LOCAL MHD ACTION ON SUPERSONIC AIR FLOW ROUND BODY

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I. Introduction

In the work a possibility to control the supersonic body streamline at the action on flow parameters in the near-surface region between the bow shock and body are investigated. As an action is used electrogasdynamic (EGD) action, the contribution of energy in the narrow near-surface region by organization of near-surface gas discharge, and magnetohydrodynamic (MHD) action when the external magnetic field is applied. In the previous work [1] the possibilities of present actions on to streamlining of nose part of the body were designed experimentally using supersonic flow of ionized xenon. The experimental data showed the increase and decrease of a distance from the shock wave to body at the different degrees of EGD and MHD actions in the near-surface region were obtained. It is occurred due to the decrease or increase of a pressure in the discharge region between the shock wave and body as result from gas heating or action of Lorentz force.

In this work the streamlining of body by supersonic air flow with various ionization degrees are considered. The aerodynamic experiment makes it possible to investigate the action on the structure and parameters of streamline of the head parts of aircraft at the different altitudes and flow velocities. To carry out this work the experimental facility which was designed on the base of the shock tube and used in previous works [1, 2] is used. The semicylindrical body is mounted on the axis of a supersonic nozzle connected with a low pressure chamber. The gas compressed in the shock tube enters to the nozzle and creates supersonic air flow in the region of body position. The experimental facility gives possibility to change the distance from body to the nozzle entry, that enables to organize the supersonic streamline of the body by air with various flow velocities. The brass electrodes installed in top and lower walls of the nozzle are used for preliminary ionization of incoming air flow, that enables to organize the surface discharge at the nose edge of body at the smaller discharge voltages.

The working regime of the shock tube was selected from following factors: sufficient time for formation of stationary flow in working region, particle concentration $N=10^{23}\div10^{24}$ m^{-3} in working region, at expanding in divergent nozzle gas temperature T_h must be higher than condensation temperature of air components and molecular impurities, temperature of heated gas after reflected shock wave in shock tube at end of shock tube must be lower than temperature at which a significant changes at molecular mixture of air occurs. Experiment was conducted at following parameters of shock-tube: Mach number in shock tube M_2 =6.2, initial pressure and temperature of gas p_1=30 Torr, T_1=300 K. Flow parameter near body in working region (X_0=20 cm) Mach number is M=4.3, T=395 K, $u=1.87\cdot10^3$ m/s, $N=5.34\cdot10^{23}$ m^{-3}, ρ=0.026 kg/m^3. Doubled kinetic energy of the flow per unit of the volume is $\rho u^2=9{,}06\cdot10^4$ J/m^3.

The main EGD action on the body streamline was made by creation of near-surface discharge near nose part of the body with the help of electrodes mounted in the body's wall (the Fig. 1).

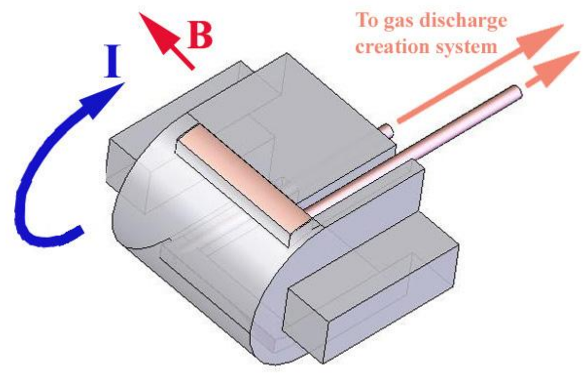

Fig.1. Model of body with horizontal electrodes.

As a voltage source a special LC-circuit were used that allow us to create a near-surface discharge of different intensities without special keys. The discharge switch-on at arriving of ionized flow to the body and flew near nose part of the body by semicircle trajectory. Discharge remains in the region near body after shock wave. This region has size about L=0.5cm×l=3.5cm×h=4.5cm. For organization of MHD action on the flow the additional magnetic field with the magnitude up to 1.5 T perpendicular to the flow created by Helmholtz coils were switched on during experiment. For flow visualization a special schlieren system on the base of semiconductor laser and digital camera were used.

Electrogasdynamics method (EGD) of action of flow structure is based on gas heating in electric field at gas discharges of high intensity. In this work energy input to the flow localized in narrow near-surface region between bow shock and nose part of the body, which lead to the increase of the pressure in this region and shift of the bow shock. The main task of this work is to investigate how bow shock shift changes at air supersonic body streamline at increase of heat parameter of EGD action $N = \frac{jE\Delta t}{\rho u^2}$ is a ratio between gas heating in the discharge and doubled kinetic energy of the flow. Change of heat parameter is due to change of near-surface discharge intensity near body's nose part. Also in the work a comparison of streamline parameters at the same EGD and MHD actions at streamline of the same model in air and xenon flows is made.

II. Experimental parameters of near-surface discharge

The typical oscillograms of a gas discharge current in the near-surface region and attainable at these conditions air plasma conductivity are shown on the Fig. 2.

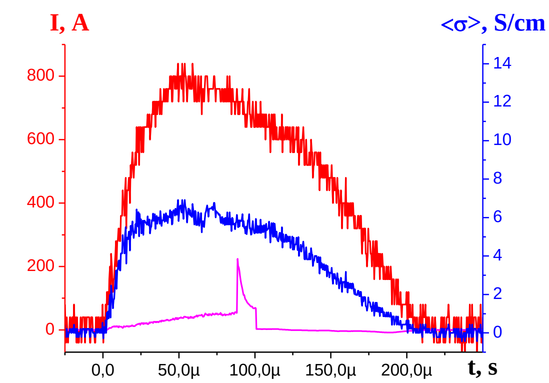

Fig. 2. Oscillograms of current (top curve) and integral conductivity (middle curve) of air plasma at near surface gas discharge. Bottom curve is diagnostic laser pulse.

The duration of discharge is about 200 mks, that corresponds to the duration of the body streamline by air flow, the record of a schlieren-picture position of shock wave is made through 100 mks after the discharge beginning, that is enough for an establishment of the stationary streamlining [3]. The pulse of a laser luminescence of the schlieren-setup corresponds to low curve on the Fig. 2.

The parameters of the surface gas discharge, which influences on the streamlining, were determined experimentally on current-voltage characteristic of the gas discharge current I in dependence from the voltage of gas discharge gap V_{pl}, shown on the Fig. 3.

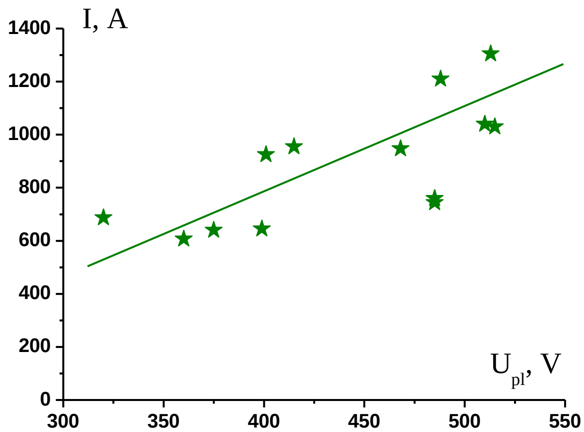

Fig. 3. Current-voltage curve of the near surface gas discharge in air.

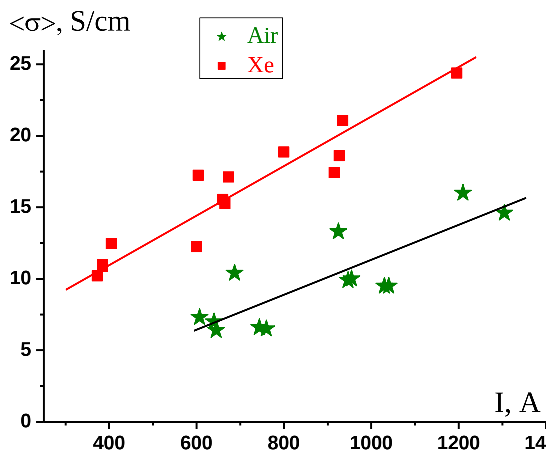

Fig. 4. Plasma conductivity in the near surface gas discharge in dependence on discharge current.

Obtained the average effective air conductivity was determined according Ohm's law for plasma:

$$j = <\sigma> E, \qquad (1)$$

where the density of discharge current is

$$j = \frac{I}{S} = \frac{I}{hl}, \qquad (2)$$

and intensity of electrical field is

$$E = \frac{V_{pl}}{L}. \qquad (3)$$

The dependence of the average effective air conductivity obtained near surface of the model in the discharge is shown on the Fig. 4. Here for comparison the xenon conductivity at the similar discharge is shown.

The average electron concentration in the discharge was determined as:

$$< n_e > = \frac{\langle j \rangle}{e v_d}, \qquad (4)$$

where the electron drift velocity in the discharge v_d for air was determined with help of reference data [4] on the base of $\frac{E}{p}$ values. The estimation of gas pressure in the streamlining zone *p*=45 Torr was made on the base calculated on ideal shock tube theory [5] of the relative values of the stagnation temperatures and density after reflected shock wave at the various values of Mach number of shock wave M_2, and according to the relative values of the flow parameters in a linearly divergence channel calculated on the base of the isentropic formula [6]. These dependences for air are presented in paper [7]. The change of electron concentration at the change of air conductivity in surface discharge is shown on the Fig. 5.

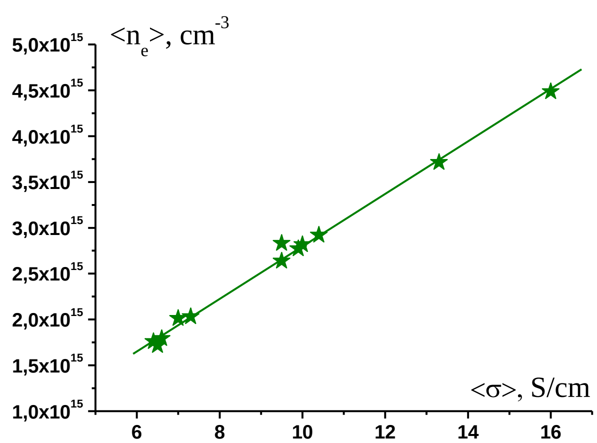

Fig. 5. Electron density of air in discharge in dependence on effective conductivity.

The average values of air conductivity in discharge at the surface EGD action are about <σ>=5÷15 S/cm, then electron concentration changes as $<n_e>=2\div4.5\cdot10^{15}$ cm^{-3}. The change, at the increase of surface discharge intensity, of heat (energetic) parameter *N* determine an energetic deposit in the near surface region of discharge and gas heat degree at the electrogasdynamic action on the streamlining structure are shown on the Fig. 6.

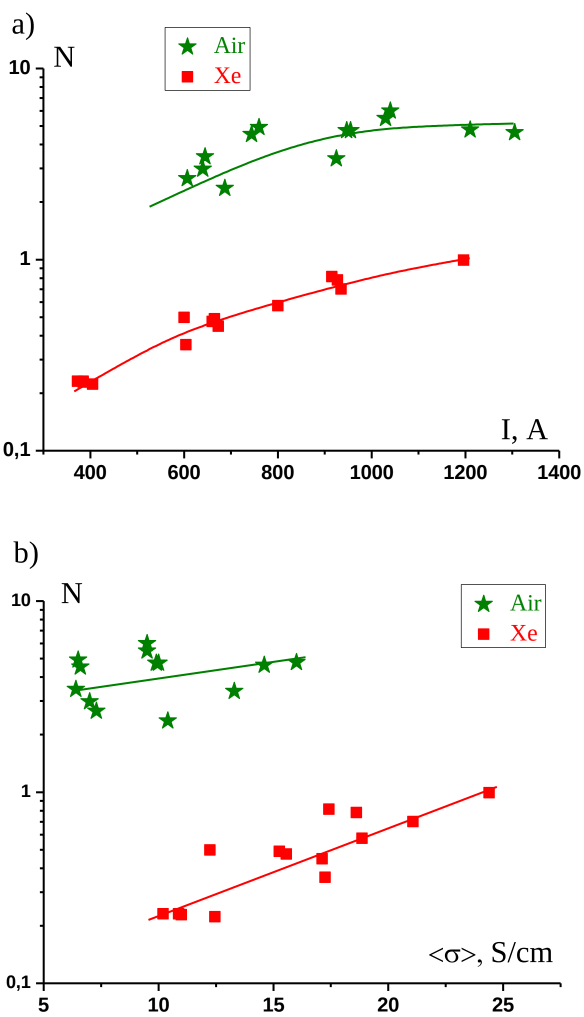

Fig. 6. Heating parameter in dependence on discharge current and conductivity.

The Fig. 6a shows how the parameter change depends on gas discharge current, and the Fig. 6b show how it depends on plasma conductivity. Here for comparison the values of parameter *N* for surface discharge in xenon are given. One can see that at the same discharge intensities the values of heat parameter in air are in 5 times more than in xenon. It is explained that for creation of discharge intensity compared with intensity in xenon, in air discharge it is need to increase the intensity of electrical field in discharge gap that leads to heat parameter increase. It is interesting that electron concentration in air discharge changes weakly with the energetic parameter growth that is seen from the Fig. 7.

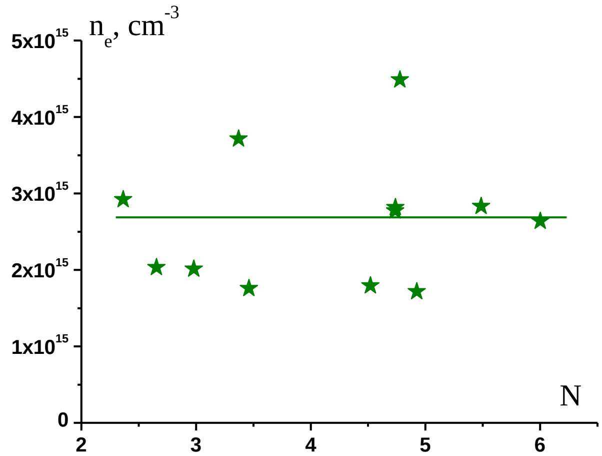

Fig. 7. Electron density in dependence on EGD parameter in near surface discharge.

III. Change of body streamline at near-surface EGD and MHD actions

The examples of bow shock shift at air body streamline at EGD interaction in near-surface region are shown in the Fig. 8. Here in the bottom part of the figures a picture of the flow without external action is shown, and upper part of the figures is the flow pictures at presence of the near-surface discharge with different thermal parameters of the action. It is clearly seen an increase of the distance between body's nose part and bow shock due to energy input to the near surface region that leads to pressure increase after shock wave.

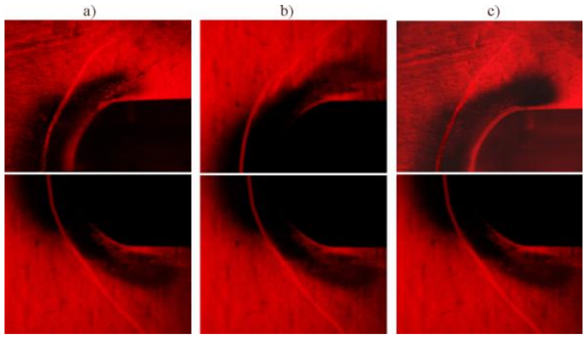

Fig. 8. Schlieren pictures of body streamline in air flow: top picture is obtained at near surface discharge without magnetic field; bottom picture is obtained without external action. a) $j=3.5\cdot10^6$ A/m^2, N=2.7, b) $j=4.3\cdot10^6$ A/m^2, N=4.9; c) $j=5.9\cdot10^6$ A/m^2, N=6.0

The Fig. 9 shows relative bow shock shift $\frac{d-d_0}{d_0}$ versus gas-discharge current and thermal parameter of EGD action.

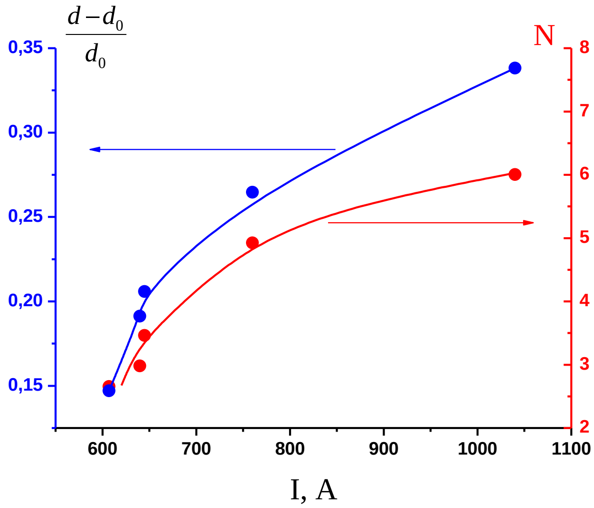

Fig. 9. Bow shock wave shift in dependence on discharge current and heating parameter.

Here d_0 is a distance from the body's nose part to the shock wave without external actions. It is clearly seen that increase in discharge intensity and thermal parameter leads to increase of bow shock shift, shock wave moves from the body.

The obtained results of EGD action in air flow is reasonable to compare with results obtained at streamlining of same body by xenon flow [1]. A change of the bow shock wave position in this case was investigated not only at EGD interaction but an MHD interaction in the near-surface region. For this an additional external magnetic field was used. In this case a Lorentz force directed to (the Fig. 10a) or from (the Fig. 10b) the body (depending on the gas discharge current direction) influence on a gas flow.

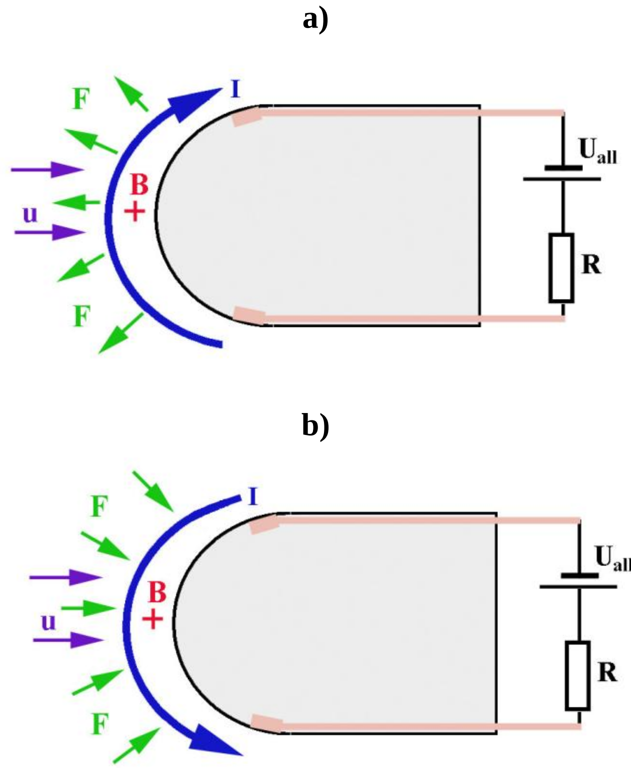

Fig. 10. Illustration of Lorentz force (vectors F) action at near-surface gas discharge.

a) Current direction bottom-top, Lorentz force out presses gas;
b) Current direction top-bottom, Lorentz force presses gas.

As a result a Lorentz force drives gas to or from the body that leads to the increase or decrease a pressure in the region between bow shock and body and change in bow shock position. In dependence on Stewart parameter

$St = \frac{jBL}{\rho u^2}$ (ratio between Lorentz force work on length of interaction and the doubled kinetic energy of the flow), which determines an impact of Lorentz force action of body streamline and in dependence on discharge current direction in the region between bow shock and body a change of body streamline and possibility to move bow shock not only from the body but and to the body relative to initial position (a EGD action that there is at MHD action contradict to this) was investigated.

The Fig. 11 and 12 shows generalized data of relative bow shock shift versus of EGD and MHD parameters in the region between bow shock and body's nose part. The Fig. 11 shows how bow shock change it position only at EGD interaction. An increase of the distance between bow shock and body's nose part at increase of the heat parameter of near-surface discharge at absence of magnetic field was observed both in xenon (squares) and in air (stars).

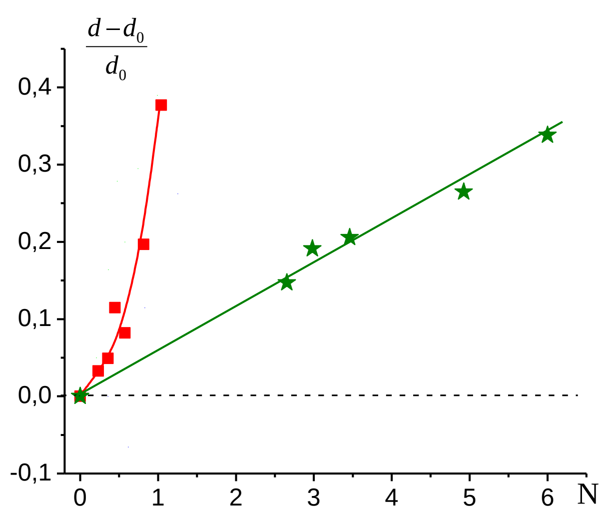

Fig. 11. Bow shock wave shift at EGD action: 1 is Xe, B=0 (squares); 2 is Air, B=0 (stares)

As can be seen from figure a bow shock shift increase rapidly in xenon than in air at increase of energy input. Approximately the same bow shock shift in air is seen at value of parameter N 5 times higher then in xenon. This mean for flow control by EGD method in air a heat input must be 5 times higher than in xenon.

At MHD interaction in near-surface region in xenon flow (the Fig. 12) there is an increase and decrease in bow shock shift. At increase of Stewart parameter at Lorentz force directed to the body (triangles) there is an additional shift of bow shock from the body. This shift becomes larger than shift at absence of magnetic field due to additional action of the Lorentz force.

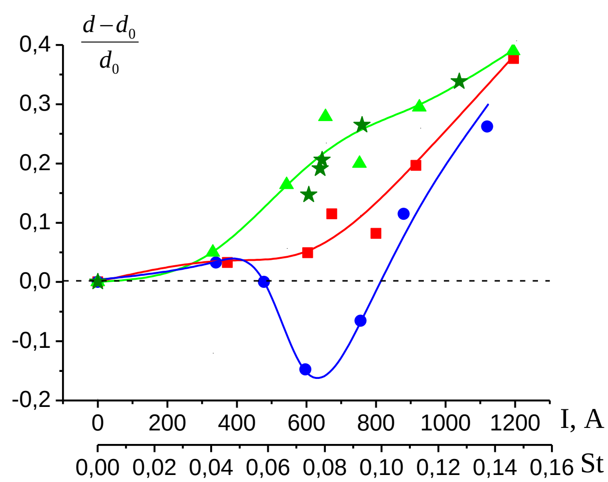

Fig. 12. Bow shock wave shift at EGD and MHD actions: 1 is Xe, B=0 (squeres); 2 is Xe, B=1.4T, Lorentz force direction is out from body (circles); 3 is Xe, B=1.4T, Lorentz force direction is up to body (triangles); 4 is Air, B=0 (stars)

At Lorentz force action in opposite direction (circles) bow shock moves from the body, after this moves to the body, again moves from the body when heat action of discharge become prevail over Lorentz force action. Relative shift of bow shock at streamlining in the air flow is shown in figure by olive stars. It is seen that this shift is nearly equal to the value obtained in xenon flow at EGD action with additional Lorentz force action. It can be described by more intense gas heating in air then in xenon at the same discharge intensity.

IV. Conclusions

Based on the results of this work it is possible to conclude that it is possible to control bow shock position of flight vehicle by energy deposition and MHD interaction in near-surface region near its nose part.

Electrogasdynamic method allows us to shift bow shock by organization of gas discharge on body's surface near it nose part after bow shock. This method is based on heating of the gas. A bow shock shift occurs due to strong gas heating in discharge in the region between bow shock wave and the model which leads to pressure increase after bow shock. By changing heating intensity (and electrogasdynamics parameter *N*) it is possible to change bow shock position. In the air a gas heating must be 5 times higher than in xenon.

At switching-on of external magnetic field orthogonal to the flow and near-surface gas discharge current it is possible to make magnetohydrodynamic control of the bow shock-wave position by Lorentz force effect. At changing of gas discharge current direction to opposite one the Lorentz force direction also changing. In this case Lorentz force will be force up or down gas near model, i.e. increase or decrease pressure in the region between bow shock wave and the model. By changing direction of Lorentz force and MHD interaction parameter *St* it is possible to change the bow shock-wave position as to move wave away from body as to approach it to body. The same relative shift of shock wave in air and xenon occurs at the approximately same Stewart parameters.

The ranges of the energetic parameter and Stewart parameter values determined in the work, corresponding to the regions of the most effective EGD and MHD actions, allow to choose the gas discharge parameters and the magnetic field for the most effective control of the shock wave position both to the increase the distance from shock wave up to body and to the approach of the shock wave to body.

Acknowledgments

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