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Control of Plasma and Joule Heating Effects on Supersonic Flow past a Cylindrically Blunted Plate

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Abstract
Bow shock wave standoff distance together with the stagnation parameters and drag force have been studied in problem of a heated ionized area effect on supersonic streamlining a hemi-cylinder body in xenon under freestream Mach number 4.3. Plasma effect has been conducted experimentally with the use of gas discharge of different intensity producing different electron temperature and different degree of non-equilibrium of the gas in the heated ionized area formed in front of the body. It has been shown that the bow shock standoff distance increases strongly with the increase of the degree of non-equilibrium. Numerical simulations have been made for Joule heating impact on the supersonic flow with the gas temperature equal to the electron temperature obtained experimentally. The comparison of the experimental and computational results showed a possible new mechanism of supersonic flow control connected with changing the degree of non-equilibrium of a gas. Complex conservative difference schemes are used in the simulations.

1. Nomenclature

M	=	freestream Mach number
γ	=	ratio of specific heats
p_∞, ρ_∞, T_∞	=	freestream pressure, density and temperature
c_∞, u_∞, v_∞	=	freestream sound speed and velocity components
α_ρ	=	degree of gas rarefaction in an energy source
ρ_i, T_i	=	density and temperature in an energy source
T_e	=	electron temperature of a gas in an energy source
t_i	=	time moment of an energy source arising in a steady flow
Δt_i	=	time of the energy release action
D	=	transverse size of an AD body
d	=	bow shock wave standoff distance
d_r	=	relative bow shock wave standoff distance

AD Aerodynamic
MW Microwave

2. Introduction

Effect of a heated plasma area on supersonic flow past different AD bodies currently is a wide scientific research direction inside flow control investigations [1, 2]. Firstly studies on this topic were conducted in the eighties years of the last century [3-5]. Now the studies invole the research of complicated shock-vortex structures and a possibility of control of different flow elements: bow shock standoff distance, generation of vortices and instabilities and flow pulsations [6-8]. Investigation of plasma influence on position and shape of a bow shock wave is of particular interest of flow control studies. A research of plasma effect on the related bow shock standoff distance has been conducted in [9]. Investigations of the effect of MW plasma on combined cylinder AD bodies with the consideration of a large number of chemical reactions and comparison of the

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numerical and experimental dynamics of the stagnation pressure were conducted in [10, 11]. Flow control by means of the plasma action via producing electrical discharges of different configuration and influence of the magnetic field has been investigated in [12-14]. In [15,16] the research of the influence of high energy plasma sheets on formation of shock wave configuration and the action of an electromagnetic wave was conducted. Analysis of control of shock-vortex configurations via an external energy deposition into supersonic flows of different gases has been fulfilled in [17, 18].
This paper is devoted to the comparison of pure heating action and plasma action which are produced by an electrical discharge. Oncoming flow of xenon at Mach number 4.3 has been investigated. In the experiments the results were obtained on the increase in the electron temperature from Joule heating and saving the gas temperature unchanged. In the simulations the maximal possible gas heating has been modelled with the gas temperature equal to the electron temperature (obtained experimentally). It means a hypothetic case when during the action of an ionized heated medium the full energy from electrons comes to the gas heating and thermal equilibrium is reached with the maximal possible resultant temperature (equal to the electron temperature).
The main goal of the work was to investigate a dependence of the bow shock wave position on the non-equilibrium degree of produced plasma, to compare the numerical and experimental dependences of the relative standoff distance on the degree of non-equilibrium and to show that the plasma effects obtained experimentally are more strong then those defined by the maximal possible pure heating of the gas. It could mean that a new mechanism of bow shock position control (together with a control of a drag force of an AD body) connected with changing the non-equilibrium degree is possible to be accomplished.

3. Experimental investigations

3.1 Experimental installation

The experiments have been carried out in the working chamber of a form of supersonic inlet which was connected with a shock tube. Supersonic flow of non-equilibrium ionized gas was formed along the inlet's axis. A photo of the shock tube and working chamber is shown in Fig. 1. The hemi-cylindrical body was placed at some distance from the inlet entrance where the supersonic flow with Mach number M=4.3 was formed. Schematic of the supersonic inlet with the placed body and the corresponding photo is shown in Fig. 2.

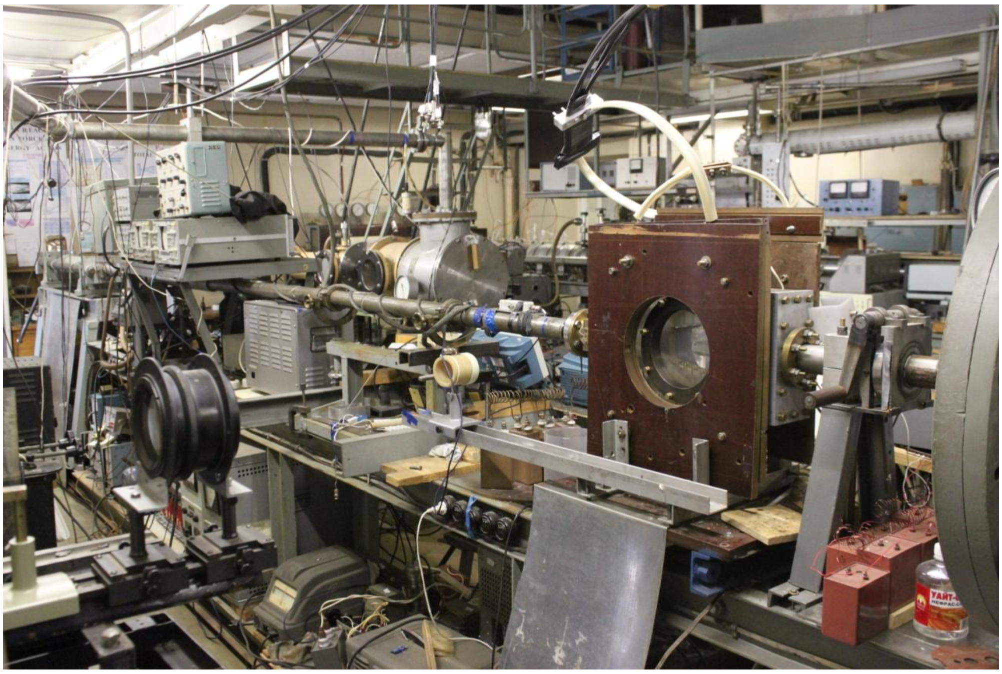

Figure 1: Experimental installation (photo)

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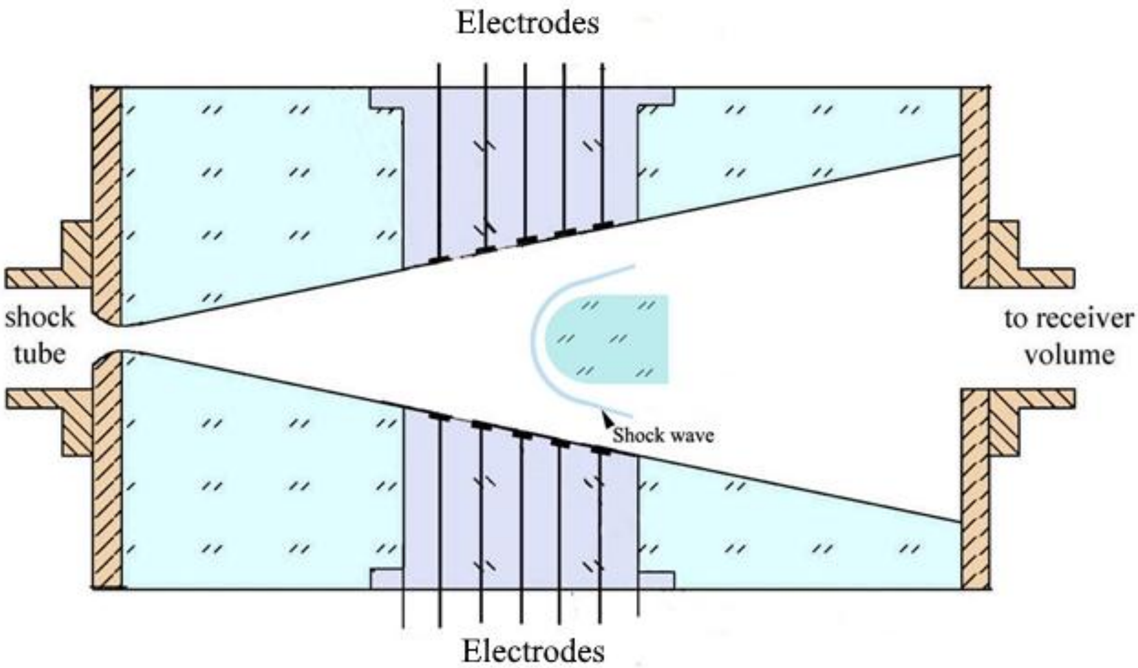
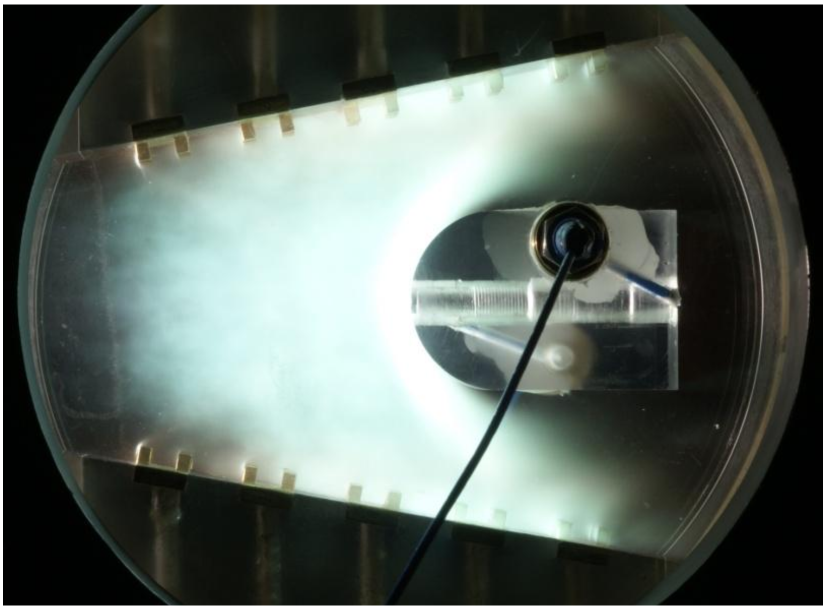
In the upper and bottom inlet walls the special electrodes were built in. The position of the electrodes is well visible on the photo in Fig. 2. The voltage supply of prescribed value to the separated electrodes allows the creating of the ionization zone with a wide changeable ionization degree in the oncoming flow. The gas incoming into the inlet has been previously ionized by means of the braking of the supersonic flow which was formed in the shock tube and then relaxed in the inlet. The electron temperature decreases in the inlet more slowly than the gas temperature. As the result the non-equilibrium supersonic flow with gas temperature T=1600 K and electron temperature T_e=4600 K was formed in front of the body without the discharge.
After that the discharge was switched on in this ionized gas flow. The duration of the discharge was selected for obtaining the increase in the electron temperature from Joule heating and saving the gas temperature unchanged. It can be obtained when the time of the energy exchange between electrons and gas particles is greater than the duration of the gas dischage.



a)



b)

Figure 2: Schematic of experimental installation (a) and a photo of supersonic inlet for the flow past the body (b).

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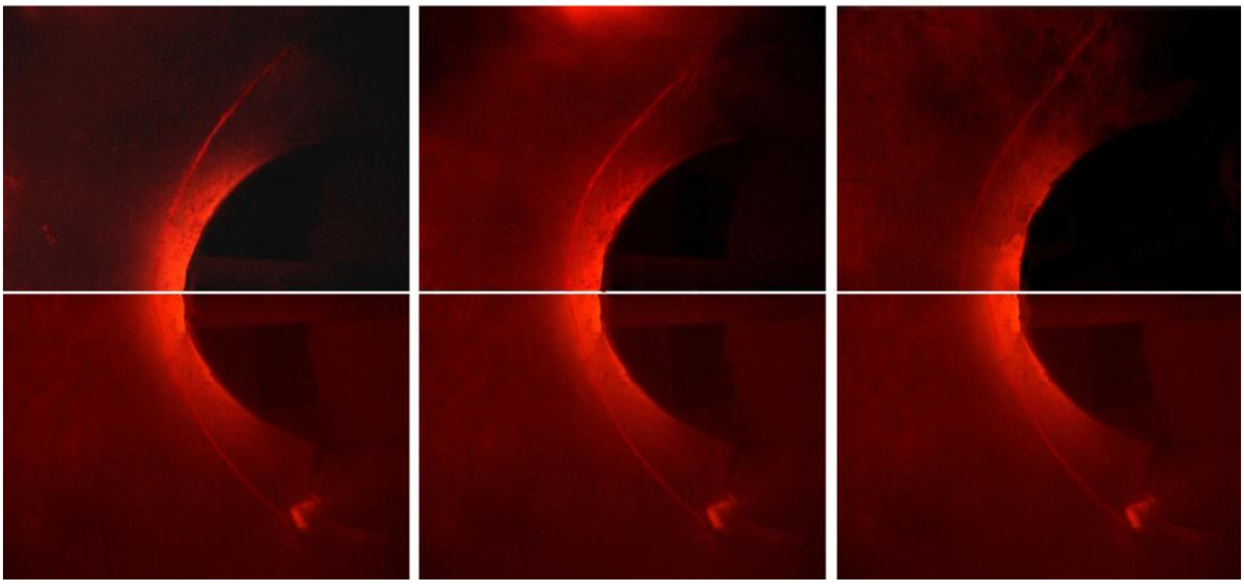
In the experiments the three types of ionised zones have been obtained which were generated by 1 , 2 or 3 pairs of electrodes dislocated in front of the body. Electron temperature of the incoming flow was increased by means of the increase in the applying voltage and gas discharge current. For obtaining the pictures of the supersonic AD body streemlining flow the Shclieren system with semiconductor laser source with pulse duration 30 ns and digital photo camera as a receiver part were used. Time delay was chosen for obtaining the flow pictures for steady ionized flow.
The electron temperature was measured by means of the measurement of luminosity intensity drop in the ultraviolet diapason; the gas temperature was taken from the calculation of a flow in the supersonic inlet [12].

3.2 Research of the bow shock wave dynamics with the use of the Schlieren technique

The Schlieren pictures of the bow shock wave near the hemi-cylindrical AD body with the radius of the cylindrical part r=20 mm at different electron temperature and non-equilibrium degree are presented in Fig.3. The bottom part of the pictures is the position of the bow shock wave at T_e=4600 K. This is a beginning stage when the oncoming flow is ionized only in the shock tube in front of the inlet entrance without the gas discharge in the inlet. The bow shock wave positions at different electron temperatures which were created by the gas discharge in front of the body are shown in the top parts of the pictures.
The distance between the bow shock wave and the body d increases with growing the electron temperature and non-equilibrium degree. Next increasing of non-equilibrium degree is followed by the instability of the bow shock wave up to the full destroying of it [12]. The change in the shock wave position can be explained by the plasma effect on the flow parameters.



a) b) c)

Figure 3: Flow dynamics in Schlieren images: a) T_e=6600K, j=2.5·10^5 A/m^2, d=4 mm b) T_e=7300K, j=3.6·10^5 A/m^2, d=4.3mm; c) T_e=7800K, j=4.4·10^5 A/m^2, d=6.9 mm.

4. Numerical simulations

4.1 Methodology

Effect of an heated area on a supersonic flow past an AD body with the shape of a plate blunted by a cylinder is studied. The simulations are based on the Euler system of equations for perfect inviscid gas (xenon) with γ=1.66:

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

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

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 AD body. At first the steady flow parameters have been calculated using (1). Steady flow mode was shown to be established at the time moment t=0.7. At this time the bow shock standoff distance agrees with the accuracy of 6.5% with the data from [19](including the accuracy of the recovery values from the figure 3 from [19]). The stagnation values of density and pressure differ from the theoretical ones by 1.1% and 2.1%, accordingly.
Energy sourse of a shape of heated rarefied area is supposed to arrise in the steady flow in front of the bow shock at the time moment t_i. The transversal size of this area is applied to be equal to that of the shock tube and the x-direction size is equal to $2D$. The density in this area is supposed to be smaller than in the freestream flow, $\rho_i=\alpha_\rho\rho_\infty$. Pressure and velocity in the area are the same as in the freestream flow, so the temperature in the area is increased in comparison with the freestream flow, $T_i=\alpha_\rho^{-1}T_\infty$. Besides, it is suggested that $T_i=T_e$ where T_e is the electron temperature obtained in the experiment. This means that there is the maximally possible Joule heating of the gas in the heated region occures. Thus, this heated area moves with the flow towards the bow shock and interacts with it. Defining flow and energy source parameters are presented in Table 1.

Table 1: Parameters of oncoming flow and energy source (heated area)

Parameter	**Dimension value**	**Non-dimension value**	**Normalizing value**
Density ρ_∞	0.127 kg/m^3	1	ρ_n =0.127 kg/m^3
Pressure p_∞	96.73498 Torr =0.12728 atm	0.12728	p_n = 1 атм = =1.01325*10^5 Pa
Temperature T_∞	1600 K	0.12728	T_n=12570.427 K
Body's transverse size D	0.04 m	0.2	l_n =0.2 m
X-axis size of the energy source	0.05 m	0.4	l_n =0.2 m
Time moment of the energy source arising in a steady flow t_i	156.961 μs	0.701	t_n=223.910 μs
Time of an energy source action in a steady flow Δt_i	28.297 μs	0.12637	t_n=223.910 μs

The problem is solved in the dimensionless variables. In figures below the normalised variables are presented. Complex conservative schemes are used in the simulations [20]. The body's boundaries are introduced into the calculation area without breaking the conservation properties. The calculation area is selected taking into account the symmetry of the flow. The staggered numerical grid is used with the equal spase steps $h_x=h_y$=0.0001 (1000 working nodes per the body's diameter D).

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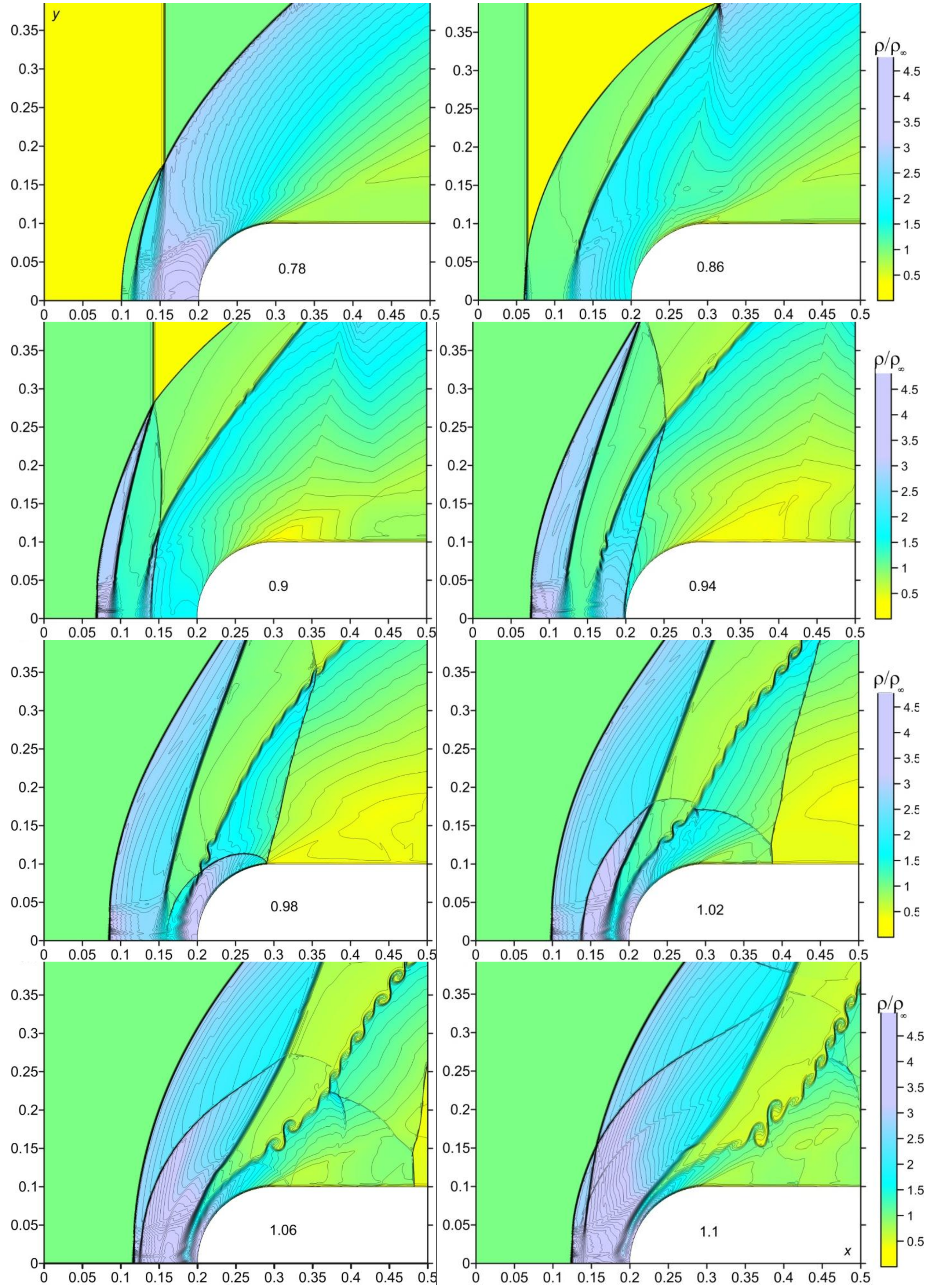

Figure 4: Flow dynamics for heated area – shock layer interaction, fields of density (levels and colours), t_i=0.701, M=4.3, γ=1.66, α_ρ=0.345, T_i=4640 K

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4.2 Numerical results

Dynamics of the flow reorganization under the action of the heated rarefied area is presented in Fig. 4 (here the dimensionless time values are indicated). Interaction of the front boundary of the heated area with the bow shock can be described in one dimensional approach via the solution of the Riemann problem [21]. One can see the elements of the solution of the Riemann problem (Fig. 4, t=0.78): the shock wave and contact discontinuity moving left and the rarefaction wave moving right. The reflection of this rarefaction wave from the body's boundary becomes a reason of the decrease in a drag force on the body's front surface [5].
Interaction of the rear boundary of the heated area with the shock wave can be described in one dimensional approach via the solution of another type of the Riemann problem [21], where the second shock wave is forming instead of the rarefaction wave (Fig. 4, t=0.9). It can be seen that the interaction of this shock configuration produces the whole flow reorganization including generation of the shear layer instabilities of Kelvin-Helmholtz type (Fig. 4, t=1.02-1.1).
Dynamics of the bow shock, stagnation parameters and front surface drag force during the interaction of the heated area with the supersonic shock layer for different temperatures and α_ρ are presented in Figs. 5, 6. Here the front surface drag force is calculated as follows:

$$F = \int_0^{0.5D} p dy.$$

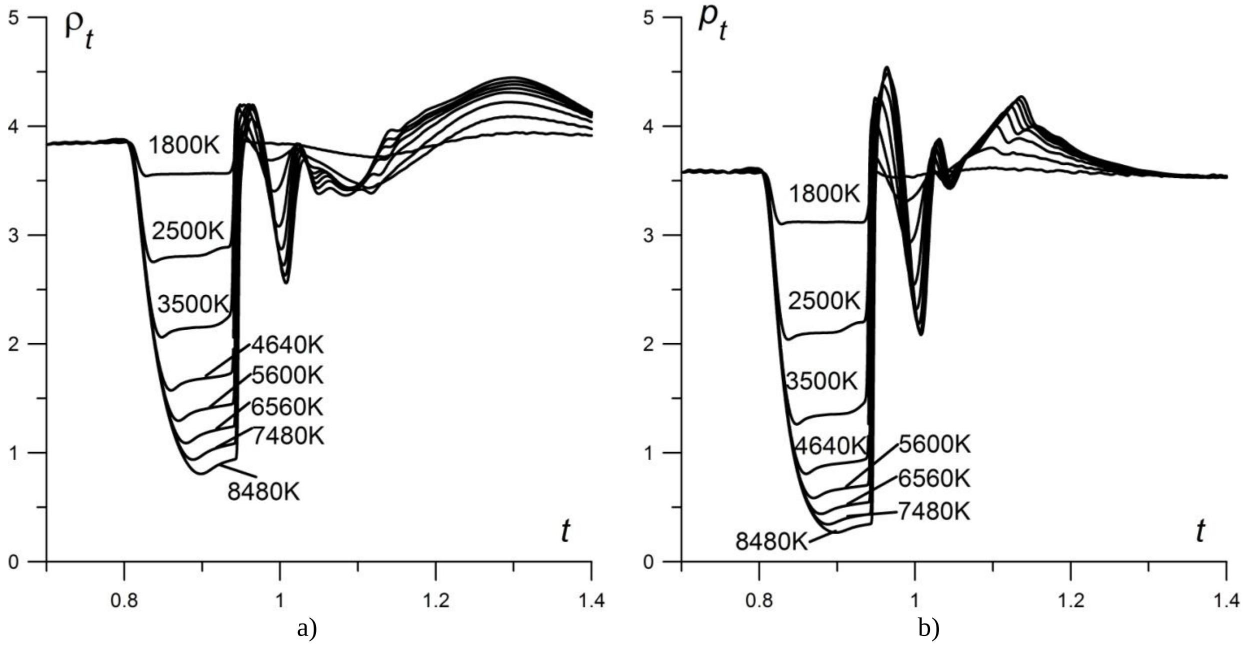

Figure 5: Dynamics of stagnation density (a) and pressure (b) for heated area – shock layer interaction; the values of temperature in the heated area are indicated

Corresponding values of rarefaction degree α_ρ are presented in Table 2. It can be seen that all the parameters are connected with each other and the greater standoff distance of the bow shock wave corresponds to the greater reduction of the drag force and a greater decline in stagnation parameters. Actually, in Fig. 7 the dependences of the minimal values of the drag force and bow shock x-coordinate on T_e/T_∞ (equal to T_i/T_∞) are presented. It can be seen that this mutual connection occurs there.

Table 2: Values of α_ρ for different values of temperature in the heated area (energy source)

Temperature T_i (K)	1800	2500	3500	4640	5600	6560	7520	7480	8480
Rarefaction degree α_ρ	0.88889	0.64000	0.45714	0.34483	0.28571	0.24390	0.21277	0.21390	0.18868

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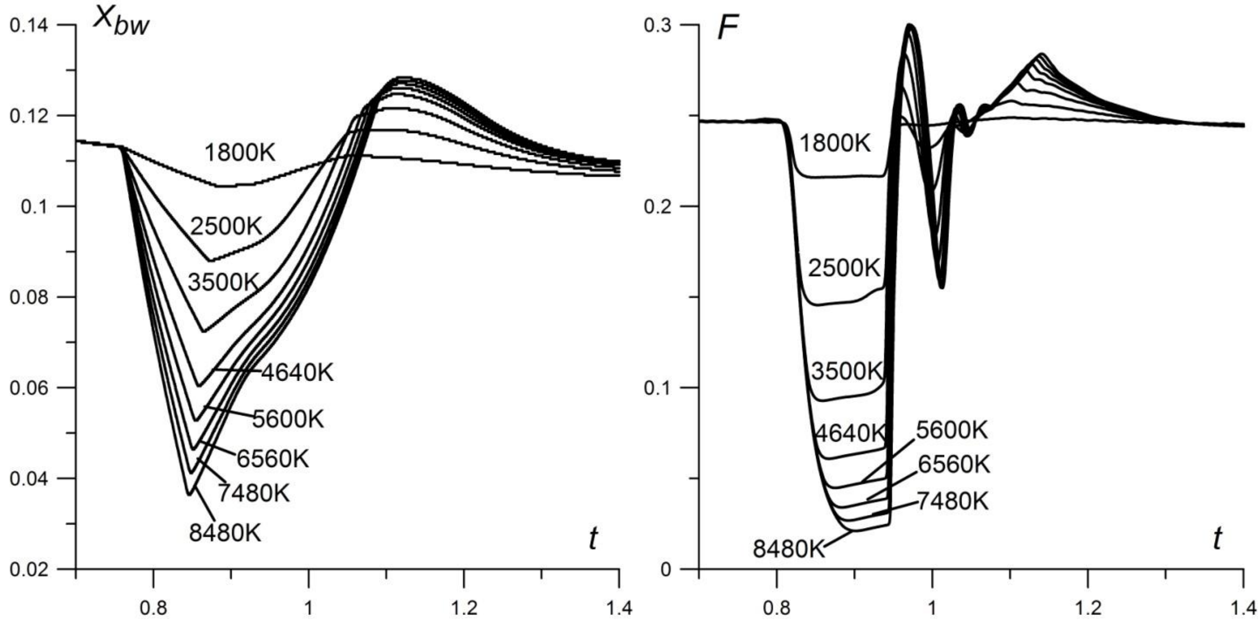

a) b)

Figure 6: Dynamics of bow shock (a) [9] and face drag force (b) for heated area – shock layer interaction; the values of temperature in the heated area are indicated

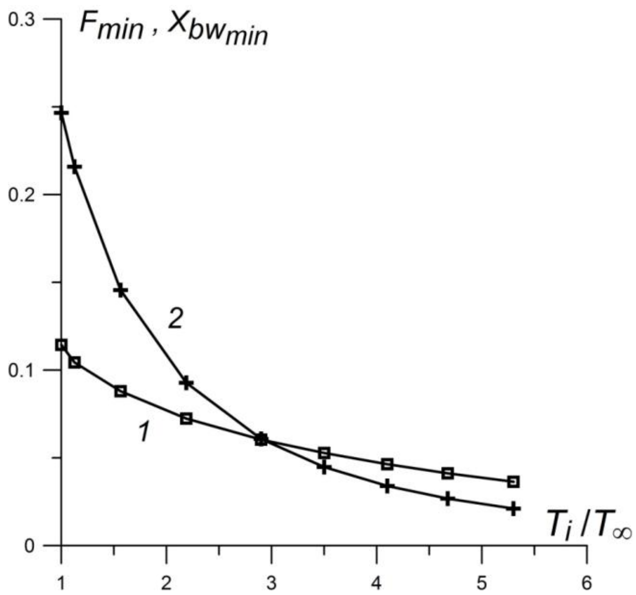

Figure 7: Dependences of the minimal values of the drag force and bow shock *x*-coordinate on the degree of non-equilibrium in the energy source [9]

Fig. 8 shows the difference in the dependences of relative bow shock wave standoff d_r on the degree of non-equilibrium T_e/T_∞ (which is equal to T_i/T_∞) of a gas in the energy source in a case when physical-chemical processes occurring in the front of the bow shock cause a decrease in γ (Fig. 8, *curve 1* - γ=1.2, *curve 2* - γ=1.66). Here $d_r=(d-d_0)/d_0$, where d is the distance from the body to the bow shock and d_0 is the same distance for the temperature in the energy source equal to the freestream temperature T_∞=1600 K.

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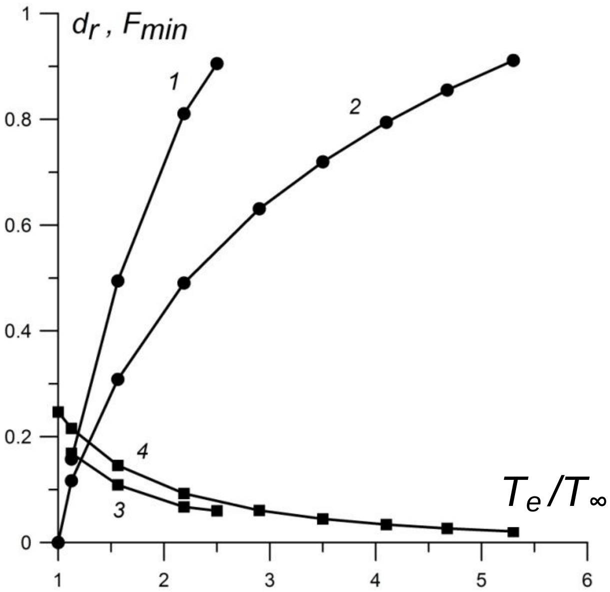

Figure 8: Dependences of the relative bow shock wave standoff d_r (*curves 1*, *2* for γ=1.2 and 1.66, accordingly) and minimal front drag force F_{min} (*curves 3*, *4* for γ=1.2 and 1.66, accordingly) on the degree of non-equilibrium

5. Analysis of the experimental and numerical results

Comparison of the experimental and numerical values of the relative bow shock wave standoff distance d_r on the degree of non-equilibrium T_e/T_∞ is presented in Fig. 9. Here $d_r=(d-d_{e0})/d_{e0}$, where d is the distance from the body to the bow shock and d_{e0} is the same distance for the temperature in the energy source equal to the initial electron temperature T_{e0}=4640 K from [9].

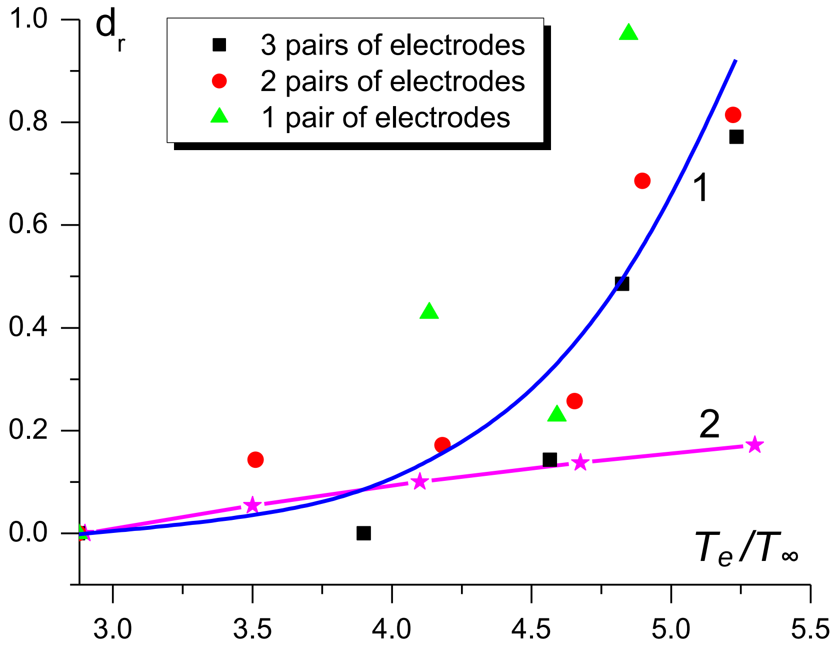

Figure 9: Dependences of the relative bow shock wave standoff on the degree of non-equilibrium in the energy source [9]: *curve 1* – experimental results for a different amount of pairs of electrodes; *curve 2*- numerical data

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This comparison shows that for the degree of non-equilibrium T_e/T_∞>4.5 the disagreement between these curves occurs, the difference being greater with increasing the non-equilibrium degree of the xenon plasma. This phenomenon is not completely understood, but from the results presented it can be concluded that the effect obtained in the experiment is caused not only by the Joule heating but also, by some plasma effects. The possible explanation is that the bow chock changes its shape and intencity via the physical-chemical proccesses occurs in its front for T_e/T_∞>4.5 which causes an additional its acceleration. In particular, it may be connected with the decrease in an «efficient» value of γ, as seen from Fig. 8. Thus, the bow shock standoff distance (together with the drag force of the AD body [22]) can be controlled not only by creation of heated regions in front of the bow shock wave but additionally, by changing the degree of non-equilibrium of the plasma region interacting with it.

6. Conclusion

Comparison of the numerical and experimental results showed that the upper limit of purely Joule heating action on the flow past an AD body influences the bow shock wave standoff distance more weakly than the action of processes taking place in plasma. Thus, based on the calculations in a wide temperature range of the effect of a heated ionized region on the shock layer, it can be concluded that the obtained experimental data indicate the existence of a plasma effect on supersonic flow past blunt AD bodies which nonlinearly increases with growing the degree of non-equilibrium in the oncoming heated region.

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References

[1] Knight, D. 2008. Survey of aerodynamic drag reduction at high speed by energy deposition. *J. Propuls. Power* 24(6):1153-1167.

[2] Russel, A., Zare-Bentash, H., Kontis, K. 2016. Joule heating flow control methods for high-speed flows. *J. of Electrostatics* 80:34-68.

[3] Georgievsky, P.Y., Levin, V.A. 1988. Supersonic flow over bodies in the presence of external energy input. *Pis'ma Zhurnal Tekh. Fiziki* 14(8):684–687 (in Russian).
Available online: http://journals.ioffe.ru/articles/viewPDF/31216

[4] Artem`ev, V.I., Bergel`son, V.I., Nemchinov, I.V., Orlova, T.I., Smirnov, V.A., Hazins, V.M. 1989. Changing the regime of supersonic streamlining obstacle via arising the thin channel of low density. *Fluid Dyn.* 24(5):779-784.

[5] Georgievsky, P.Yu., Levin, V.A. 1993. Unsteady interaction of a sphere with atmospheric temperature inhomogeneity at supersonic speed. *Fluid Dynamics* 28(4):568-574.

[6] Kolesnichenko, Y.F., Brovkin, V.G., Azarova, O.A., Grudnitsky, V.G., Lashkov, V.A., Mashek, I.Ch. 2002. Microwave Energy release regimes for drag reduction in supersonic flows. *Paper AIAA-2002-0353*, 1-12.

[7] Azarova, O.A. Knight, D., Kolesnichenko, Yu. F. 2011. Pulsating stochastic flows accompanying microwave filament / supersonic shock layer interaction. *Shock Waves* 21(5):439–450.

[8] Azarova, O.A. 2009. Simulation of stochastic pulsating flows with instabilities using minimum-stencil difference schemes. J. *Comp. Math. Math. Phys*. 49(8):1397–1414.

[9] Azarova, O.A., Erofeev, A.V., Lapushkina, T.A. 2017. A comparison of plasma and thermal effects upon supersonic flow past aerodynamic bodies. *Tech. Phys. Lett.* 43(4):401–404.

[10] Knight, D., Kolesnichenko, Y.F., Brovkin, V.G., Khmara, D., Lashkov, V.A., Mashek, I.Ch. 2009. Interaction of microwave-generated plasma with a hemisphere cylinder at mach 2.1. *AIAA Journal* 47(12):2996-3010.

[11] Knight, D., Kolesnichenko, Y.F., Brovkin, V.G., Lashkov, V.A., Mashek, I.Ch. 2010. Interaction of microwave-generated plasma with hemisphere-cone-cylinder. *Paper AIAA-2010-1005*, 1-16.

[12] Lapushkina T.A., Erofeev A.V., Ponyaev S.A., and Bobashev S.V. 2009. Supersonic flow of a non-equilibrium gas-discharge plasma around a body. *Tech. Phys.* 54(6): 840-848.

[13] Lapushkina T.A., Erofeev A.V., Ponyaev S.A. 2011. Supersonic flow about a body exposed to electric and magnetic fields. *Tech. Phys.* 56(5):616-622.

[14] Lapushkina T.A., Erofeev A.V., Ponyaev S.A. 2014. Pressure variation by a magnetohydrodynamic method at the surface of a body placed in a supersonic flow. *Tech. Phys*. 59(7):968-974.

DOI: 10.13009/EUCASS2017-85

[15] Jin, J., Mursenkova, I.V., Sysoev, N.N., Vinnichenko, N.A., Znamenskaya, I.A., Glazyrin, F.N. 2011. Experimental investigation of blast waves from plasma sheet using the background oriented Schlieren and shadow methods. *J. Flow Visualization Image Process*. 18(4):311-328.
[16] Bityurin, V.A., Bocharov, A.N., Tatarinov, A.V., Degtyar', V.G., Kalashnikov, S.T., and Khlybov, V.I. 2015. Numerical simulation of electromagnetic wave propagation through the shock layer around a blunt-nosed body. *High Temp*. 53(5):703-708.
[17] Azarova, O.A. and Gvozdeva, L.G. 2016. Unsteady triple-shock configurations and vortex-contact structures initiated by the interaction of an energy source with a shock layer in Gases. *Tech. Phys. Lett.* 42(8):799-803.
[18] Azarova, O.A., Gvozdeva, L.G. 2017. Control of triple-shock configurations and vortex structures forming in high speed flows of gaseous media past AD body under the action of external energy sources. *Aerospace* 4(1):1-13.
[19] Blagosklonov, V.I. and Minailos, A.N. 1972. The flow past a circular cylinder in supersonic flow of a perfect gas. *Uch. Zap. TsAGI* 3(2):130-134 (in Russian).
[20] Azarova, O.A. 2015. Complex conservative difference schemes for computing supersonic flows past simple aerodynamic forms. *J. Comp. Math. Math. Phys.* 55(12):2025-2049.
[21] Rozhdestvenskii, B.P. and Yanenko, N.N. 1978. Systems of quasi-linear equations: Nauka. Moscow. 668p. (in Russian).
[22] Maikapar, G.I. 1971. Calculation of a body drag via a bow shock wave shape. *Uch. Zap. TsAGI* 2(6):23-31 (in Russian).