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Lift Forces, Heat Fluxes and Self-Sustained Oscillations over Supersonic Bodies under Asymmetric Energy Deposition

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Abstract

The study is devoted to the development of the subject of an asymmetrical energy source impact on the flow around supersonic AD bodies in a viscous heat-conducting gas (air). The research is based on the full system of Navier-Stokes equations. The viscosity coefficient and the coefficient of thermal conductivity are considered to be dependent on the flow temperature. Freestream Mach number is equal to 2.5. Dynamics of drag and lift forces have been researched at the dependence on the characteristics of the energy deposition. The fields of temperature and heat fluxes were analyzed. Comparison of the flow parameters was conducted to clarify the contribution of viscosity and thermal conductivity of the gas. Self-sustaining flow oscillations have been obtained and studied; the conditions of their presence in a flow have been set. Possible approaches for elimination of these oscillations via the energy source characteristics and location relative to the AD body are discussed.

1. Nomenclature

M = freestream Mach number
Re = Reynolds number
γ = ratio of specific heats
p_∞, ρ_∞, u_∞, v_∞ = freestream pressure, density and velocity components
D = transverse size of AD body
t_i = time moment of an energy source arising
ρ_i = density in an energy source
α_ρ = rarefaction parameter in the energy source
d = transverse size of an energy source

AD	Aerodynamic
MW	Microwave

2. Introduction

At this time the possibility of non-mechanical control of supersonic flow via an energy deposition to the shock layer either in front of the bow shock wave or at different points on an AD body or close to its surfase is a widely investigating direction of aerospace engineering [1-4]. Ideas of the controlling of supersonic flow/flight characteristics with the use of energy sources of different nature were expressed from the end of the previous century and at the beginning of our century [5-9]. Drag reduction effect of the MW energy deposition was obtained experimentally and explained numerically as the vortex structure forming and acting to the frontal drag force in [10].

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Asymmetrically located longitudinal plasma area has been shown to form asymmetrical vortex structures which can produce a temporary increase in stagnation pressure and frontal drag force [11]. Pulsing flows characterised by self-sustained oscillations of a flow parameters under the constantly acting energy deposition were obtained and studied in [12, 13] where the mechanism of arising the pulsations has been described.

In our previous works a supersonic flow containing external constantly acting energy source dislocated asymmetrically relative to an AD bodies has been studied [14, 15]. It has been established that the impact of an energy source becomes the reason of complicated asymmetric rearrangement of a flow pattern behind the bow shock front which causes the front deformation, displacement of the stagnation point and appearance of a lift (pitch) force at zero angle of attack [16]. The dynamics of drag and lift forces have been obtained on the base of the Euler system of equations and periodical oscillations in the dynamics of drag and lift forces were found when establishing quasi-steady flow modes.

The present paper is devoted to the development of the research of influence of an asymmetrical energy deposition to produce the controlling effect on a supersonic flow via the characteristics and location of an energy source. Effects of viscosity and heat condactivity of the gas are under consideration on a base of the full system of Navier-Stokes equations. Special attention is paid to the generation of the flow modes characterised by the arising of self-sustained oscillations unfer the constantly acting asymmetrically located longitudinal continuous energy source.

3.1 Methodology

Supersonic flow over AD body “double wedge - plate” with $\beta=45^o$ under the impact of an energy deposition is studied. Here β is a half angle at the top of the double wedge. The simulations are based on the Navier-Stokes system of equations for perfect viscous heat conductive gas with the ratio of specific heats γ=1.4. The dimensionless problem is solved. The divergent form of the full Navier-Stokes system of equations [17] is considered:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial(\mathbf{F}+\mathbf{F}_{\mathrm{v}})}{\partial x}+\frac{\partial(\mathbf{G}+\mathbf{G}_{\mathrm{v}})}{\partial y}=\mathbf{0} \qquad (1)$$

$$\mathbf{U}=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ E\end{pmatrix},\mathbf{F}=\begin{pmatrix}\rho u\\ p+\rho u^2\\ \rho uv\\ u(E+p)\end{pmatrix},\mathbf{G}=\begin{pmatrix}\rho v\\ \rho uv\\ p+\rho v^2\\ v(E+p)\end{pmatrix}$$

$$\mathbf{F_v}=-\begin{pmatrix}0\\ \mu/\mathrm{Re}(4/3u_x-2/3v_y)\\ \mu/\mathrm{Re}(v_x+u_y)\\ \mu\pi_1/\mathrm{Re}-(1/\mathrm{N})kT_x\end{pmatrix},\mathbf{G_v}=-\begin{pmatrix}0\\ \mu/\mathrm{Re}(v_x+u_y)\\ \mu/\mathrm{Re}(4/3v_y-2/3u_x)\\ \mu\pi_2/\mathrm{Re}-(1/\mathrm{N})kT_y\end{pmatrix}$$

$$\pi_1=u(4/3u_x-2/3v_y)+v(v_x+u_y),\pi_2=v(4/3v_y-2/3u_x)+u(v_x+u_y)$$

$$E=\rho(\varepsilon+0.5(u^2+v^2)),\mathrm{N}=\mathrm{Re}\,\mathrm{Pr}(\gamma-1)/\gamma$$

The state equation for a perfect gas is used:

$$\varepsilon=p/(\rho(\gamma-1)).$$

Here ρ, p, u, v are the gas density, pressure and velocity x- and y-components, ε is the specific internal energy.
The Sutherland formula is used to approximate the dependence of dynamic viscosity on temperature:

$$\mu=T^{1.5}(1+s_1)/(T+s_1),$$

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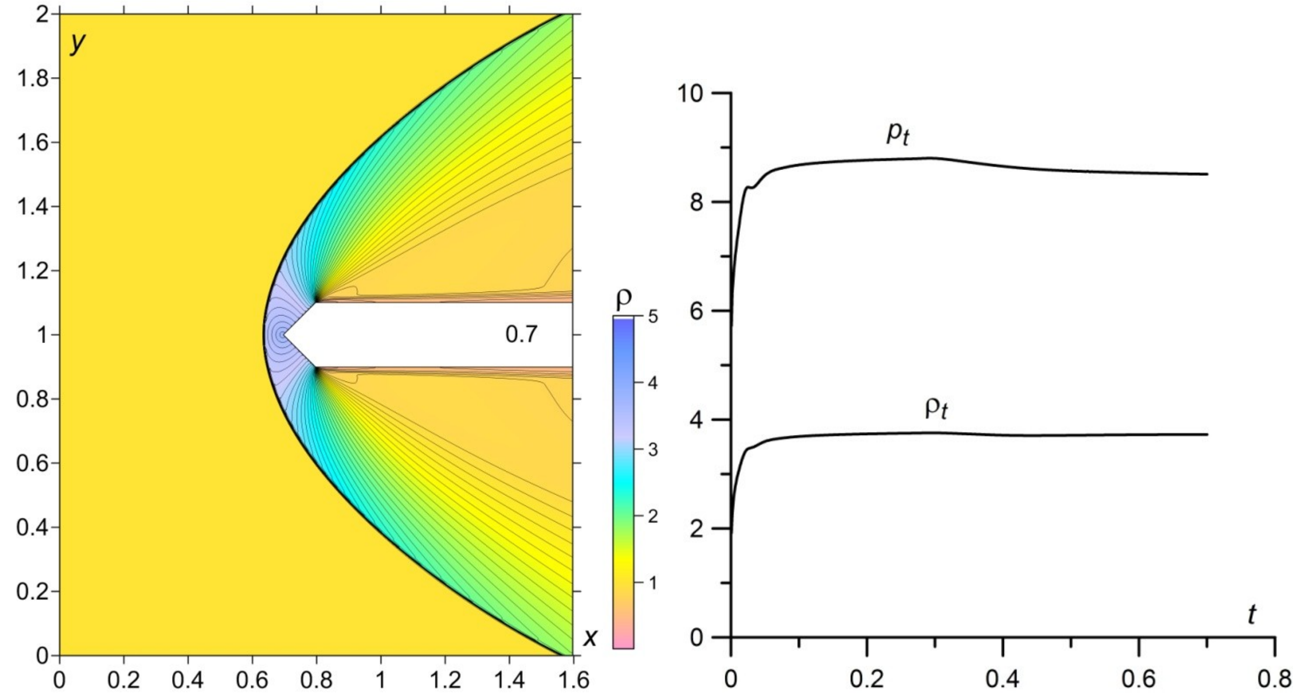
where s_1=0.409556. The coefficient of heat condactivity k is supposed to depend on temperature as:

$$k = T^{0.5}.$$

Freeatream Mach number M is equal to 2.5 and the Reynolds number Re is 9500. The freestream parameters are used as the normalized values:

$$\rho_n = \rho_\infty, p_n = p_\infty, T_n = T_\infty, u_n = (p_\infty / \rho_\infty)^{0.5}, t_n = l_n / u_n.$$

In the simulations the length scale $l_n = D^{-1} D_{dim}$ where D and D_{dim} are nondimensional and dimensional thickness of the wedge and the Reynolds number is based on the length scale l_n.



a) b)

Figure 1 : Steady flow: density, isolines and colors (a); dynamics of parameters at the top of a double wedge (b)

Initial conditions for the problem are the fields of gas parameters in a converged supersonic steady flow past the body (Fig.1, dimensionless time instant is indicated). The boundary conditions provide no-slip conditions for the adiabatic wall at the steady state. Conditions of the absent of reflection (in the direction normal to the boundary) were used at the exit boundaries.

Energy sourse of a shape of heated rarefied gas layer is supposed to arrise instantly in the steady flow in front of the bow shock wave at the time moment t_i and after some time interval it begins to interact with the bow shock. It supposed to act continuiously during the whole considered process. The value of density in the energy source ρ_i is suppose to be smaller than the density in the surraunding gas, $\rho_i = \alpha_\rho \rho_0$, $0 < \alpha_\rho < 1$. The static pressure and velocity of the energy source are equal to those of the undisturbed flow. Thus, the temperature is increased and the energy source is regarded as an infinite heated layer. Defining flow and energy source parameters are collected in Table 1. In the figures below the nondimensional variables in x- and y-axes are presented.

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Table 1: Parameters of oncoming flow, AD body and energy source

Description	**Definition**	**Value**
Freestream Max number	M_∞	2.5
Ratio of specific heats	γ	1.4
Reynolds number	Re	9500
Prandtl number (20C)	Pr	0.703
Relation of the transverse sizes of energy source and the body	d/D	0.25
Rarefaction parameter in the energy source	α_ρ	0.4, 0.5, 0.6
Length of the energy source	L	∞

The code for the numerical solving the system of full Navier-Stokes equations[§] was used in the simulations. The code is based on the complex conservative difference schemes [18] of the second order of approximation in space and in time. The body's boundaries are approximated by stepwise lines; they are introduced into the calculation area without breaking the conservation properties in it. Two staggered numerical grids were used in the simulations (Table 2).

Table 2: Characteristics of the using difference grids

Difference grid	**Amount of working nodes in the calculation area**	**Amount of working nodes on the body transverse size**	**The space steps values**
Grid 1	$2.5*10^6$	252	h_x=h_y=0.0008
Grid 2	$6.2*10^5$	128	h_x=h_y=0.0016

4. Results and discussion

Initial stage of dynamics of energy source-shock layer interaction is presented in Fig. 2 (Grid 1, α_ρ=0.4, the dimensionless time instants are indicated). It can be seen that under the action of energy release the flow becomes asymmetrical. The interaction causes the formation of shock-vortex structures in front of the body which contain two asymmetrical vortices and two triple-shock configurations upper from which is weaker than lower one (t=1.1). This shock-vortex structure causes the reorganization of the flow with formation of an area of higher density and pressure in the vicinity of the bottom wedge surface (after the reflected shock which is included in a triple configuration). It causes generation of a lift (pitch) force acting to the wedge part of the body [16] (t=1.4 – 1.8). The flows adjacent to the horizontal surfaces have different pressure and density, too. So the pressure difference effects to the total lift force acting on the body as well.

[§] The code has been created by O.A. Azarova

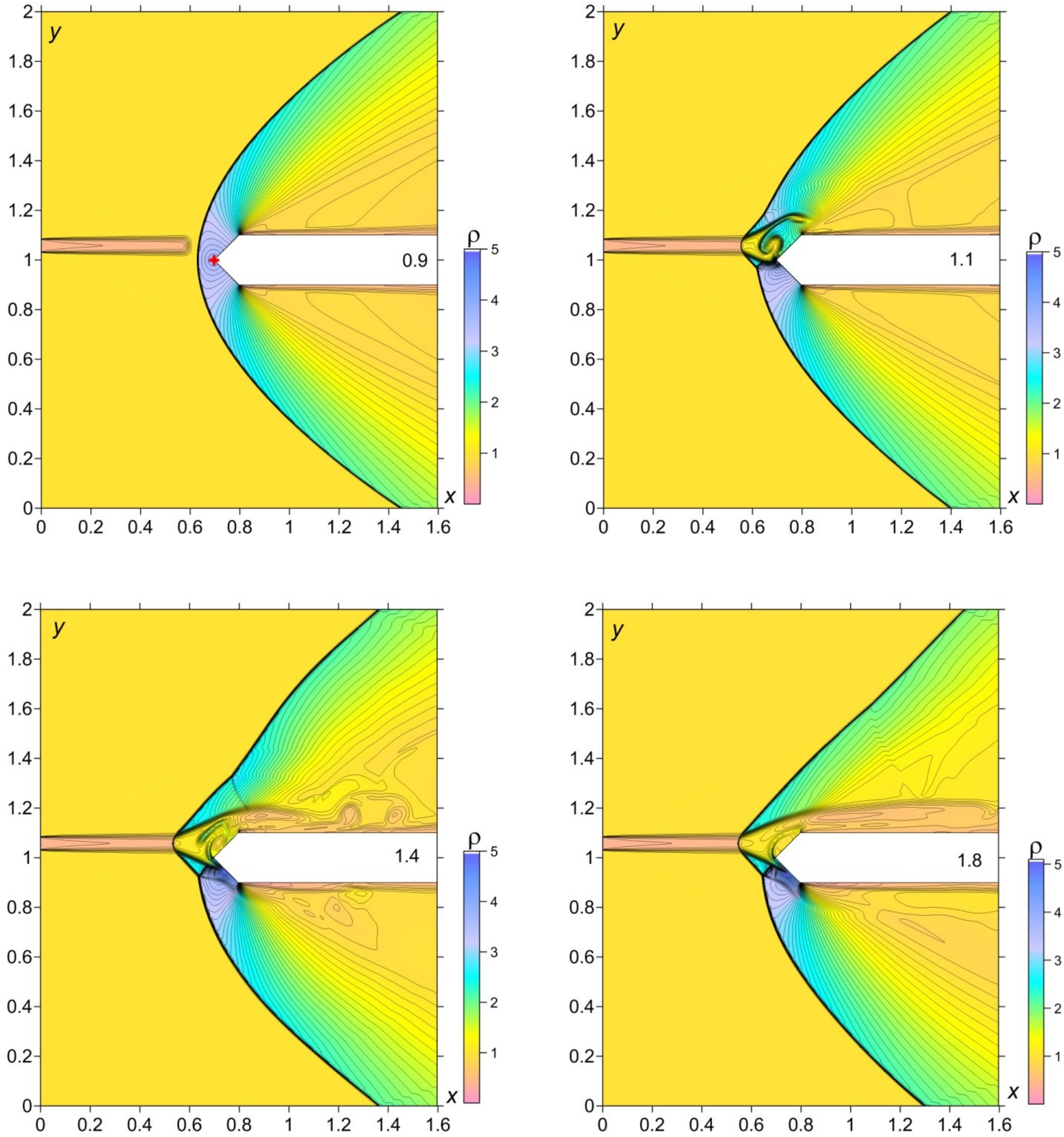

Figure 2 : Initial stage of dynamics of energy source-shock layer interaction, α_ρ=0.4, Grid 1

The calculations showed that from the time *t*=2.0 the flow begins to pulse: self-sustained flow oscillattions have been obtained (Fig. 3). This figure shows the oscillations of pressure at the top of the double wedge (marked by *red cross* in the first frame in Fig. 2) calculated using the full Navier-Stokes equations on different Grids 1 and 2 in comparison with the Euler inviscid simulations (CFL - Courant–Friedrichs–Lewy coefficient). Note, that there is some small difference in the geometries for Grid 1 and Grid 2 which causes a small shift in the curves seen in Fig. 3. Indeed, the oscillations of the whole flow occur; these oscillations are caused by the processes originated at one point, a top of the double wedge. In addition, as can be concluded from Fig. 3, the viscousity and heat conductivity at this point play the decisive role for the arising of these oscillations and for the values of atittudes of their parameters.

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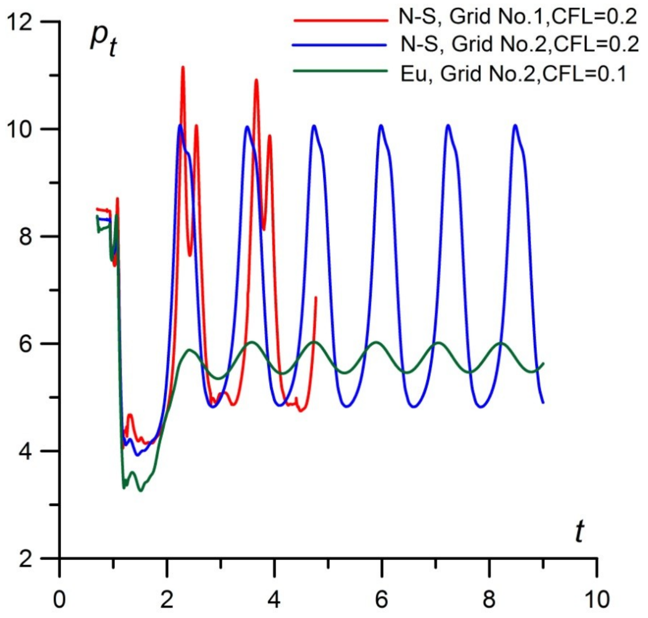

Figure 3 : Dynamics of pressure at the top of double wedge, α_ρ=0.4

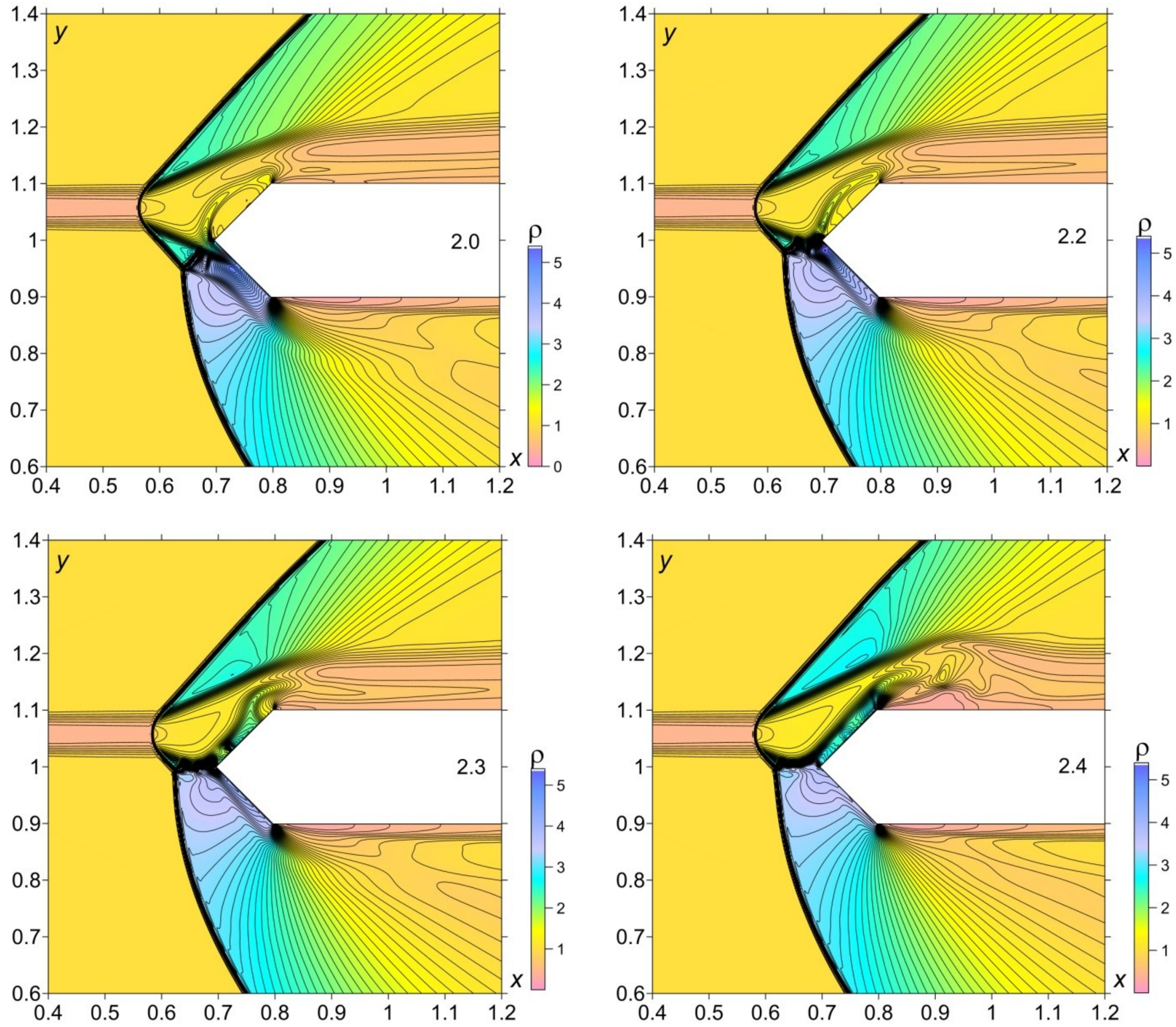

Figure 4 : Pulsation stage of dynamics of energy source-shock layer interaction: density fields, α_ρ=0.4, Grid 1.

In Fig. 4 mechanism of the origination of the pulsations is analysed (the figures have been enlarged). The impact of the energy release causes changing a shape of the bow shock and arising the additional shocks. One can see a triple configuration in front of the bottom wedge surface and the increase in density (and pressure) at this surface produced by the reflection shock wave which is an element of this triple structure.

On the upper wedge surface it is seen the flow separation bubble with the decreased density values. The heated gas with low density (*yellow*) is separated from the more cold one (*blue*) by two contact discontinuities (shear layers) (*t*=2). Then the triple point is going up causing the inleakage of the compressed gas to the top point increasing pressure in it (*t*=2.2, 2.3). At the upper wedge surface the heated flow begins to push back from the surface by the more cold gas and the pressure at the top point decreases (*t*=2.4).

Then the triple point begins to move down increasing the pressure again (Fig. 4 (continuation), *t*=2.545). Together with it the heated gas breaks to the upper surface, replacing the colder gas, decreasing the pressure and forming the new separation region (*t*=2.6, 2.8). The flow returns to its original state (compare frames for *t*=2 and *t*=2.8) and the situation is repeated under the developed conditions. So the pulsations are repeated. Last figure in Fig. 4 (continuation) shows the time instants of the presented frames on the curve of the dynamics of pressure at the top of the double wedge (*blue dashed* lines).

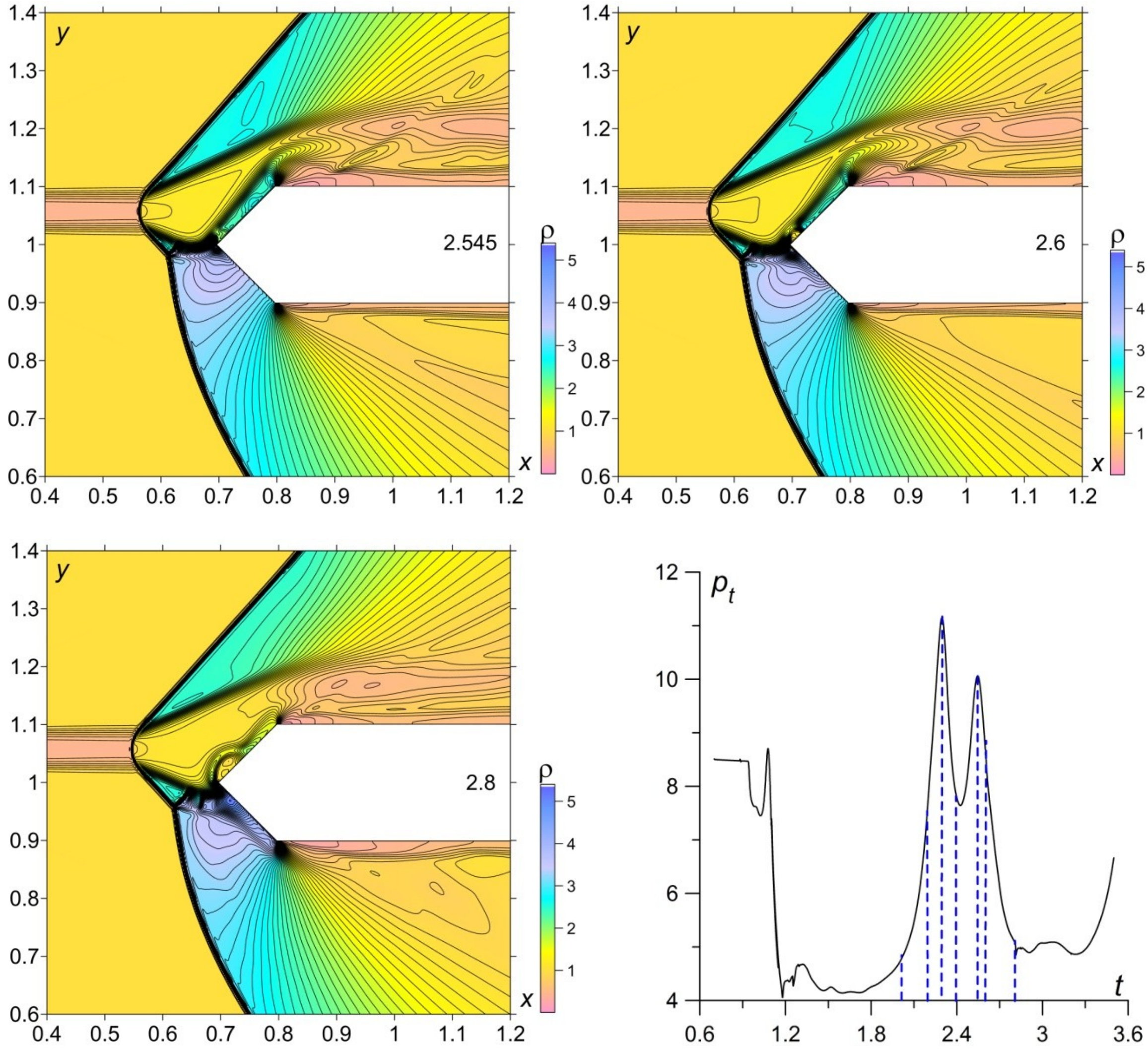

Figure 4 (continuation) : Pulsation stage of dynamics of energy source - shock layer interaction, density fields, α_ρ=0.4, Grid 1. *Last figure* - dynamics of pressure at the top of double wedge, time instants defined (*blue dashed lines*)

According fields of pressure and temperature at the time moment of the local maximum value of pressure at the top point of the wedge (*t*=2.545) are presented in Fig. 5.

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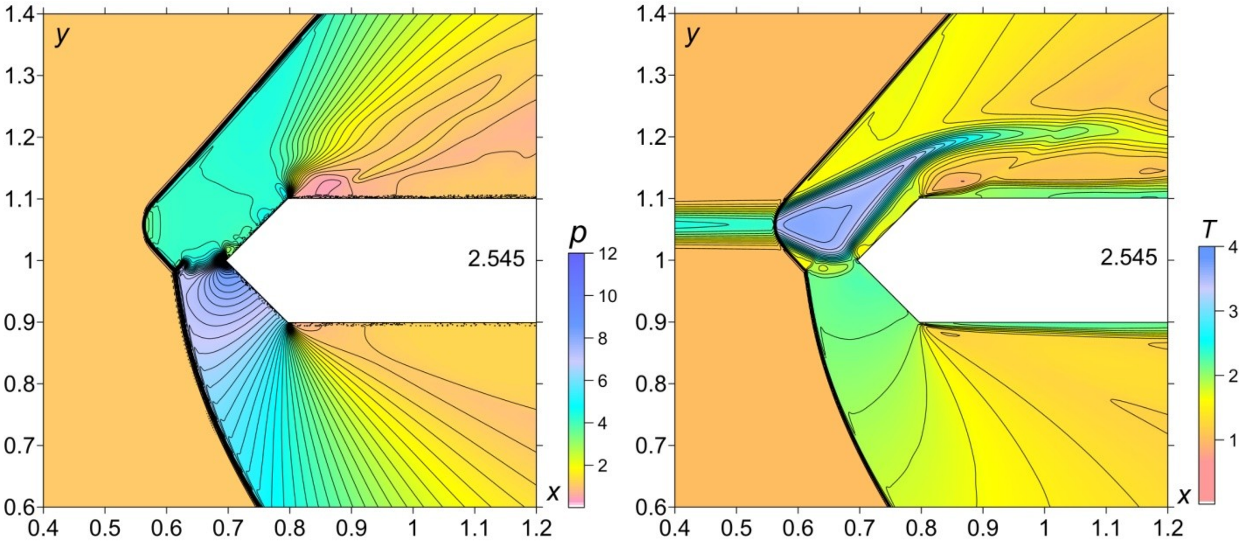


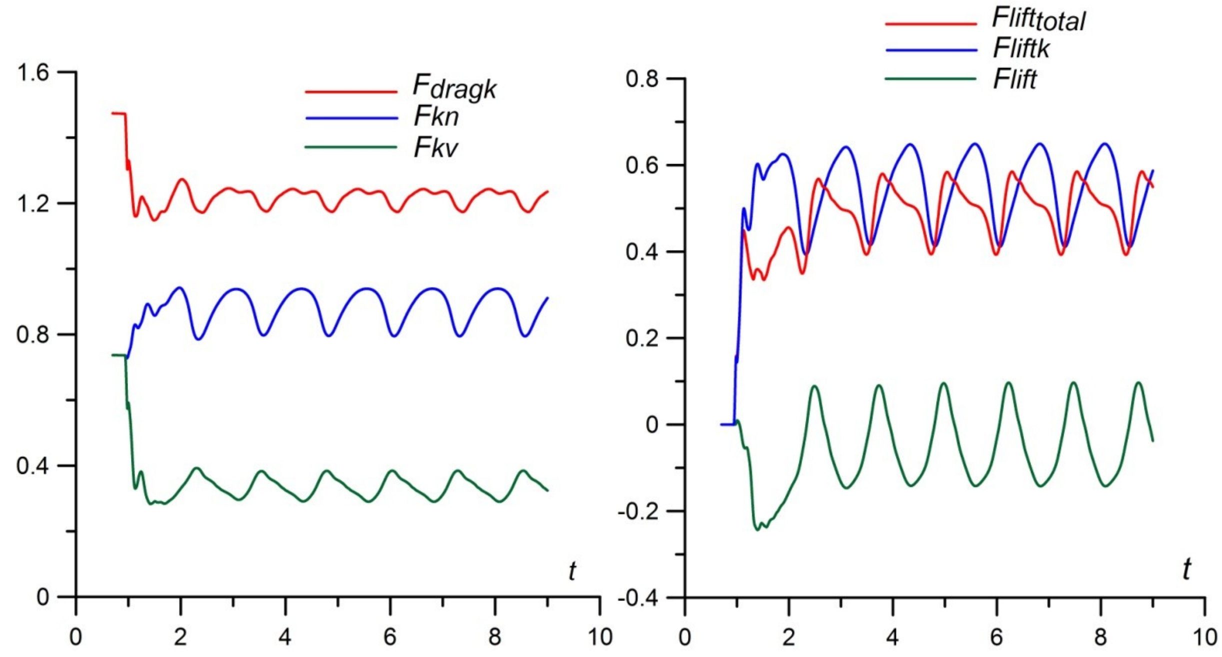
a) b)

Figure 5 : Fields of pressure (a) and temperature (b), α_ρ=0.4, t=2.545

The pulsations of the parameters at the top of the double wedge are the reason for a pulsing character of the whole flow, together with the drag and lift forces (Fig. 6, α_ρ=0.4, Grid 2). Here

$$F_{dragk} = \int_{y_b}^{y_b+D} p dy, \qquad F_{lift} = F_n - F_v,$$

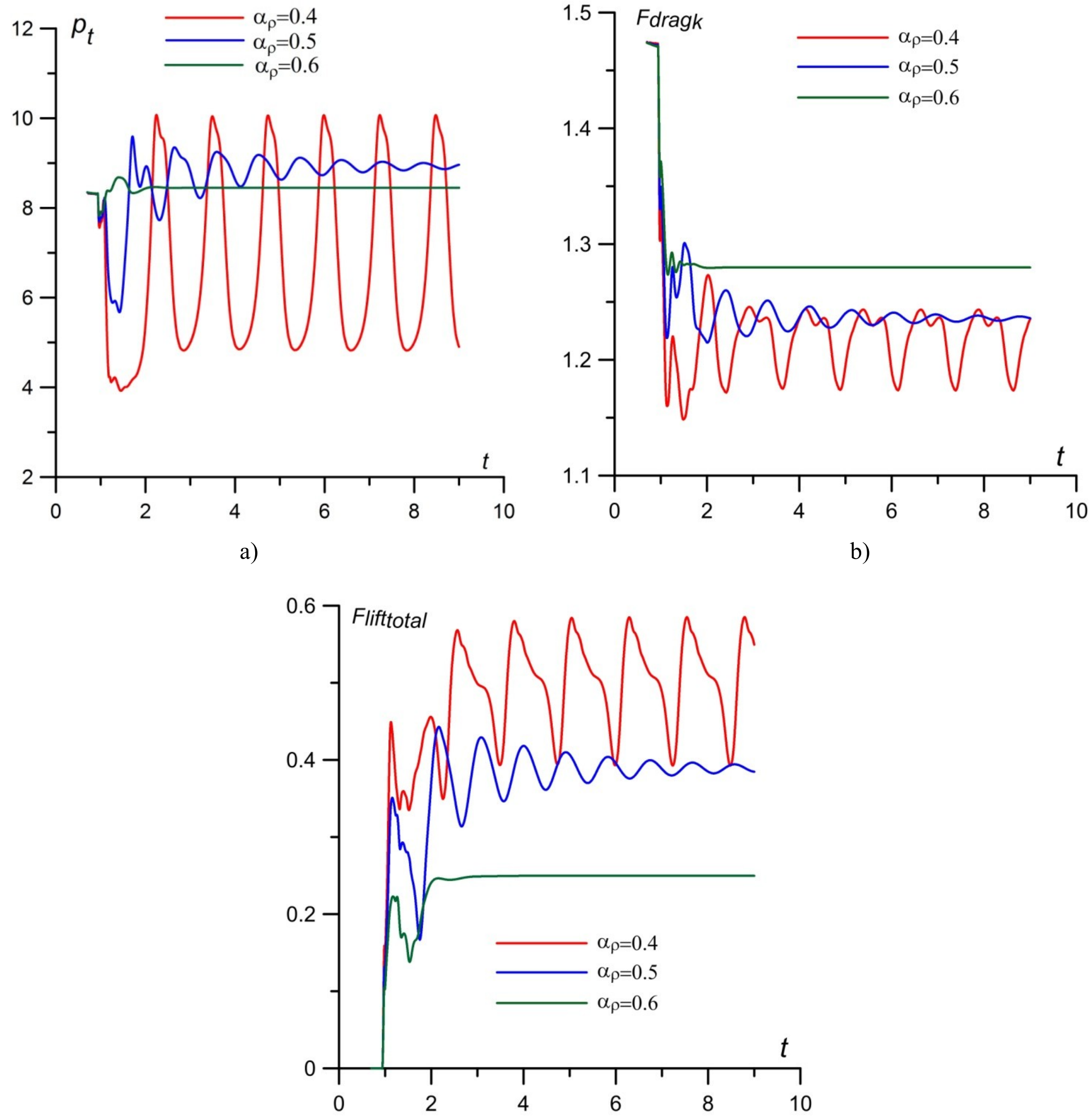
where y_b is the lower body's y-coordinate, F_n and F_v are the drag forces of the lower and upper body's surfaces. In Figs. 6 - 8 F_{k_n} and F_{k_v} are the front drag force components for the bottom and top surfaces of the double wedge, so $F_{dragk} = F_{k_n} + F_{k_v}$. Here F_{lift} and F_{lift_k} are the lift forces formed by the upper and lower lateral surfaces and the lift force formed by upper and lower surfaces of the double wedge, and $F_{lift_{total}} = F_{lift} + F_{lift_k}$.



a) b)

Figure 6: Pulsation character of front drag (a) and lift (pitch) (b) forces, α_ρ=0.4, Grid 2

In Fig. 7 the dynamics of pressure at the top of the wedge, frontal drag and total lift (pitch) forces for different values of density in the energy source with α_ρ=0.4, 0.5, 0.6 are presented. It is seen that the lower density (and higher temperature) in the energy source the greater the attitude of the pulsations. The pulsations of the pressure at the top of the double wedge for α_ρ=0.4 are strong and undamped, for α_ρ=0.5 the pulsations are fading and for α_ρ=0.6 they do not arise. The same behavior is observed for the frontal drag forces (Fig. 7b) and for the lift forces (Fig. 7c).
Two different locations of the energy source relatively a body were considered, when the distance between the lower energy source boundary and the axes of symmetry was equal to 0.032 (0.16*D*) (*geometry 1*) and when this distance was smaller and equal to 0.0192 (0.09*D*) (*geometry 2*) (Fig. 8). The transverse size of the energy source was not changed in these variants. It can be seen that with approaching the source to the axis the pressure at the top point decreases, the frontal drag force increases and the total lift force decreases; the pulsations are more quickly fading there.

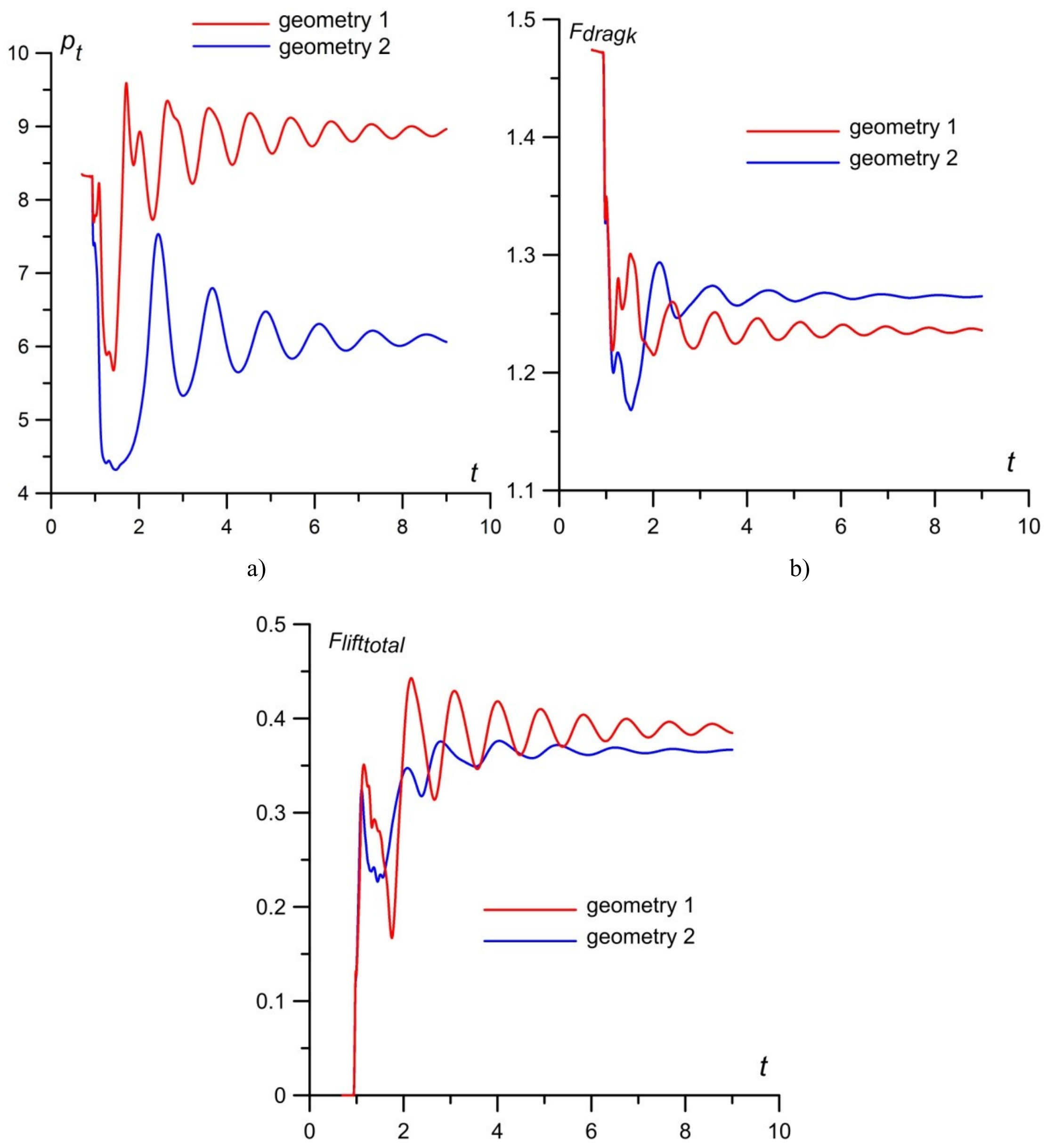


a)

b)

c)

Figure 7: Dynamics of pressure at the top point (a), frontal drag force for the double wedge (b) and total lift (pitch) force (c) for α_ρ=0.4, 0.5, 0.6, Grid 2



a) b)

c)

Figure 8: Dynamics of pressure at the top point (a), frontal drag force for the double wedge (b) and total lift (pitch) force (c) for different energy source location, Grid 2

In Fig. 9 the curves present the parameters at the top of the double wedge during the pulsation stage of the flow under the energy deposition for α_ρ=0.4 (Grid 2, geometry 1). Comparison of the Navier-Stokes (*N-S*) with the according inviscid simulations (*Eu*) is presented. From Fig. 9 it can be concluded that the action of viscosity and heat conductivity at the top of the double wedge is significant and influences not only density and pressure at this point but also the flow temperature which is of the pulsing character, too.

Let us consider the vector field of heat flux $\bar{Q}$ in the coordinates (*x*, *y*):

$$\bar{Q} = -k(T_x, T_y).$$

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Fields of $\bar{Q}$ and T are presented in Figs. 10a, 10b (the figures are obtained by the numerical images overlapping). The images correspond to the time moments of maximal (Fig. 10a) and minimal (Fig. 10b) values of pressure at the top of the double wedge (marked by *black dashed* lines in Fig. 9).

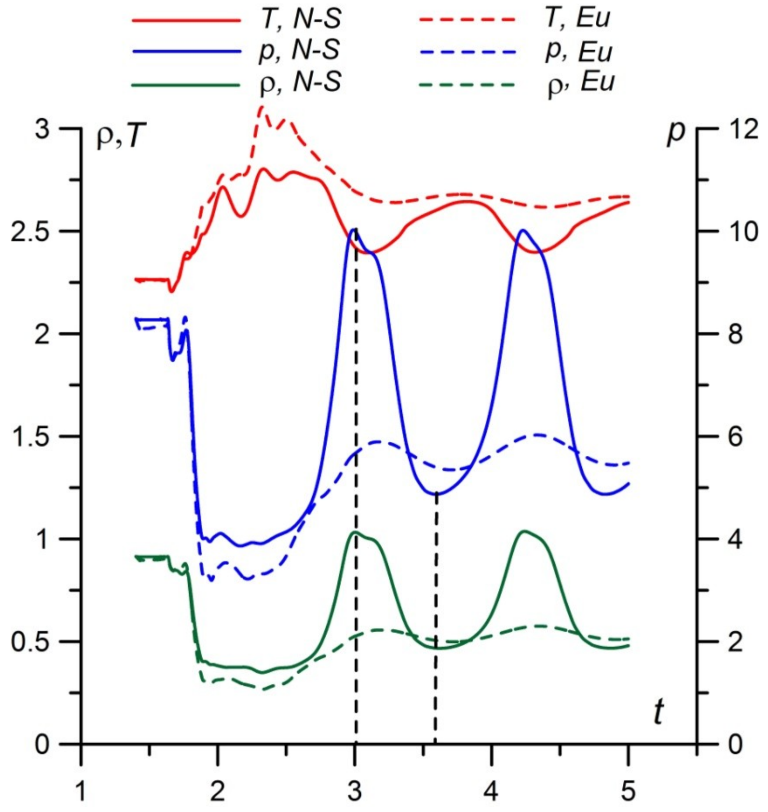
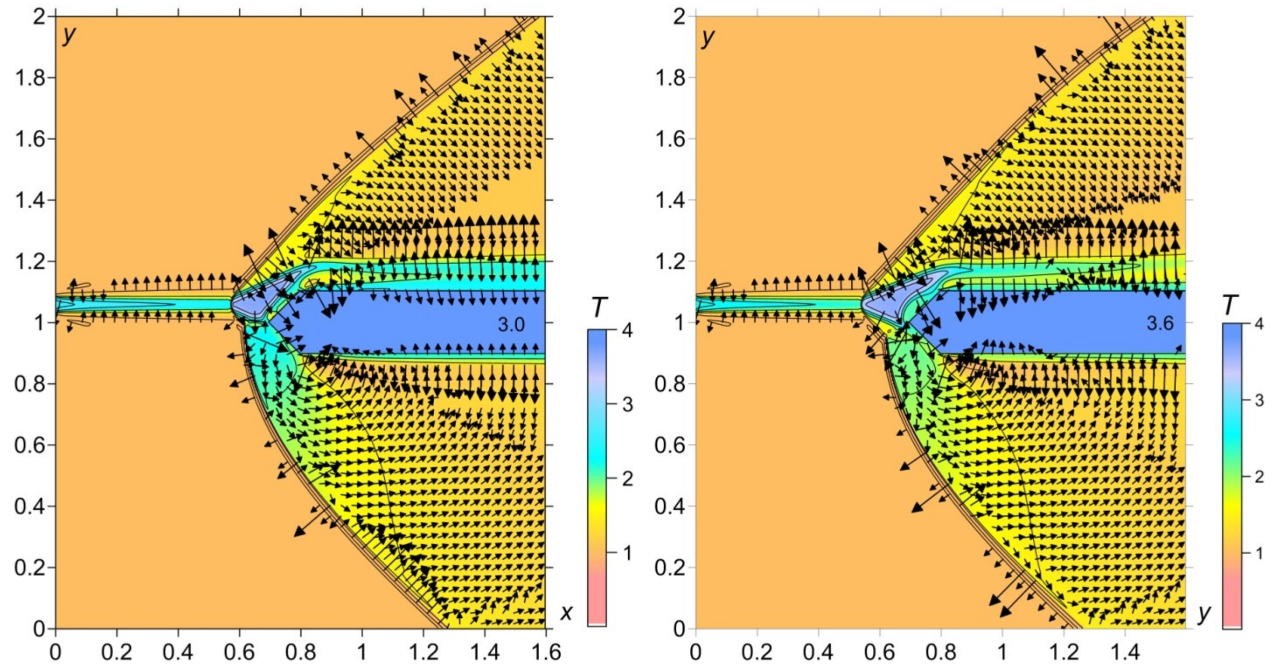


Figure 9: Dynamics of density, pressure and temperature at the top point of the double wedge, α_ρ=0.4

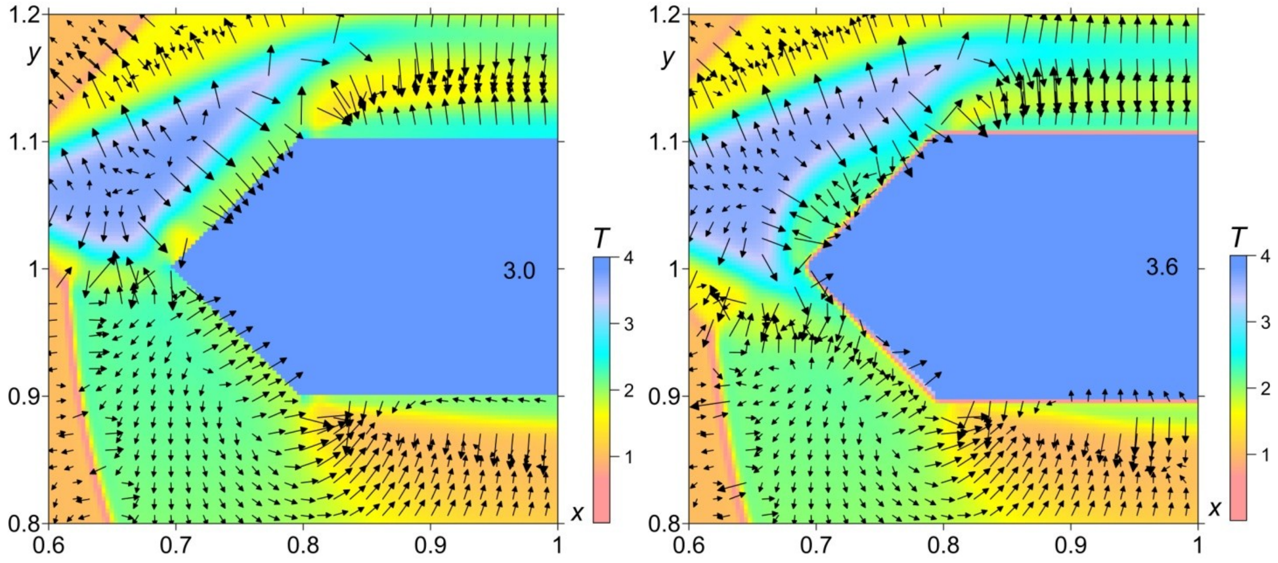


a)

b)

Figure 10: Fields of the heat flux $\bar{Q}$ (arrows) and temperature T (colors), α_ρ=0.4: a) – t=3.0, b) – t=3.6

According enlarged figures are presented in Figs. 11a, 11b. One can see that when the top pressure is maximal the separation bubble is absent and the heat flux to the upper wedge surface is taken place. Heat flux to the down wedge surface can be seen, too. When the top pressure is minimal the separation bubble (vortex) is present; the temperature near the body forms the colder boundary layer. At the bottom surface it can be seen the vortex phenomena, as well, and the colder boundary layer is present. As the result the wedge surface turns out to be enclosed by a colder gas layer. Note, that these pictures replace one another obeying the whole flow oscillations.



a) b)

Figure 11: Fields of the heat flux $\bar{Q}$ (arrows) and temperature T (colors), in the vicinity of the double wedge, α_ρ=0.4 : a) – t=3.0, b) – t=3.6

5. Summary

- Impact of a longitudinal asymmetrically located energy source on the flow around supersonic AD body “double wedge - plate” in a viscous heat-conducting gas (air) has been studied. The research is based on the full system of Navier-Stokes equations.
- Self-sustaining flow oscillations have been obtained.
- By means of the comparison with inviscid simulations it has been shown that these oscillations are the consequence of viscous and heat conducting effects which are happening at the vicinity of the top of a double wedge.
- It has been obtained that the dynamics of drag and lift forces are of the pulsing character, too, obeying the whole flow oscillations. These forces have been researched at the dependence on the characteristics and location of the energy source.
- It has been shown that the oscillations are stronger and undamped for higher temperature (smaller α_ρ) in the energy source. For lower temperature in the energy source the generated oscillations become damping and fade out.
- It was shown that with approaching the source to the axis of symmetry at the steady flow mode the frontal drag force increases (decreasing at the initial stage), the total lift force decreases and the pulsations are more quickly fading.
- The fields of temperature and heat flux were analyzed. It has been shown that the pulsations obtained are in connection with near-surfaces vortex phenomena and a colder layer periodically arises near the body surfaces; this effect is connected with the pulsation dynamics of near-surfaces heat fluxes.

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