Detonation control in a supersonic gas flow in a plane channel

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Abstract

Using a detailed chemical kinetics, detonation combustion of a stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a plane symmetrical channel with a constriction was investigated with the purpose of both determination of conditions that provide detonation stabilization in the flow and study of methods of stabilized detonation location control.

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 incoming gas mixture and the width of the outflow channel cross section on stabilized detonation location was examined. Some methods of controlling of detonation location in the flow that ensure 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 input has been detected.

1 Introduction

One of the main areas of research of the process of detonation combustion is the investigation of detonation wave propagation in a supersonic gas flow [1], in particular, the determination of conditions that provide detonation stabilization in the flow. A detailed review of works devoted to this theme was presented in [2]. So, the conditions of stabilization of the formed detonation wave 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 [3]. The stability of the formed gas flow with detonation to strong disturbances excited by an energy input has been examined in [4].

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 is carried out, and some methods of control of stabilized detonation location are examined.

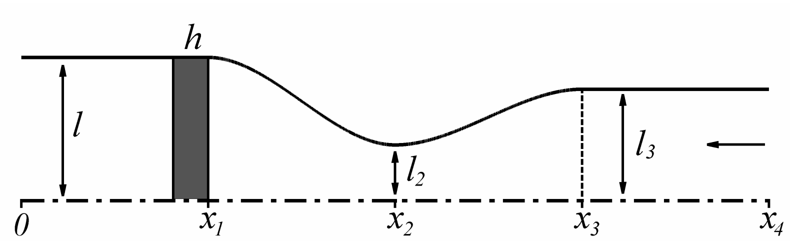

Figure 1: The schematic of the upper channel part (above the plane of symmetry). The arrow shows to flow direction

2 Mathematical Model

Similarly to [3], [4] detonation propagation in a premixed stoichiometrical hydrogen-air mixture flowing at a supersonic velocity into a plane symmetric channel with constriction 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 $x = 0$. In contrast to the cited researches the gas flow in a channel with an output cross section size exceeding the input one is considered. The combustible gas mixture under the normal conditions (p_0=1atm, T_0=298K) is incoming into the channel parallel to its plane of symmetry 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 assumed to be a mixture of the H_2, O_2, N_2 and Ar gases in the volume ratio $42 : 21 : 78 : 1$, respectively.
The set of gas dynamics equations describing a plain two-dimensional nonstationary flow of the inviscid reactive multi-component gas mixture is:

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

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

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

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

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

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 specific enthalpy, respectively; n_i is the specific molar concentration of the ith species in the mixture; and ω_i is the specific rate of formation/depletion of the ith component.

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

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

Here T is the temperature, R_0 is the universal gas constant. The partial enthalpy $h_i(T)$ of the ith mixture component are determined from the reduced Gibbs energies of the corresponding mixture components [5].

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.

As the initial condition the steady plane channel 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 the geometric parameters of the channel were chosen so that the steady flow formed in the channel is supersonic everywhere. The initial instantaneous supercritical energy input E_0 (sufficient for direct initiation of detonation combustion) 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 is used for detonation initiation.

A set of Euler gas dynamics equations coupled with detailed chemical kinetics equations [6] has been solved using a finite-difference method based on the Godunov's scheme [7]. The size of mesh of a computational grid was selected so that the flow behind the detonation front (in particular, the flow in the induction zone) was represented correctly. Thus numerical investigations were carried out on the grid at step 0.02 mm – 0.04 mm.

In this research the plane channels with constriction the geometrical parameters of which differ from channel parameters of [4] 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 $l > l_3$.

3 Detonation stabilization in the supersonic flow

The initial supercritical energy input E_0 results in formation of two detonation waves: one of which propagates downstream and rapidly is carried away from the channel, whereas the other wave travels upstream. The conditions that provide stabilization of the second wave in the flow, so that the formed flow develops thrust, were studied. In the case under consideration thrust was defined as follows

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

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

It has been established that for some inflow Mach number M_0 the value of half-width l of the output cross section can be selected so that the thrust developing flow with detonation stabilized in the divergent channel part is formed. In particular, it was

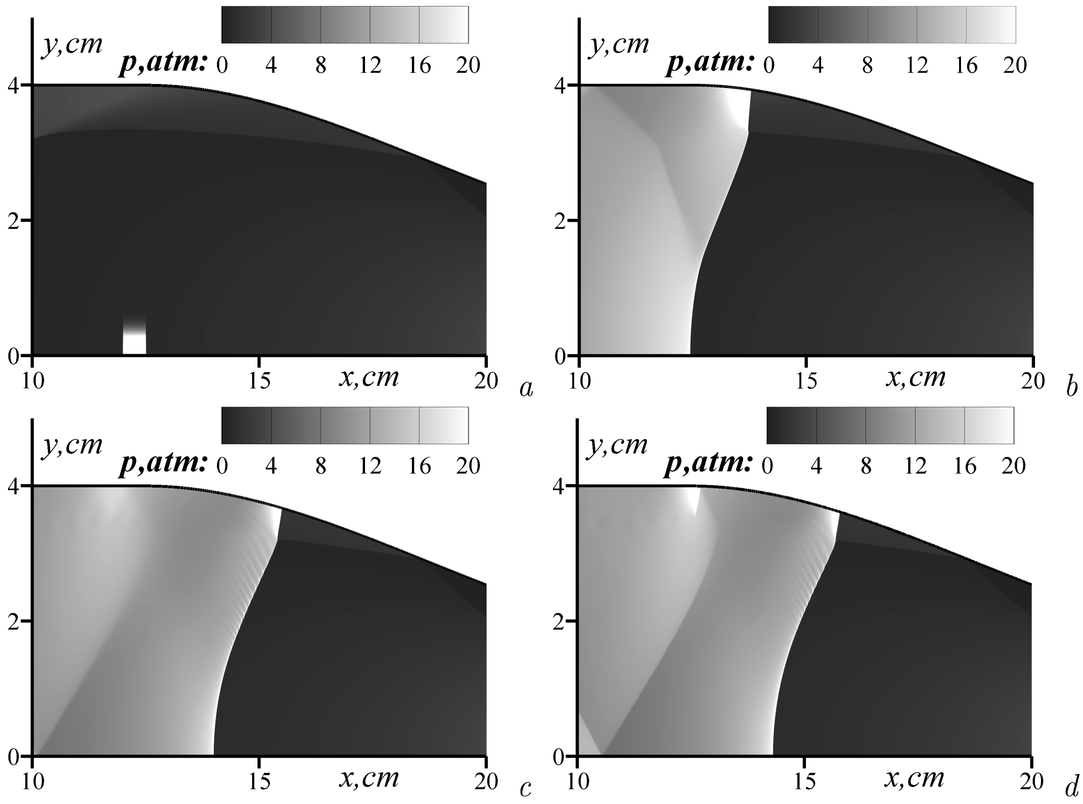

Figure 2: Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0=5 and l=0.04 m: a – t=0.0 ms; b – t=0.2 ms; c – t=1.0 ms; d – t=3.1 ms

obtained that in the $M_0 = 5$ case the sufficient condition for effective stabilization of the detonation wave is the use of the channel with $l = 0.04$ m (Fig. 2). Note that, for the detailed representation of the flow in Fig. 2 (and in the figures that follow below) 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 (near to the symmetry plane). It forms a three-shock Mach configuration with the oblique shock wave of the stationary flow.

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 channel section was studied with the purpose of increase in the efficiency of detonation combustion. The extended over multi-component mixtures [4] the one-velocity and one-temperature model [8], which describes the flow of gas with very small inert particles, was used for dusty-gas mixture flow simulation.

So, the decrease M_0 ($M_0 = 4.9$) leads to the situation in which the detonation wave moves through the throat and leaves the channel in counterflow direction (Fig. 3). It has been established that the addition of fine inert dust particles into the gas flow may be used for detonation stabilization. Thus, in case of dust density ρ_{s0}

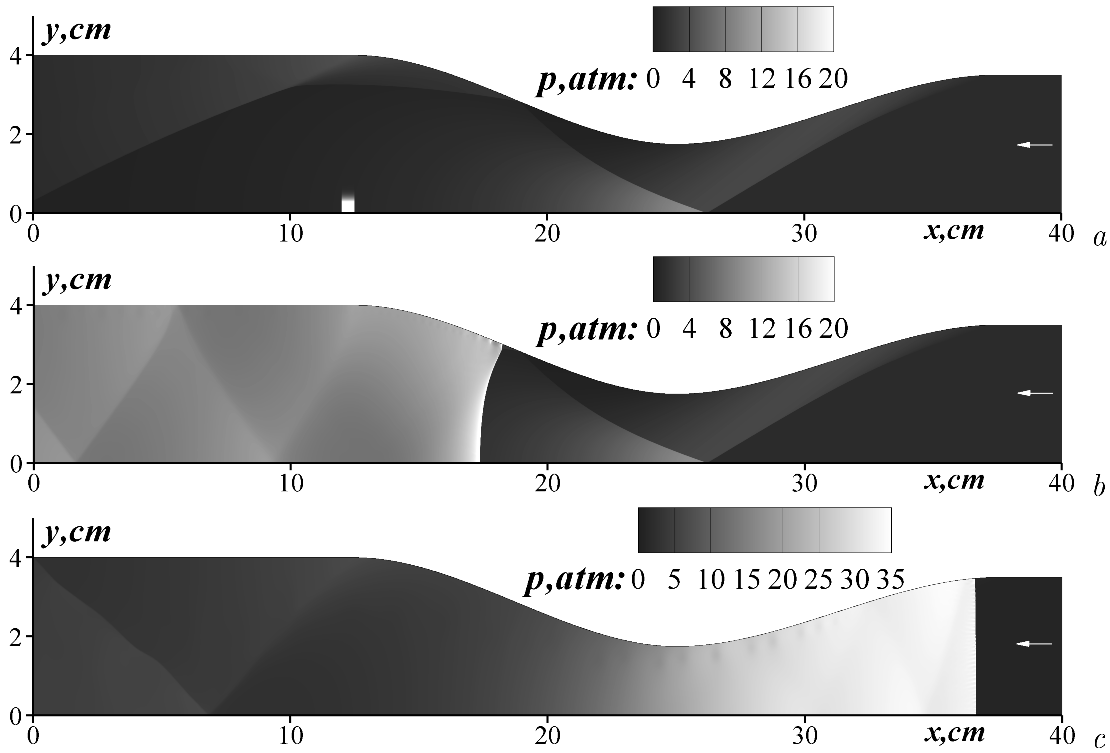

Figure 3: Propagation of the detonation wave in the channel in case of M_0=4.9 and l=0.04 m: a – t=0.0 ms; b – t=2.0 ms; c – t=3.0 ms

=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. 4) upstream of detonation location in the pure mixture in case of $M_0 = 5$ and thrust increases more than 3 times. Moreover, it was found that variation of a dust density in the incoming flow makes it possible to control the location of stabilized detonation.

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 the considered case of M_0=5. Thus, the small expansion of the output cross section (l = 0.045 m) in case of M_0=4.9 provides detonation stabilization in the divergent channel part and more than 2.5 times increase of thrust as compared to the considered case of M_0=5 (Fig. 5).

The possibility of detonation initiation and formation of the thrust developing flow with the stabilized detonation wave in the channel without any energy consumption has been detected. In these cases the obstacle (barrier) was used for detonation initiation. Thus, in the latter considered case of M_0=4.9 and l=0.045 m a detonation wave may be initiated by means of the barrier with height h=0.005 m located on the plane of symmetry near the x_b=0.1375 m section for period of time t=0.05 ms (Fig. 6). The detonation wave, formed in front of the barrier, 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

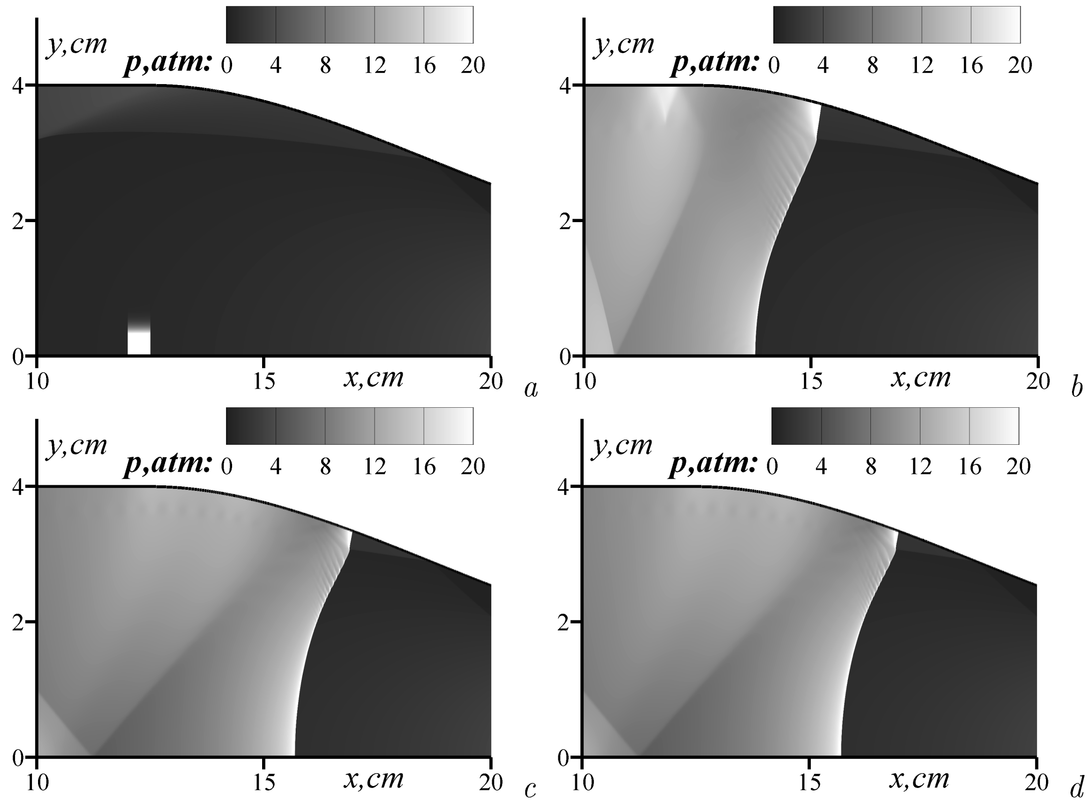

Figure 4: Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0=4.9, l=0.04 m and dust density in the incoming flow ρ_{s0}=0.1 kg/m^3: a – t=0.0 ms; b – t=0.5 ms; c – t=3.5 ms; d – t=3.9 ms

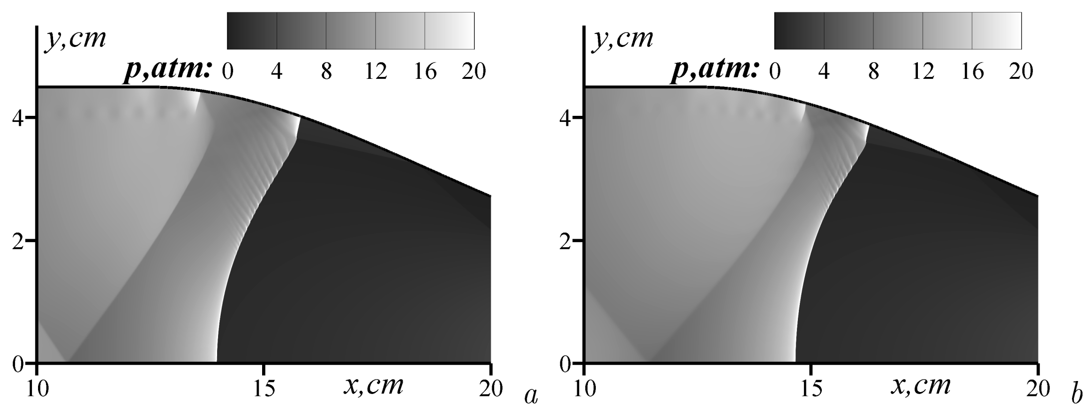

Figure 5: Formation of the flow with the stabilized detonation wave in the channel with constriction in case of M_0=4.9 and l=0.045 m: a – t=0.5 ms; b – t=2.0 ms

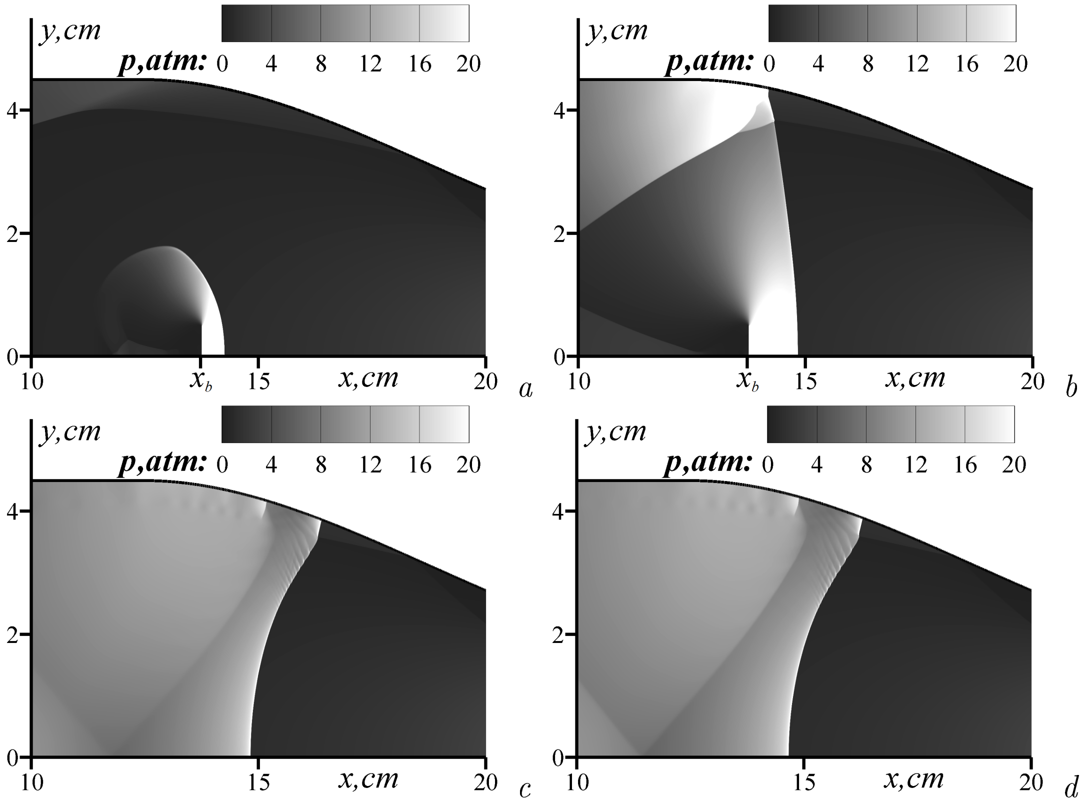

Figure 6: Formation of the flow with stabilized detonation in case of using the barrier for detonation initiation for M_0=4.9 and l=0.045 m: a – t=0.01 ms; b – t=0.05 ms; c – t=0.5 ms; d – t=2.5 ms

without any energy consumption.

4 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 in the channel with constriction without energy consumption has been detected.

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References

[1] Vasil'ev A.A., Zvegintsev V.I., Nalivaichenko D.G. Detonation waves in a reactive supersonic flow. Combustion, Explosion, and Shock Waves. 2006. 42(5). P. 85–100

[2] Zhuravskaya T.A., Levin V.A. Stabilization of detonation combustion of a high-velocity combustible gas mixture flow in a plane channel. Fluid Dynamics. 2015. 50(2). P. 283–293.

[3] Zhuravskaya T.A., Levin V.A. Investigation of certain techniques for stabilizing detonation waves in a supersonic flow. Fluid Dynamics. 2012. 47(6). P. 793–801.

[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. Fluid Dynamics. 2016. 51(4). P. 544–551.

[5] Glushko V.P. et al. (eds.) Thermodynamic properties of individual substances. Moscow: Nauka, 1978 [in Russia].

[6] Starik A.M., Titova N.S., Sharipov A.S., Kozlov V.E. Syngas Oxidation Mechanism. Combustion, Explosion, and Shock Waves. 2010. 46(5). P. 491–506.

[7] Godunov S.K., Zabrodin A.V., Ivanov M.Ya., Kraiko A.N., Prokopov G.P. Numerical Solution of Multidimensional Problems of Gasdynamics. Moscow: Nauka, 1976. 400 p. [in Russia].

[8] Sedov L.I. Similarity and dimensional methods in mechanics. 10th ed. Boca Raton: CRC Press, 1993. 493 p.

[9] Sadovnichy V., Tikhonravov A., Voevodin Vl., Opanasenko V. "Lomonosov": Supercomputing at Moscow State University. In Contemporary High Performance Computing: From Petascale toward Exascale (Chapman and Hall/CRC Computational Science). Boca Raton, USA: CRC Press, 2013. P .283–307.

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