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Control of Triple-Shock Configurations in High Speed Flows past AD Bodies in Different Gases

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Abstract
Triple-shock configurations have been studied in problem of energy source effect on supersonic streamlining a body of a shape of plate blunted by a cylinder. Freestream Mach numbers were changed from 3 to 4.2. Energy source is suggested to have a form of a heated rarefied channel (layer). Changing the angles of elements of the triple-shock configurations with the flow direction are researched for different gas mixtures with the specific heats ratio from 1.1 to 1.4. Dependences of triple-shock configurations on the Mach number and characteristics of the energy release have been obtained. Complicated shock-vortex structures with multiple reflection of simple waves accompanying triple-shock configurations together with the Richtmyer-Meshkov instability have been studied for M=7, 8. Complex conservative difference schemes are used in the simulations.

1. Nomenclature

M	=	freestream Mach number
γ	=	ratio of specific heats
p_∞, ρ_∞, u_∞, v_∞	=	freestream pressure, density and velocity components
α_ρ	=	degree of gas rarefaction in an energy source
$\rho_i = \alpha_\rho \rho_\infty$	=	density in an energy source
t_i	=	time moment of an energy source arising
Δt_i	=	time of the energy release action
D	=	transverse size of an AD body
d	=	transverse size of an energy source
$\omega 1$	=	angle of an incident shock wave with the flow direction
$\omega 2$	=	angle of a reflected shock wave with the flow direction
$\omega 3$	=	angle of a Mach wave with the flow direction
$\omega 4$	=	angle of direction of a shear layer with the flow direction

AD Aerodynamic
MW Microwave

2. Introduction

Flow control with the use of energy deposition to oncoming flow is currently of wide interest in modern aerospace science [1, 2]. Reorganization of unsteady flow under the action of an external energy deposition was firstly researched in [3] for supersonic streamlining a sphere. In air the effect of the external energy source was shown to lead to the decrease of the stagnation pressure together with the drag force of an AD body. Energy sources of different types (micro-wave, laser, discharge) were used for these purposes [4, 5]. In [4] the vortex mechanism of drag force reduction has been obtained in simulations of MW discharge effect on a supersonic flow. This vortex was forming simultaneously with a triple-shock configuration causing by the energy release. So a research of characteristics and dynamics of triple-shock configurations is necessary for

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understanding the details of generation of the vortex and the vortex drag reduction of an AD body. The control of triple-shock configurations using energy release dislocated in an oncoming flow for different gas media and gas mixtures was suggested in [6] and the triple-shock configurations were investigated in [7]together with generated vortex structures.

Triple-shock configurations are basic elements of flowfields which define the essential phenomena occurring in the flow [8, 9]. For calculation of triple configurations the assumptions of a steady flow and of the self-similar flow mode (in the case of an unsteady flow) are usually used [10]. In [11] it was shown that the self-similar assumption becomes possible in the case where thermodynamic equilibrium becomes established behind a shock wave. Unsteady triple-shock configurations in air, nitrogen and carbon dioxide have been studied in [12, 13]. It has been shown that real gas effects which lead to decrease in the ratio of specific heats γ strongly influence the front positions of elements of a triple-shock configuration. In [14] the influence of the ratio of specific heats on the behavior of shear layers was investigated. It was shown that the increase of the Mach number and the decrease of γ lead to the greater instability of the shear layers.

This paper is devoted to the research of the effect of an external energy source on triple-shock configurations and vortex structures generated in different gases on the first self-similar stage of supersonic streamlining the body "a plate blunted by a cylinder". The problem is considered for gaseous media with the ratio of specific heats γ in the range from 1.1 to 1.4 and the freestream Mach numbers from 3 to 4.2. The dependences of the angles in a triple-shock configuration on the characteristics of an energy source and on the angle of the incident shock have been obtained. Modeling of the shock-vortex structures with multiple reflection of simple waves accompanying the formation of triple-shock configurations together with generation of the Richtmyer-Meshkov instability has been made for the greater Mach numbers (M=7, 8).

3. Methodology

Effect of an energy deposition on a supersonic flow past an AD body "a plate blunted by a cylinder" is studied. The simulations are based on the Euler system of equations for perfect inviscid gas with γ in the range from 1.1 to 1.4:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{0}, \tag{1}$$

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

Here ρ, p – density and pressure of the gas, u and v are x- and y- components of the gas velocity, $\varepsilon=p/(\rho(\gamma-1))$, $E=\rho(\varepsilon+0.5(u^2+v^2))$ is the total energy per unit volume, ε is the specific internal energy. Initial conditions for the problem are the fields of gas parameters in a converged supersonic steady flow past the body.

Energy sourse of a shape of long heated channel (layer) is supposed to arrise in the steady flow in front of the bow shock at the time moment t_i. The density in the channel is smaller than in the surrounding flow, $\rho_i=\alpha_\rho\rho_\infty$, and pressure and velocity are the same (so the temperature in the energy source is increased in comparison with the surrounding flow). By this way the energy source is turned out to be frozen into the flow, it moves towards the bow shock and interacts with it. Defining flow and energy source parameters are collected in Table 1.

This model of the energy deposition was suggested in [15] and has been used for evaluation of the stagnation parameters in the experiments on laser and MW energy release effect on a supersonic flow [16]. The problem is solved in the dimensionless variables. In figures below the normalised variables in x- and y-axes are presented. Complex conservative schemes are used in the simulations [17]. The body's boundaries are introduced into the calculation area without breaking conservation properties in it. The staggered numerical grid in the calculation area (selected taking into account the symmetry of the flow) contains about $1.5{*}10^6$ working nodes and about 1500 nodes are dislocated on the body's boundary (500 nodes per body's radius).

The interaction of the heated rarefied channel was shown to provide the reorganisation of the whole flow which is characterised by generation of triple-shock configurations accompanying the formation of vortex structures. The influence on the angles in a triple-shock configuration of characteristic of an energy source

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(α_ρ) together with flow parameters γ and M is considered. A schematic of triple-shock configuration is presented in Fig. 1. The researched angles are indicated as it has been used in the three-shock theory [11]. The angles of the elements of a triple-shock configuration with the oncoming flow are considered: a precursor plays the role of the incident wave (ω1), bow shock is associated with the Mach wave (ω3). Additionally, the angle of the reflected wave (ω2) and the angle of the direction of the shear layer (ω4) are seen.

Table 1: Parameters of oncoming flow and energy source

Parameter	Dimension value	Non-dimension value	Normalizing value
Density ρ_∞	1.293 kg/m^3	1	ρ_n =1.293 kg/m^3
Pressure p_∞	1.01325*10^5 Pa	0.2	p_n =5.06625* 10^5 Pa
Velocity[a] u_∞			$u_n=(p_n/\rho_n)^{0.5}$=627m/s
Body's transverse size D	0.02m	0.2	l_n =0.1m
Transverse size of the energy source d	0.005m	0.05	l_n =0.1m
Time moment of an energy source arising in a steady flow t_i	96μs	0.601	t_n=159.8μs

[a]Different values are considered

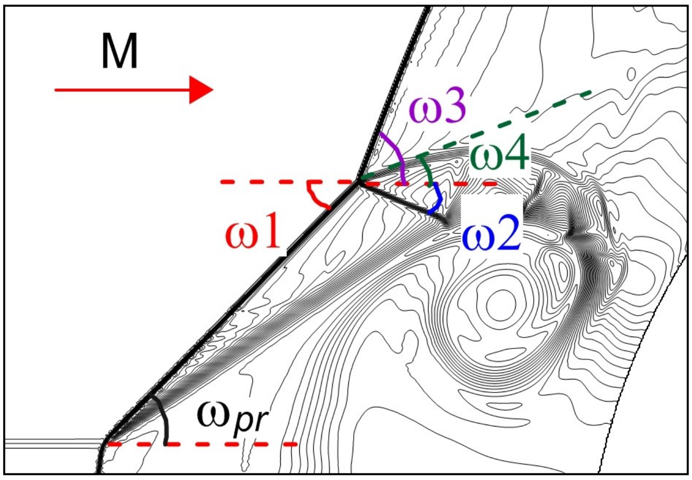

Figure 1 : Generated triple-shock structure (schematic) and considered angles

4. Results and discussion

4.1 Development of triple-shock configurations and possibility of comparison analysis for different M, γ and α_ρ

It has been established that at the beginning stage of the process of the energy release – shock layer interaction the flow mode is close to the self-similar one. During this flow phase an unsteady flow structure containing triple-shock configuration and developing vortex is forming (Fig. 2, time values are indicated).

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This vortex has been shown to be a reason of changing stagnation parameters and as the result a reduction of drag force of the front surface of a body [4]. In Fig. 2 it can be seen a flow structure generation consisting from reflected simple waves in a region between two shear layers accompanying the vortex formation. The beginning of these multiple reflection is given by the reflection wave interaction with the lower shear layer. Thus, the characteristics of the triple-shock configuration (in particular, of the reflection wave) may effect onto AD body characteristics (especially, in hypersonic flows).
Characteristics of triple configurations depend on freestream Mach number M and physical-chemical properties of gas medium described in this study via the specific heats ratio γ. A possibility of control of triple-shock structure characteristics using an energy deposition into the oncoming flow is connected with the dependence of them on the temperature of a gas in the energy source which is described via the rarefaction degree α_ρ.
For investigation of triple configurations in dependence on M, γ and α_ρ it was nesessary to establish the time interval where the flow mode is close to the self-similar one. In Fig. 3 which is obtained by the overlay of the calculated imajes for different time values it is seen that here the flow is close to the self-similar stage in the time interval [0.74 - 0.8]. In this interval the velocity of the shock wave inside the energy source is close to constant and the velocity of the center of the triple-shock configuration is close to constant, too.

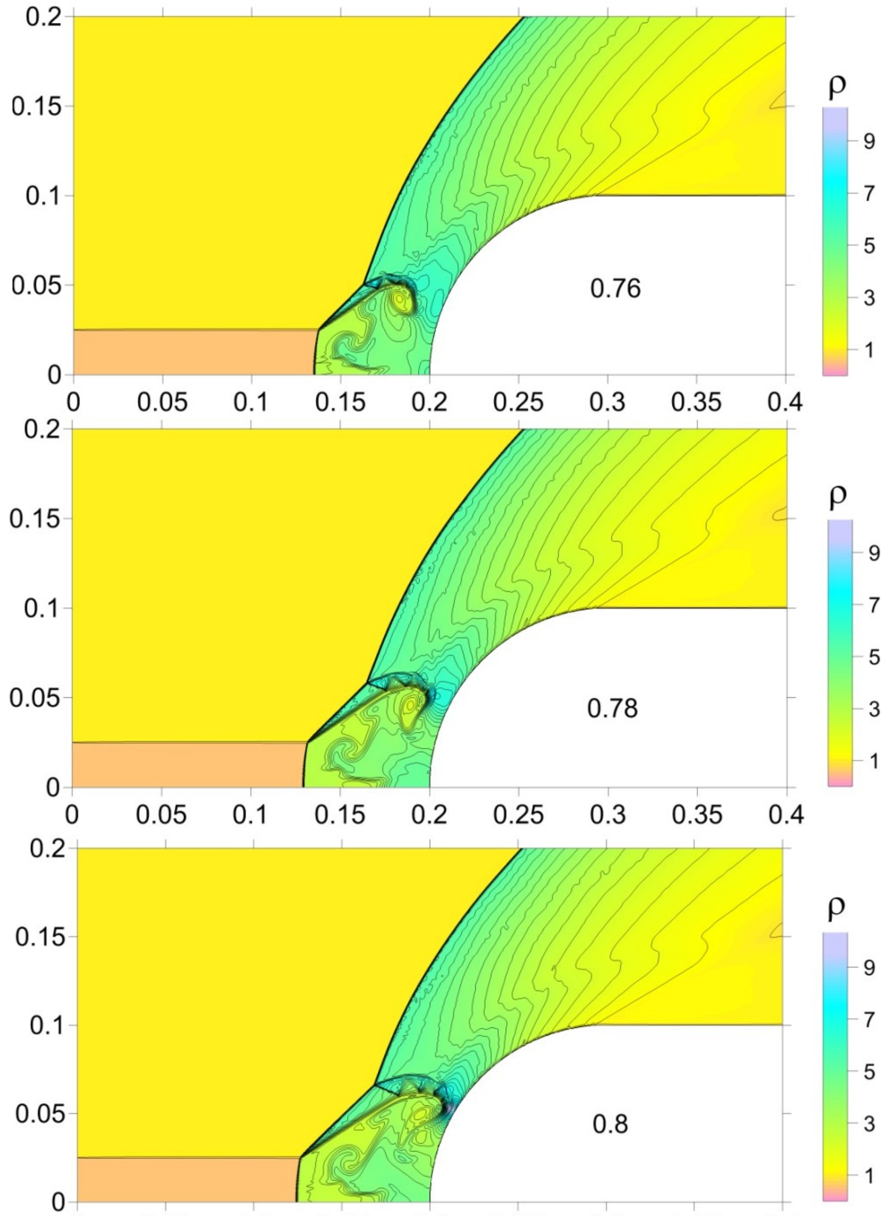

Figure 2: Dynamics of development of unsteady triple-shock configuration, M=4.2, γ=1.2, α_ρ=0.5

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The angles in the triple-shock configurations do not change practically during this time period because of the self-similar flow mode. It gives the possibility to compare the triple-shock configurations for different flow and energy source parameters.

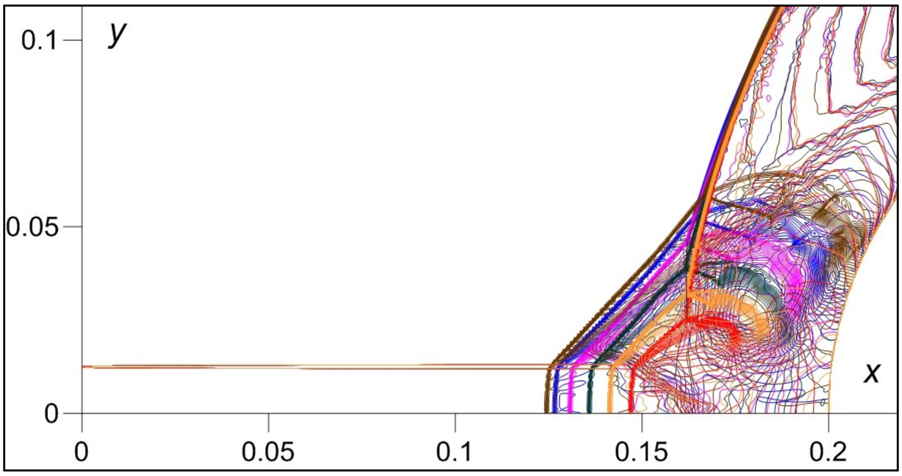
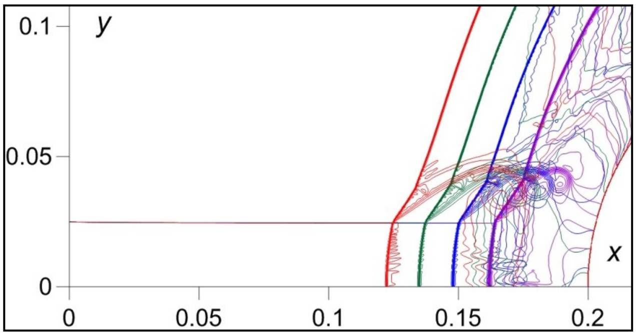


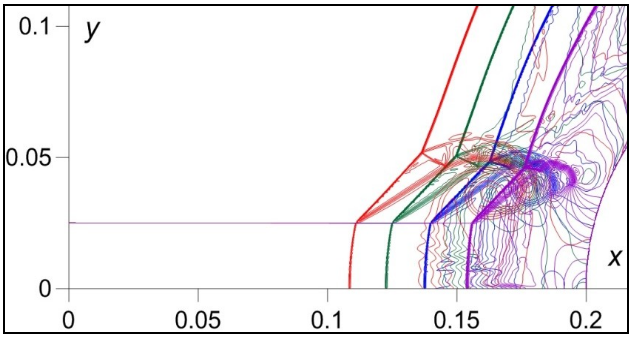
Figure 3: Development of unsteady triple-shock configuration, M=4.2, γ=1.2, α_ρ=0.5
(overlay of the calculated imajes for different time values, enlarged):
t=0.72 - red; t=0.74 - yellow; t=0.76 - green; t=0.78 - pink; t=0.8 - blue; t=0.82 - brown

4.2 Research of the detailes of flows for different M, γ and α_ρ

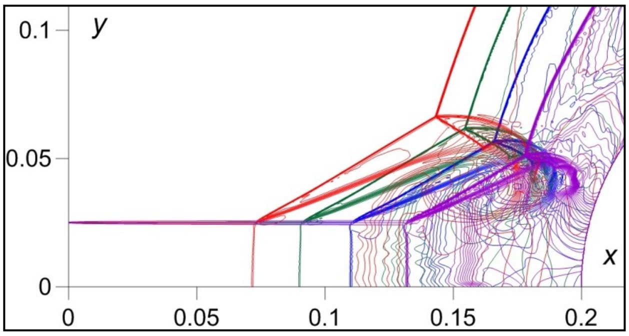
Flow imajes for M=4 and different γ and α_ρ are presented in Fig. 4. It is seen that the characteristics of the energy source effect significantly on the shape and elements of forming shock-vortex structure. The reason is



a)



b)



c)

Figure 4: Dependence of the angles in triple-shock configurations on γ for M=4, t=0.76
(overlay of the calculation images, γ=1.1 – violet, γ=1.2 – blue, γ=1.3 – green, γ=1.4 – red):
a) – ω_1=55°, α_ρ=0.67; b) – ω_1=45°, α_ρ=0.5; c) – ω_1=30°, α_ρ=0.25

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that the angle of the incident shock is strongly dependent on the rarefaction factor in the region of energy deposition. Thus, changing the characteristics of an energy release it is possible to influence the shape and parameters of triple-shock configuration and generated vortex.
The evolution of the shock structure for M=3 and different γ with the use of the overlay technique is presented in Fig. 5. It can be seen that the influence of γ on the shape and dynamics of the triple configuration is less pronaunced than the influence of the characteristics of the energy source.

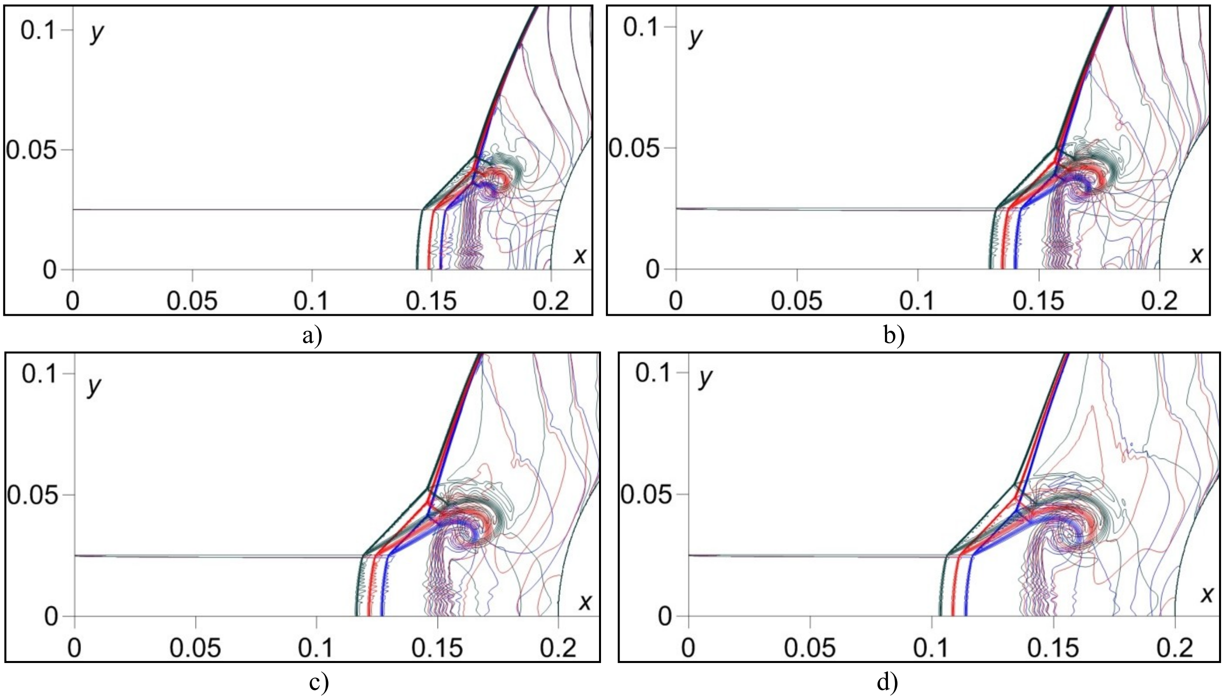

Figure 5: Dynamics of unsteady triple-shock configurations and vortices for M=3, α_ρ=0.5 and different γ (overlay of the calculation images for different time moments, enlarged, t=0.76 – blue, t=0.78 – red, t=0.8 – green): a) – γ=1.1; b) – γ=1.2; c) – γ=1.3; d) – γ=1.4

4.3 Study of the angles in triple-shock configuration for different M, γ and α_ρ

The dependences of the angles between the elements of the triple-shock configurations with the flow direction on γ are presented in Fig. 6 for M=4 and 3 for α_ρ=0.5. It can be seen that in the case of M=4 the angle

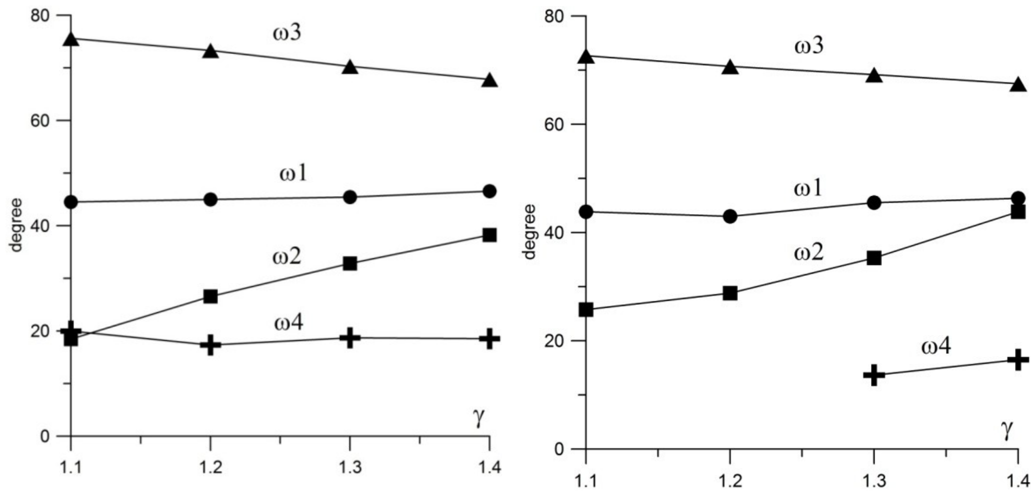

Figure 6: Dependences of the angles of triple-shock configurations with flow direction on γ, α_ρ=0.5: left – M=4 [6] ; right – M=3

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formed by the reflected shock ω_2 is changing significantly against γ (by 51.8%), the angle of the Mach wave ω_3 is changing not so strongly (by 11.5%) and the angles ω_1 and ω_4 are practically independent of γ. For M=3 a tendency of the considered angles behavior is saved, the values of ω_2 for M=3 are a bit larger than the values of ω_2 for M=4 and the values of ω_4 for M=3 are a bit smaller than the values of ω_4 for M=4. Note, than for γ=1.1 and 1.2 the upper shear layer is so weak that doesn't seen in the figures (Figs. 5a, 5b).

For the study of the dependence of the angles in triple configurations on rarefaction degree α_ρ the research has been conducted of the dynamics of the centers of triple configurations which has showed that for considered values of α_ρ their velocities were constant (and the dynamics of the coordinates of the centers were expressed by the straingh lines, Fig. 7).

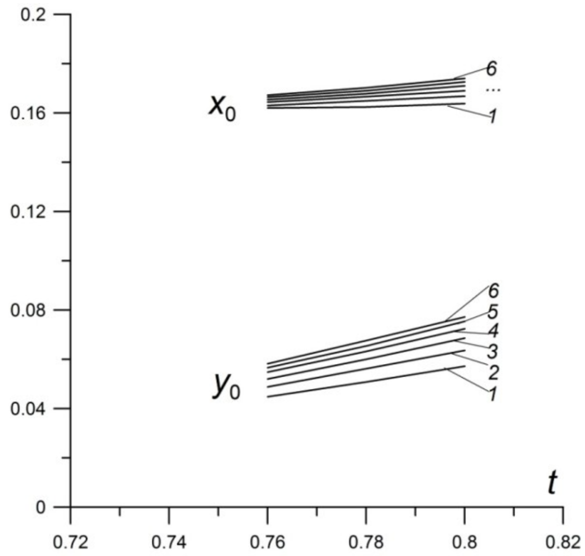

Figure 7: Dynamics of the coordinates of the centres of triple configurations, M=4, γ=1.2:
curve 1 - α_ρ= 0.59, *curve 2* - α_ρ= 0.50, *curve 3* - α_ρ= 0.41, *curve 4* - α_ρ= 0.33, *curve 5* - α_ρ= 0.25, *curve 6* - α_ρ= 0.18

It has been established that the angle ω_1 is well approximated (about 3% for moderate α_ρ) by the formula:

$$\sin^2 \omega_{pr}=\alpha_\rho \qquad (2)$$

which was obtained in [15] for the precursor angle ω_{pr} (see Fig. 8). So ω_1 increases against α_ρ and is independent of γ (and of freestream Mach number, too). This conclusion is confirmed by the obtained values of ω_1 presented in Fig. 6.

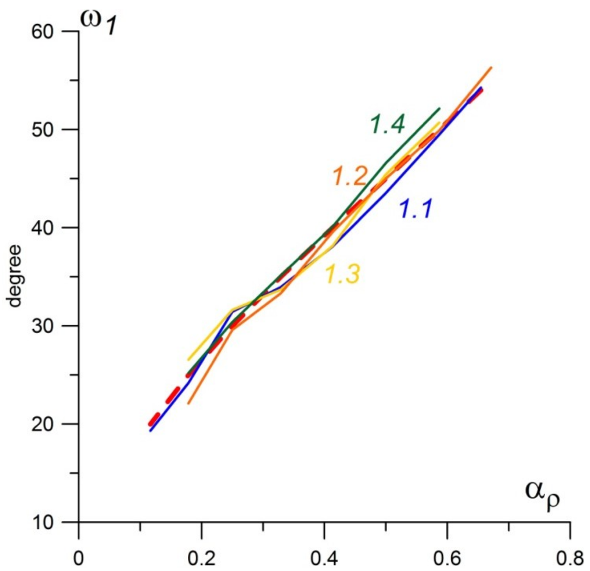

Figure 8: Dependence of the angle ω_1 (solid lines) and ω_{pr} (dashed line) on α_ρ for different γ, M=4

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Dependences of the considered angles on α_ρ and ω_1 for different γ are presented in Figs. 9, 10. It has been obtained [6, 7] that the angle of the reflected shock ω_2 has a local minimum in the considered interval, the angle of the Mach shock ω_3 decreases slightly against α_ρ (and against ω_1, too) and the angle of the shear layer direction ω_4 increases against α_ρ (and against ω_1, too). At the same time ω_2 decreases with decreasing γ, ω_3 slightly increases with decreasing γ and the dependence on γ is not seen through the behavior of ω_4.

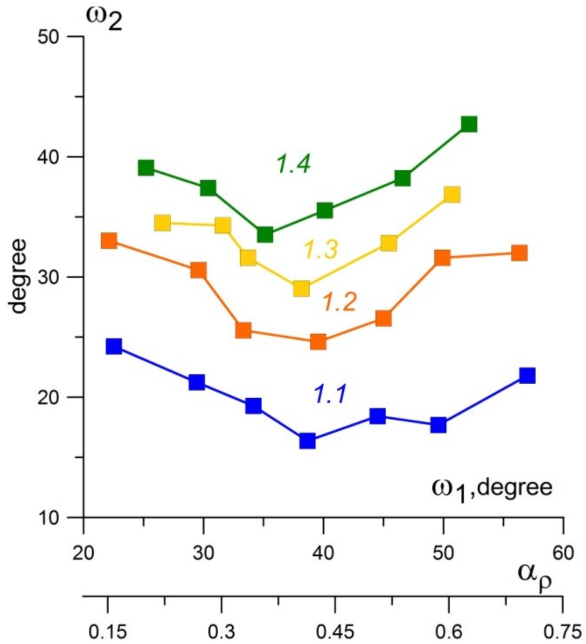

Figure 9: Dependences of the angle of rarefaction wave ω_2 on α_ρ and the angle of incidence ω_1 for different γ [7]

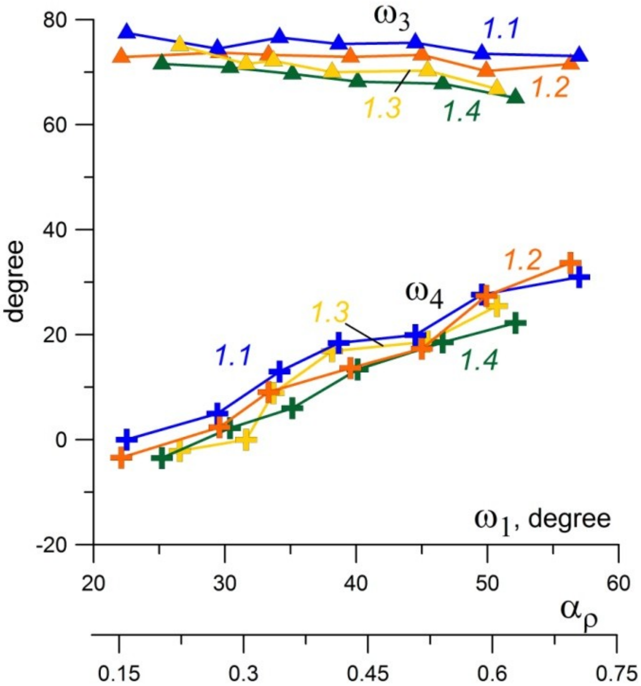

Figure 10: Dependences of the angle of Mach wave ω_3 and angle of shear layer direction ω_4 on α_ρ and ω_1 for different γ [7]

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For applying the three-shock theory [11] there should be accomplished a transition to a system of co-ordinates connected with the center of a triple configuration and the new angles ω_1', ω_2', ω_3' and ω_4' should be analyzed (see Fig. 11). Here the straight line *1* is the trajectory of the center of a triple configuration. These angles are expressed via the considered angles ω_1, ω_2, ω_3 and ω_4 as follows:

$$\omega_1' = \omega_1+\delta;\ \omega_2' = \omega_2-\delta;\ \omega_3' = \omega_3+\delta;\ \omega_4' = \omega_4+\delta.$$

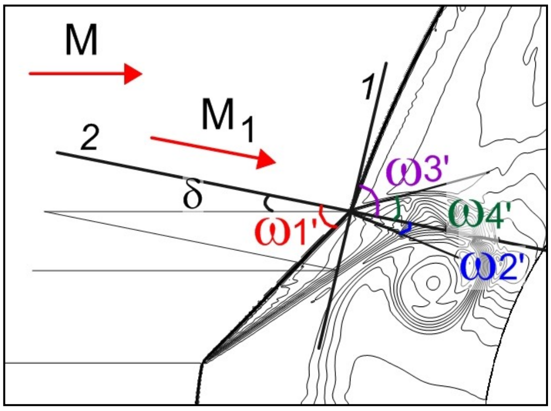
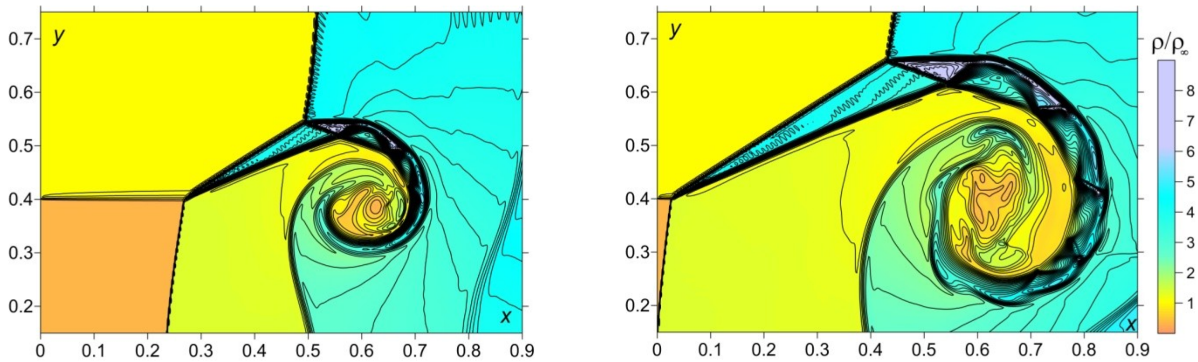


Figure 11: Possibility of the triple-shock structure analysis from the point of view of the triple-shock theory [11] (schematic)

Note, that this analysis should be fulfilled on the time interval on which the trajectory of the center of a triple configuration is close to a straight line (i.e. the flow mode is close to the self-similar one), the angle δ being different for different flow and energy source parameters.
The scheme accuracy of the calculations of shock fronts positions constitutes tenth parts of a percent. But the total accuracy of a triple-shock configuration angles evaluation is connected with using the flow images for the angles calculations and consists 1-2° for moderate α_ρ (ω_1 varies from 30° to 60°) and 3-4° for small α_ρ (ω_1 varies from 20° to 30°). To evaluate the influence of the boundary conditions [18], the simulations have been conducted for the enlarged calculation area: $0 \le x \le 0.5$, $0 \le y \le 0.5$. The difference in the calculations of the angles for two different calculation areas was 0.9° for ω_1, 3.4° for ω_2, 1° for ω_3 and 2.7° for ω_4.

4.4 Modeling of shock-vortex structures with multiple reflection of simple waves and the Richmyer-Meshkov instability

Here the problem of interaction of a plane shock wave with a boundary of heated and cold gases is considered for different gases and greater Mach numbers. This problem models generation of triple-shock configurations in the considered problems of supersonic streamlining with external energy deposition.



a) b)

Figure 12: Dynamics of shock-vortex structure with multiple reflection of simple waves accompanying the formation of triple-shock configuration. Density (colors and isochors), M=7, γ=1.4 (air), α_ρ=0. 3, enlarged [7]: a) - t=0.2; b) - t=0.3

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It has been shown that in the case of greater Mach numbers the formation of triple-shock configuration is accompanied by the more complicated shock-vortex structure containing multiple reflected simple waves (Fig. 12). The multiple reflection is taken place in a region between two contact discontinuities (shear layers). The examples of such type of structures for M=7-9 are presented in [7].
Fig. 13 demonstrates generation of the Richtmyer-Meshkov instability during the development of such kind of structure. Here a symmetry of the mushroom-like structure initiated by the Richtmyer-Meshkov instability is broken because of the asymmetry of the vortex flow around the structure. The reason of this instability generation is a secondary shock wave arising as a result of the interaction of "a head" of this structure with it's "tail" (Fig. 13b). Interaction of this shock wave with the contact discontinuity (shear layer) according to [19] gives rise to the instability generation (Fig. 13c).

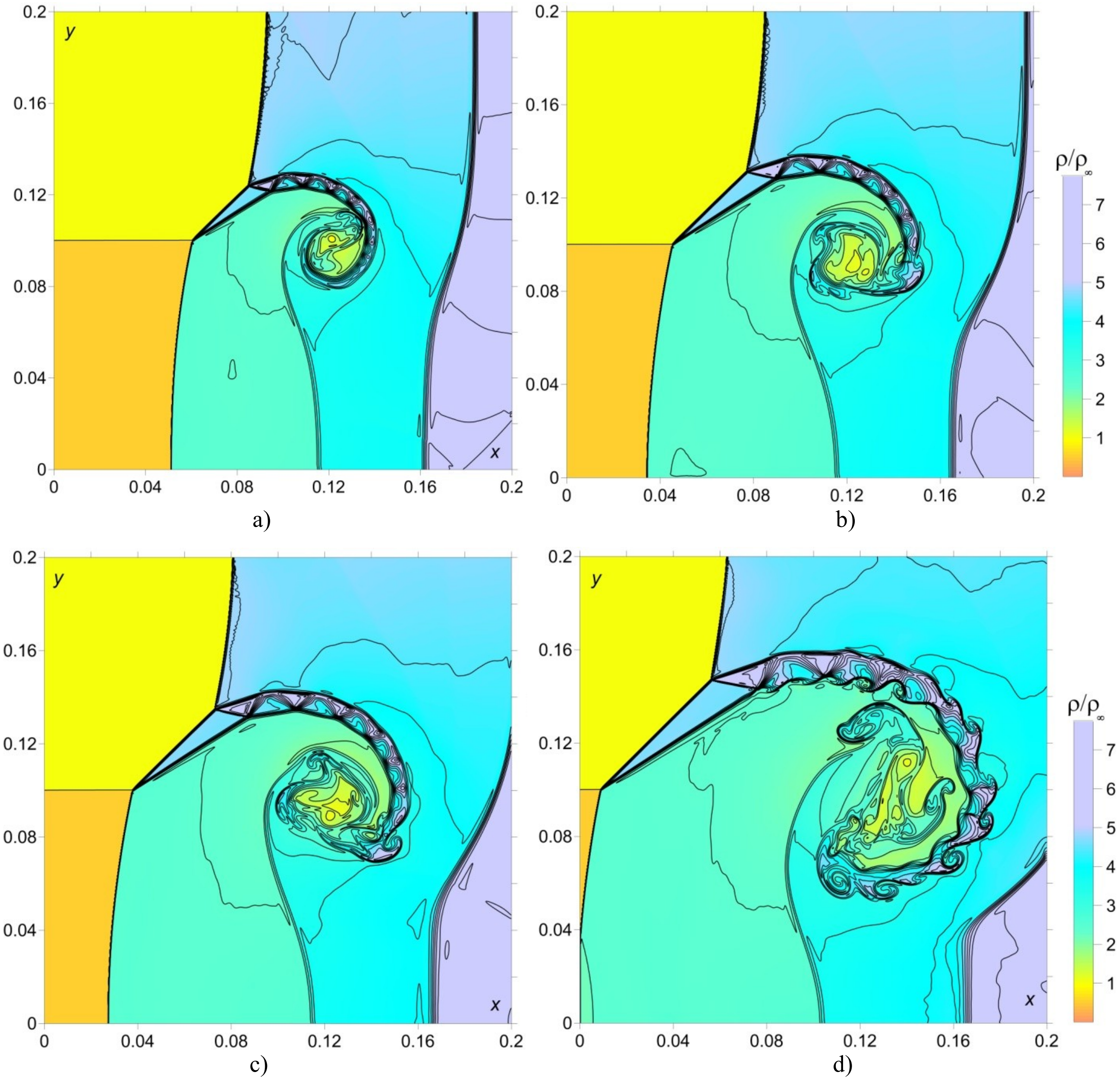

Figure 13: Dynamics of generation of the Richtmyer-Meshkov instability. Density (colors and isochors), M=8, γ=1.4, α_ρ=0.5: a) - t=0.1; b) - t=0.12; c) - t=0.13; d) - t=0.17

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5. Summary

- Unsteady Mach triple-shock configurations have been studied at the first stage of the process of interaction of an energy source of a shape of a heated rarefied channel (layer) with a shock layer in the flow mode close to the self-similar one.
- The dependences of the angles of a triple-shock configuration on γ changing from 1.1 to 1.4 have been obtained for freestream Mach numbers 3 and 4 and their comparison has been made.
- The dependences of the angles of a triple-shock configuration on the rarefaction degree of a gas in an energy source α_ρ and on the angle of incidence ω_1 have been obtained for freestream Mach number 4.
- For the evaluation of the angle of incident shock ω_1 the formulae (2) can be used which gives the connection of ω_1 and the rarefaction parameter α_ρ of a gas in an energy source.
- The angle of incident shock ω_1 is independent of γ and M (for the considered parameters).
- With decreasing γ from 1.4 to 1.1 the angle of the reflected shock ω_2 decreases (by 51.8% for ω_1=45^o and α_ρ=0.5), the angle of the Mach shock ω_3 increases (by 11.5% for ω_1=45^o and α_ρ=0.5), and the angle of the contact discontinuity ω_4 is practically independent of γ (M=4).
- The angle of the contact discontinuity ω_4 increases against α_ρ (and against ω_1), the angle of the reflected shock ω_2 has local minimum in the considered intervals of α_ρ and ω_1, and the angle of the Mach shock ω_3 decreases slightly against α_ρ (and against ω_1) (M=4).
- For M=7, 8 the shock-vortex structures (accompanying the formation of the triple-shock configurations) have been obtained which are characterized by the multiple reflection of simple waves (rarefaction waves and compression waves).
- Generation of the Richtmyer-Meshkov instability has been modelled for M=8 during the shock-vortex structure developing.

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