MHD Control for Scramjet Inlet

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The potentialities of MHD effect for flow control in a scramjet inlet are discussed in [1-8]. In the papers [3-6] it is shown that the MHD interaction allows one to control the oblique shocks position and to make the flow field in the inlet at off-design conditions quite similar to one at design conditions in the case when the flight Mach number M_∞ is greater than the design Mach number M_d. This effect is achieved at various configurations of the magnetic field and the area of the MHD interaction. In the papers [1-4, 7] it is shown that the MHD control allows one to increase both the air capture and the flow compression in the inlet at flight Mach number $M_\infty < M_d$. According to [4] this

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effect is observed not for all configurations of the magnetic field, but only for the case when the vector of magnetic flux density has a negative projection on the direction of an incident flow. In the present paper the significance of such characteristics as the magnetic field orientation, the power spent on the flow ionization and geometric proportions of the ionized region in the MHD control by the scramjet inlet will be analyzed.

The model of the MHD controlled inlet with non-equilibrium conductivity, that is described in [3] is used in calculations. 2D Euler approach is considered. The non-equilibrium conductivity of a flow is supposed to be ensured by the electron beam ionizer. The modeling approximation in which the power density q_i put into ionization of a flow is assumed to be a constant in the region of the MHD interaction is considered. The local conductivity of a flow at given flow parameters and value of q_i is calculated by using the results of [3]. In order to define the region of ionization it is necessary to take into account that electrons of the e-beam at typical energies (1-100 keV) and the magnetic induction B>1T propagate practically along the magnetic field. Hence the configuration of the region with the non-equilibrium conductivity created by the e-beam strongly correlates with the magnetic field configuration. The homogeneous magnetic field $\boldsymbol{B}$ which is characterized by the modulus $B=|\boldsymbol{B}|$ and by the angle α between the magnetic field lines and the incident flow is considered.

Typical configuration for the MHD controlled inlet is shown in Fig.1. As the ionized region we define the region which is enclosed with the lines that are parallel to the magnetic field lines: $y_0 + (x - x_0 - \Delta x)\tan(\alpha) \le y(x) \le y_0 + (x - x_0 + \Delta x)\tan(\alpha)$; the line $y(x) \le 1$ and the inlet body. The parameters x_0, y_0 and Δx determine the position and the width of the ionized region.

Fig.2 demonstrates, obtained in the paper [4], the density distribution in the MHD controlled inlet. The dash-dot line in the figure encloses the area of the MHD interaction in which the flow conductivity is ensured by the e-beam. One can see from Fig.2 that the streamline entering the region of the MHD interaction is deviated to the inlet body. The streamline deviation is accompanied by increase both the air capture and the flow compression in the MHD controlled inlet. Fig.3 shows the spatial orientation of the magnetic induction $\boldsymbol{B}$, the current density $\boldsymbol{j}$ in the MHD channel and the Lorentz force density $\boldsymbol{f}_L = \boldsymbol{j} \times \boldsymbol{B}$ which correspond to conditions of Fig.2. In the configuration under consideration, the component of the Lorentz force directed to the body $(f_y<0)$ has a significant magnitude. Hence it is reasonable to suppose that just the Lorentz force influence produces the streamline curving when it reaches into the region of the MHD interaction. And it is the Lorentz force that causes the air capture in the MHD controlled inlet to be increased at $M_\infty<M_d$.

Fig.4 shows dependencies of relative values for the air mass flow φ/φ_0 and the flow compression p/p_0 in the MHD controlled inlet in function of the angle α which determines the magnetic field orientation. Here φ is the air mass flow in the inlet; p is the static pressure at the inlet exit. The subindex 0 determines the corresponding parameters for the inlet without the MHD control. According to Fig.4 a maximum for the air capture and for the static pressure are achieved at different orientations of the magnetic field.

The results shown in the Figs 5,6 indicate that the Lorentz force has a dominant influence on the increasing of the air capture in the MHD controlled inlet. Fig.5 shows the components f_y and f_n of the Lorentz force acting on the streamline near the second wedge of the inlet depending on the magnetic field orientation. The Lorentz force component f_n which is normal to the surface of the second wedge is determined by the evident relation: $f_n=f_y\cos(\theta_N)-f_x\sin(\theta_N)$. Here θ_N is the total turning angle of a flow in the inlet. In the configuration considered it is the angle between the second wedge and the incoming flow. Components f_y and f_x for Faraday MHD generator are determined by the relations: $f_y=j_zB_x$; $f_x=-j_zB_y$. The results obtained show that the position of the maximum for the relative air mass flow in the MHD controlled inlet is practically coincides with the position of minimum for the Lorentz force components f_y and f_n. According to Fig.6 the coincidence is observed for various magnitudes of the power density spent on flow ionization. The magnitude of the angle α at which minimal value for the component f_y is achieved is shown by the dashed line and by the solid line for the component f_n. Thus the preliminary choice of the magnetic field configuration which allows us to significantly increase the air mass flow in the MHD controlled inlet at $M_\infty<M_d$ is possible in analyzing the spatial distribution of the Lorentz force acting on the flow.

In order to estimate the efficiency of the MHD control in the inlet we calculated the specific impulse for the scramjet with the MHD controlled inlet in assuming that all the power produced by the MHD generator, less the power spent on flow ionization, is transferred to the MHD accelerator located downstream of the combustion chamber. The calculations were made analogously to the paper [4]. The nozzle located downstream of the MHD accelerator is considered as a fully expanded nozzle. Fig.7 shows the relative specific impulse (the specific impulse for the scramjet with the MHD control divided by the scramjet specific impulse) and the relative thrust (the relative specific impulse multiplied by the relative air mass flow) for the propulsion depending on the α angle. The results obtained show that position of maximum for the specific impulse and for the thrust is practically coincides with the position of maximum for the air mass flow in the MHD controlled inlet.

Now we will analyze characteristics of the MHD controlled inlet depending on the power density q_i spent on the flow ionization and on the geometrical proportions of the ionized region in the modeling approximation with a constant magnitude of q_i in the ionized region. The results of calculations are shown in the Figs 8-11. Here the power $W_i = \int_{S_i} q_i dxdy$ put into the flow ionization (normalized on the unit of length in the transverse direction z) is fixed. While increasing the value of q_i the constant magnitude W_i is ensured by decreasing the width Δx for the region of MHD interaction. It follows from Fig.8 that at given value of W_i there is optimal magnitude of q_i (or Δx) at which the air mass flow in the MHD controlled inlet achieves a maximum. At the range of parameters variation corresponding to Fig.9 the increase of Δx (or decrease of q_i) leads to decreasing the total pressure recovery coefficient (a negative tendency for the inlet) and to increasing the static pressure (a positive tendency for the inlet). Most likely such behavior of the MHD controlled inlet characteristics justifies the dependency of the specific impulse for the propulsion shown in Fig.10. According to Fig.10 there is some intermediate value of q_i parameter at which specific impulse of the scramjet with MHD control achieves a maximum. The maximum for the thrust is achieved approximately at the same value of q_i. Fig.11 shows dependencies of the relative thrust for the scramjet with MHD control upon the width of the MHD interaction Δx at various values of W_i. One can see that Δx but not q_i is more significant parameter for choosing the optimal regime of MHD interaction in the scramjet. Really, according to Fig.11, the maximal thrust for the scramjet with the MHD control at three various magnitudes of W_i is achieved in using regions of the MHD interaction with practically coincident values of Δx. The results adduced in Fig.12 demonstrate that at the chosen configuration of the magnetic field and the geometry of the ionized region there is optimal value of the power density q_i at which the maximal thrust of the scramjet with the MHD control is achieved.

The obtained results show that there is optimal configuration for the MHD controlled inlet at $M_\infty < M_d$. The results can be used to formulate requirements for the magnetic field configuration, for the location and parameters of e-beam in the inlet. It gives us the opportunity to make a deliberate choice of configuration of the MHD controlled inlet with a non-homogeneous magnetic field.

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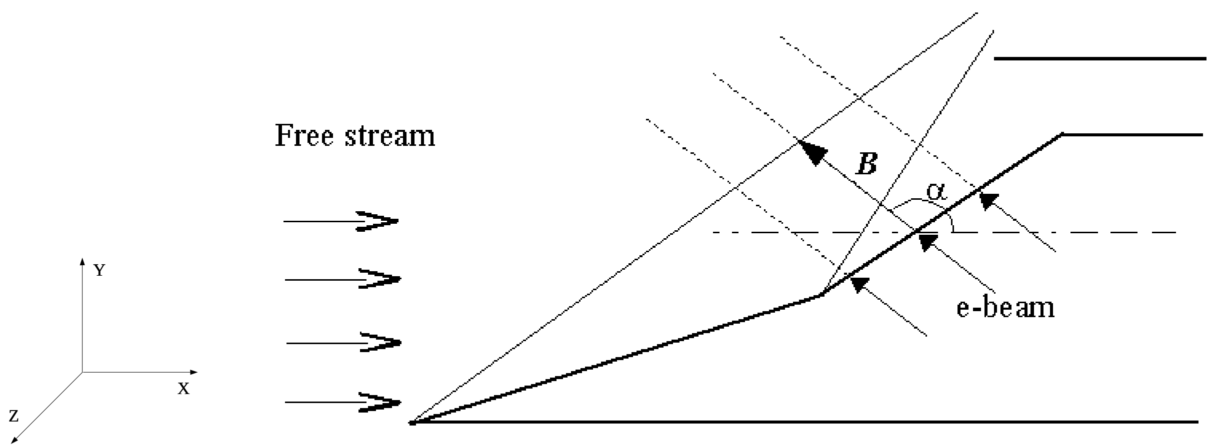


Fig.1. The sketch for the MHD controlled inlet with e-beam as a flow ionizer

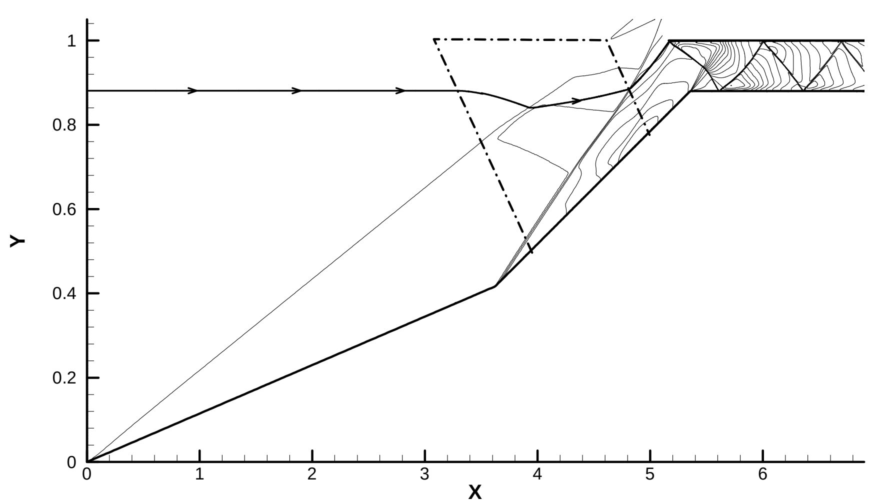


Fig.2. The density contour lines in the MHD controlled inlet. M_∞=8, M_d=10, B=5T, α=150°, k=0.3, q_i=1W/cm^3

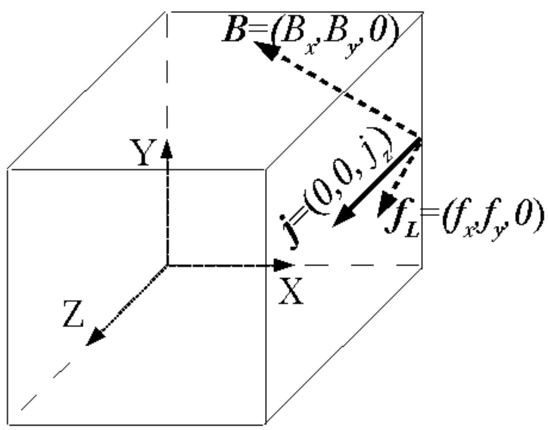


Fig.3. The spatial orientation of vectors ***j***, ***B*** and $\boldsymbol{f_L}$ corresponding to the conditions of Fig.2

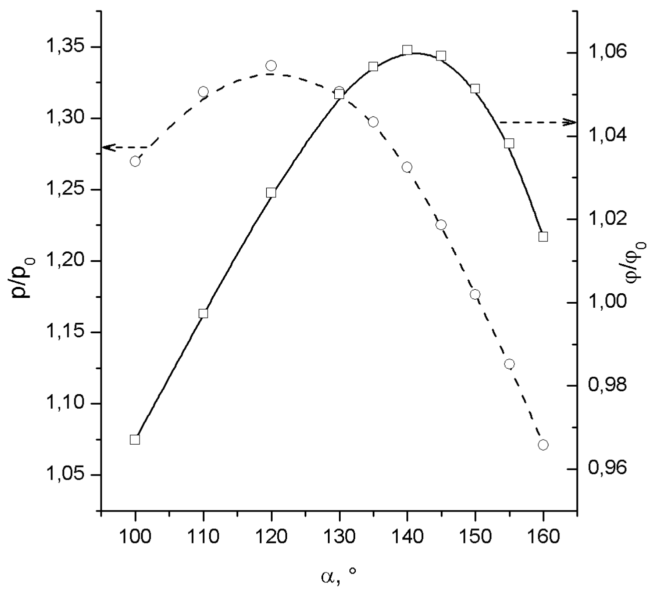


Fig.4. Relative characteristics of the MHD controlled inlet. M_∞=8, M_d=10, θ_N=15°, B=2T, k=0.3, q_i=1W/cm^3, Δx=0.76m.

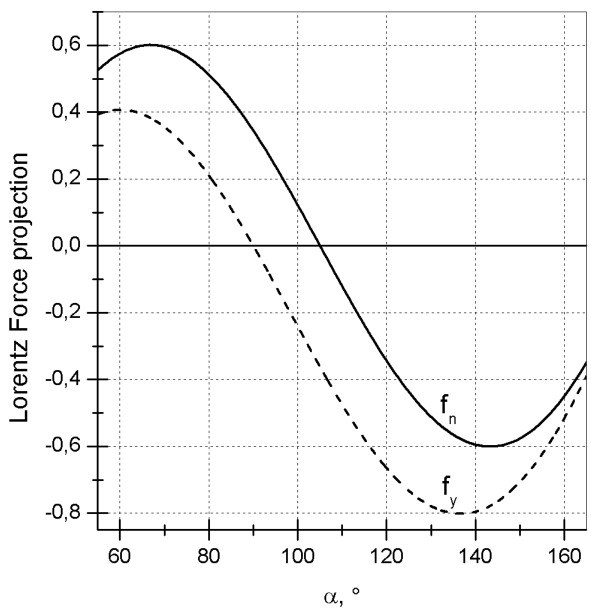


Fig.5. Relative projections f_y and f_n of the Lorentz force acting on a streamline in the region of the MHD interaction near the second wedge. θ_N=15°, k=0.3.

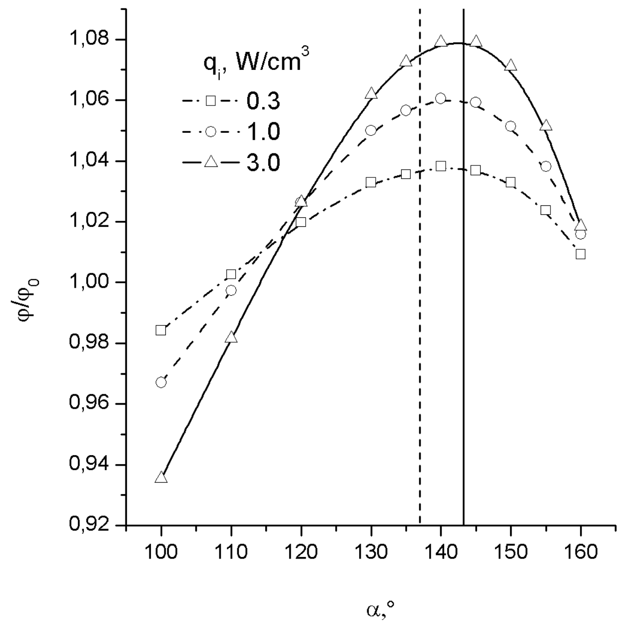


Fig.6. Relative air mass flow in the MHD controlled inlet at various values of the power density spent on flow ionization. M_∞=8, M_d=10, θ_N=15°, B=2T, k=0.3, Δx=0.76m.

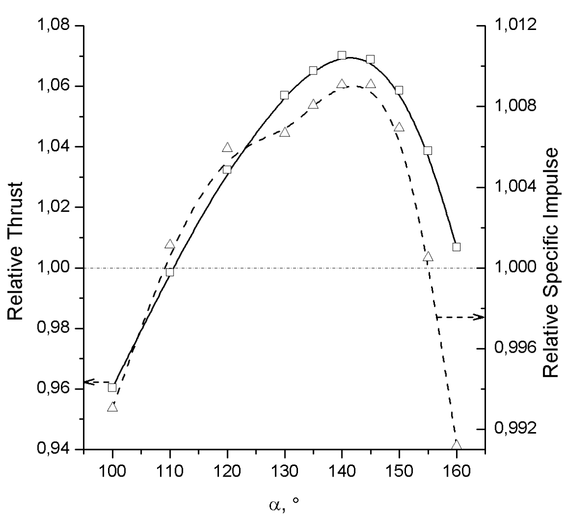


Fig.7. Relative characteristics of the scramjet with the MHD controlled inlet. M_∞=8, M_d=10, θ_N=15°, B=2T, k=0.3, Δx=0.76m, q_i=1W/cm^3.

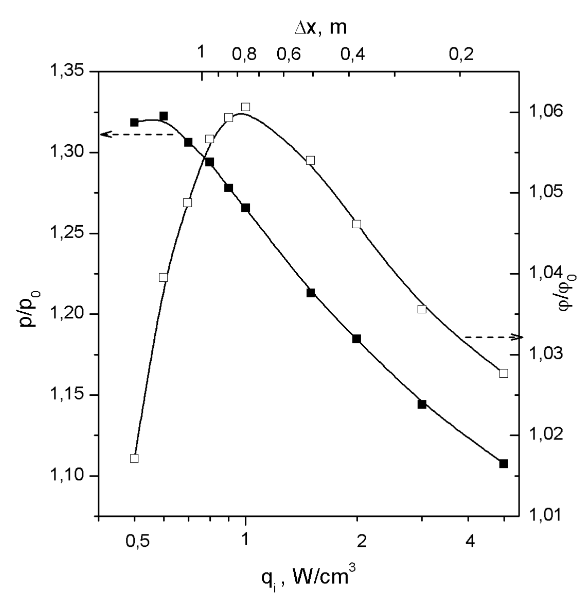


Fig.8. Relative characteristics of the MHD controlled inlet at given value of the power spent on ionization W_i=0.55 MW/m. M_∞=8,

M_d=10, θ_N=15°, B=2T, α=140°, k=0.3.

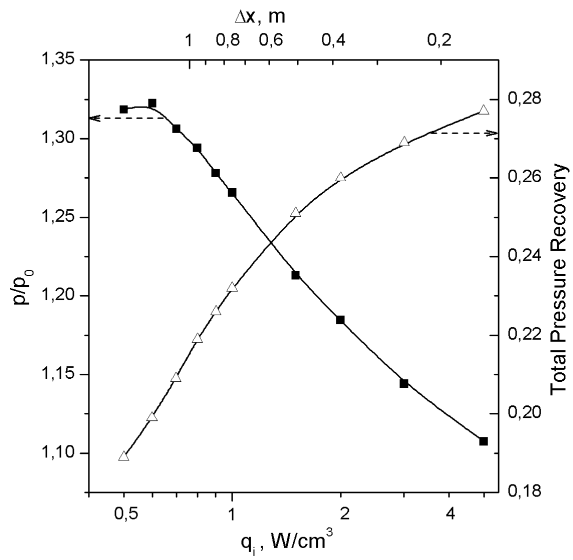


Fig.9. Relative characteristics of the MHD controlled inlet at given value of the power spent on ionization W_i=0.55 MW/m. M_∞=8, M_d=10, θ_N=15°, B=2T, α=140°, k=0.3.

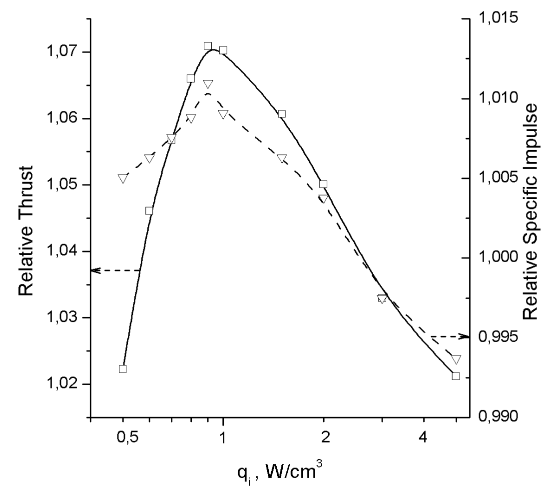
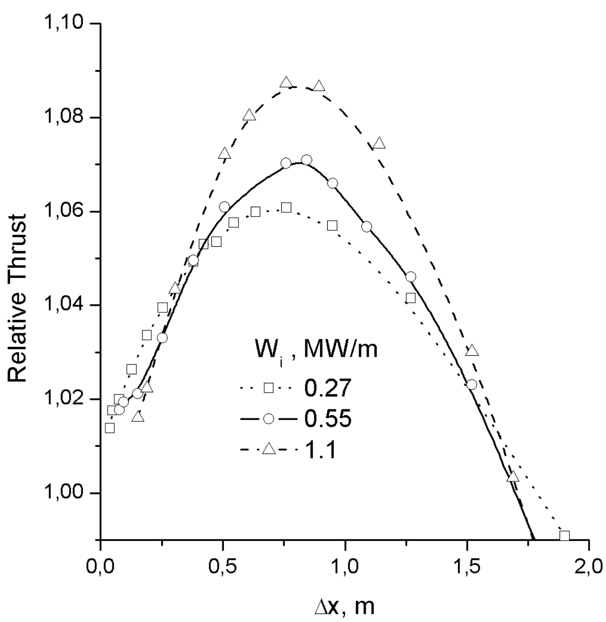


Fig.10. Relative characteristics of the scramjet with the MHD controlled inlet at given value of the power spent on ionization W_i=0.55 MW/m. M_∞=8, M_d=10, θ_N=15°, B=2T, α=140°, k=0.3.



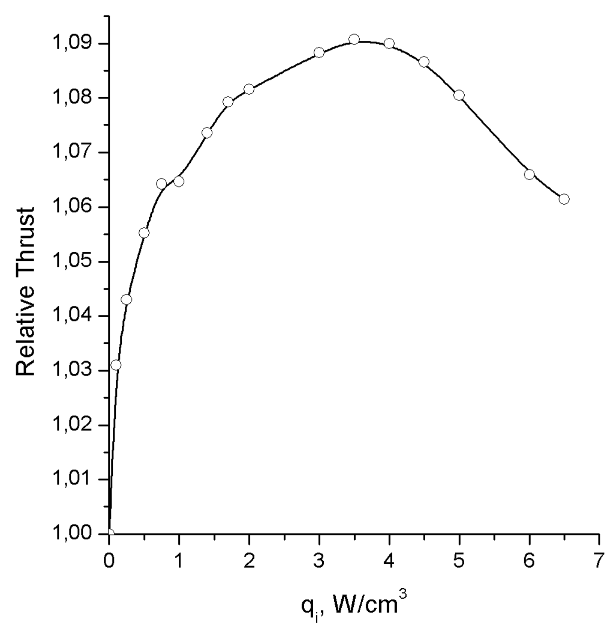


Fig.11. Relative thrust of the scramjet with the

Fig.12. Relative thrust of the scramjet with the

MHD controlled inlet at three various values of the power spent on ionization. M_∞=8, M_d=10, θ_N=15°, B=2T, α=140°, k=0.3.

MHD controlled inlet at given geometry of the ionized region. M_∞=8, M_d=10, θ_N=15°, B=2T, α=140°, Δx=0.76m, k=0.3.