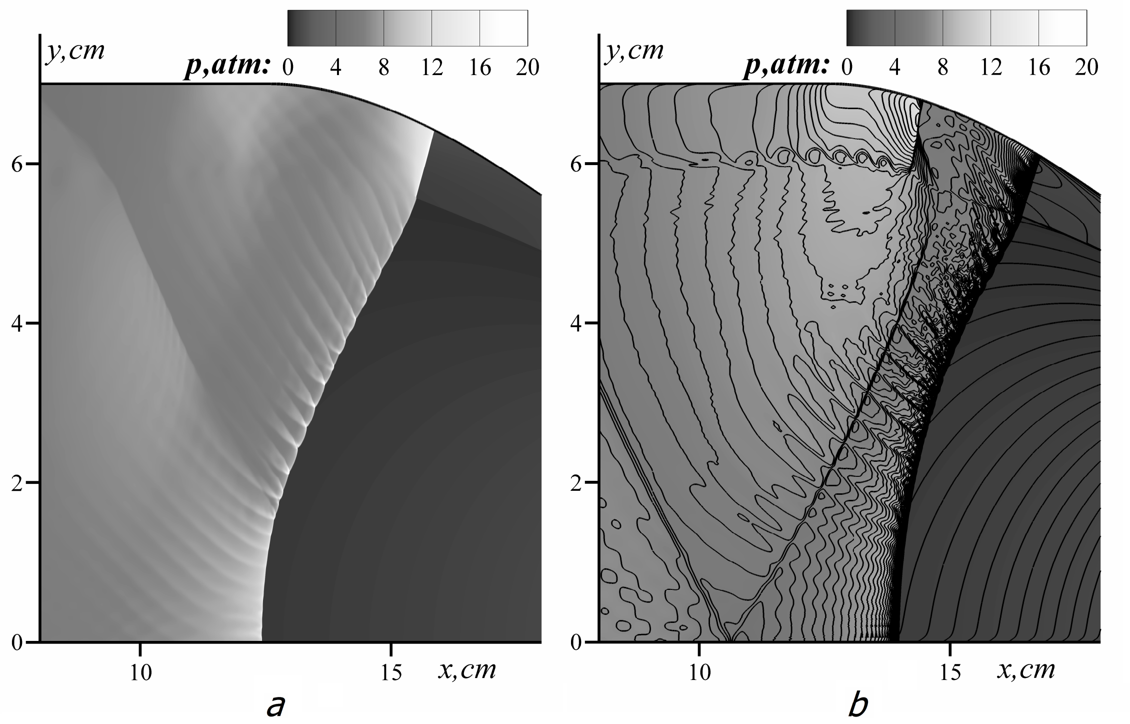

Fig 6. Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0 = 4.8, α = 0.65, l = 0.07 m: a – t = 0.3 ms (pressure field); b – t = 2.7 ms (pressure field and density contours)

In channels that provide stabilization of detonation initiated by energy input the possibility of formation of the thrust developing flow with a stabilized wave without any energy expenditure has been detected. In these cases, an obstacle (barrier) was used to initiate detonation. The effect of variations of barrier height, its location, and existence time on detonation stabilization in the flow has been studied.

In addition, conditions that guarantee formation of the thrust developing flow with stabilized detonation in case when a velocity of the inflow is less than a velocity of propagation of the self-sustained detonation wave have been detected.

5. Acknowledgments

This research has been supported by the Ministry of Education and Science of the Russian Federation (contract 14.G39.31.0001 on 13.02.2017). Influence of the addition of fine inert dust particles into gas mixture on detonation stabilization has been studied with the assistance of the Russian Foundation for Basic Research (projects 16-29-01092, 18-01-00883). The research is carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University [14].

References

1. Kraiko, A.N.: Theoretical and Experimental Validation of the Concept of a Pulsed Engine with a Detonation Wave Moving counter a Supersonic Flow. In: Frolov, S.M. (ed.) Pulsed Detonation Engines, pp. 569–590. Torus Press, Moscow (2006)
2. Zhuravskaya, T.A., Levin, V.A.: Investigation of certain techniques for stabilizing detonation waves in a supersonic flow. Fluid Dynamics. 47(6), 793–801 (2012)
3. Zhuravskaya, T.A., Levin, V.A.: Stabilization of detonation combustion of a high-velocity combustible gas mixture flow in a plane channel. Fluid Dynamics. 50(2), 283–293 (2015)

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4. Zhuravskaya, T.A., Levin, V.A.: Stability of Gas Mixture Flow with a Stabilized Detonation Wave in a Plane Channel with a Constriction. Fluid Dynamics. 51(4), 544−551 (2016)
5. Glushko, V.P. (ed.): Thermodynamic properties of individual substances. Nauka, Moscow (1978) [in Russian]
6. Starik, A.M., Titova, N.S., Sharipov, A.S., Kozlov, V.E.: Syngas Oxidation Mechanism. Combustion, Explosion, and Shock Waves. 46(5), 491–506 (2010)
7. Godunov, S.K., Zabrodin, A.V., Ivanov, M.Ya., Kraiko, A.N., Prokopov, G.P.: Numerical Solution of Multidimensional Problems of Gasdynamics. Nauka, Moscow (1976) [in Russian]
8. Sedov, L.I.: Similarity and dimensional methods in mechanics. 10th ed. Boca Raton, CRC Press (1993)
9. Soloukhin, R.I.: Shock Waves and Detonations in Gases. Fizmatgiz, Moscow (1963) [in Russian]
10. Lee, John H.S.: The detonation phenomenon. Cambridge University Press, New York (2008)
11. Bedarev, I.A., Fedorov, A.V.: Mathematical modeling of the detonation wave and inert particles interaction at the macro and micro levels. J. Phys.: Conf. Ser. 894 (1), 012008 (2017)
12. Vasil’ev, A.A., Pinaev, A.V., Trubitsyn, A.A., Grachev, A.Yu., Trotsyuk, A.V., Fomin, P.A., Trilis, A.V.: What is burning in coal mines: Methane or coal dust? Combust. Explos. Shock Waves. 53, 8–14 (2017)
13. Zhuravskaya, T.A.: Propagation of Detonation Waves in Plane Channels with Obstacles. Fluid Dynamics. 42(6), 987−994 (2007)
14. Sadovnichy, V., Tikhonravov, A., Voevodin, Vl., Opanasenko, V.: "Lomonosov": Supercomputing at Moscow State University. In: Contemporary High Performance Computing: From Petascale toward Exascale (Chapman & Hall/CRC Computational Science), pp. 283–307. CRC Press, Boca Raton, USA (2013)

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