Numerical simulations on MHD break in hypersonic flow

V.A. Bityurin\textsuperscript{1}, A.N. Bocharov\textsuperscript{1} and N.A. Popov\textsuperscript{2}
\textsuperscript{1}Joint Institute of High Temperatures, Russian Academy of Sciences
\textsuperscript{2}Moscow State University, Moscow, Russia

E-mail: bocharov.ya@yandex.ru

Abstract. One of possible effect of electromagnetic field on the high-speed ionized airflow is considered. Namely, deceleration of the flying body due to interaction of the electric current induced around the body with the magnetic field generated by on-board magnetic system is studied. The principal scheme of magnetohydrodynamic interaction over the flat plate is presented. The goal of the study is to demonstrate the deceleration effect in terms of standard aerodynamic drag. Two test cases are considered: small-scale (lab-scale) interaction zone size and large-scale (space-scale) one.

The primary result of the study is a feasibility to increase the total drag of the body in more than order of magnitude relative to the original one. The effect can be achieved by means of practically reasonable magnetic field amplitudes. Common for both cases is that the total drag grows as the magnetic field increases. The difference between two cases is that significantly smaller magnetic fields are required in space-scale case to increase aerodynamic drag than in the lab-scale case. In any case, the drag control could be used as a potential for high-speed flow control.

Introduction

This paper presents one of possible application of MHD interaction in high-speed air flow over the body called MHD parachute. Original MHD parachute \cite{1} was considered as a surface short-current MHD generator providing a maximal force of interaction. Numerical estimations of MHD parachute effect made under conditions of ground-based experimental facility have shown that aerodynamic drag can be increased in several times. Besides direct flow control by the MHD interaction, the MHD parachute provides a possibility of heat flux mitigation \cite{2} during re-entry due to deceleration of the vehicle in atmospheric layers where the heat loads are still rather low.

In the current paper, MHD parachute effect is considered for typical Earth re-entry flight conditions. In general, the physical and computational model is similar to that reported in papers \cite{3,4}. Real-air thermochemical model is used to numerically simulate a hypersonic flow over the flat plate of finite thickness. The influence of MHD interaction on the air flow is considered in terms of aerodynamic drag. Scaling effects are discussed. The lab-scale wing-like model means that the length of the plate along the flow is 0.32 m, and the thickness of the plate is 0.032 m. The space-scale model implies that both dimensions increase in ten times.
Results and discussion
The principal scheme for studying MHD interaction over the flat plate is shown in Fig.1. Magnetic field is assumed to be generated by two linear conductors with opposite currents. We shall characterize the magnetic field, $B^*$, by the maximum value at the plate surface (this is the same as those at the surface of one conductor). Also, the value of magnetic field at the center of magnetic system will be used. This mid-point value, $B_m$, is nearly 5 times less than the characteristic value $B^*$. Let’s consider a flow around the flat plate schematically shown in Fig.1. The following free-stream conditions are specified for both lab-scale and space-scale plate models:

\[ \rho_\infty = 2.34 \cdot 10^{-4} \text{ kg/m}^3, \quad U_\infty = 11137 \text{ m/s}, \quad T_\infty = 238.5 \text{ K}, \quad P_\infty = 16.1 \text{ Pa}, \quad M_\infty = 35.8. \]

The spatial scale, $L^*$, will be characterized by the distance between conductor centers. $L^*_{\text{lab}} = 0.32 \text{ m}$ for lab-scale case, and $L^*_{\text{space}} = 3.2 \text{ m}$ for space-scale case.

Figure 1. Sketch of on-board MHD generator (a) and layout of computational domain in xy plane (b). $E^* = E + U \times B$, $E$ is electric field strength.

A pattern of the flow structure can be seen in Fig.2 for lab-scale model and in Fig.3 for space-scale one. In the figures, the electric conductivity (filled contours) and ponderomotive force (vectors) are presented. Original field of conductivity is shown by contour lines for both cases.

Figure 2. Electric conductivity (filled contours) and force (vectors) at $B^* = 1.8 \text{T}$ for lab-scale model. Contour lines show conductivity at $B^* = 0$. 
From the viewpoint of flow control, the primary feature of MHD interaction is the increase in the aerodynamic drag. Quantitative characterization of the deceleration is presented in Fig. 4 by the relative total drag $D/D_0$ as function of characteristic magnetic field value. The total drag is treated as the sum of aerodynamic drag (pressure drag and viscous drag) and magnetic drag. The latter is the integral of the component of magnetic force along the flow direction over the domain. $D_0$ is the original drag at $B^* = 0$.

Possibility to increase the total aerodynamic drag in more than order of magnitude seems to be an important means for the flow control and/or a vehicle’s trajectory control. Note, that a deceleration of the body is due to the interaction of electric currents in plasma with the current generating magnetic field. This body force is exactly those induced in plasma bulk.

**Figure 3.** Electric conductivity (filled contours) and force (vectors) at $B^*=0.4T$ for space-scale model. Contour lines show conductivity at $B^*=0$.

**Figure 4.** Total relative drag: a) drag vs characteristic magnetic field $B^*$; b) drag vs MHD interaction factor $S_I$. 

The primary result of the study is a feasibility to increase the total drag of the body in more than order of magnitude relative to the original one. The effect can be achieved by means of practically reasonable magnetic field amplitudes. Common for both cases is that the total drag grows as the magnetic field increases. The difference between two cases is that significantly smaller magnetic fields are required in space-scale case to increase aerodynamic drag than in the lab-scale case. In any case, the drag control could be used as a potential for high-speed flow control.

The second difference can be seen from Fig.4a. Namely, there is a jump in relative drag for lab-scale model. This jump was observed for other magnetic systems with close spatial scale. At the same time, the jump in drag was not observed for space-scale models and magnetic systems. It should be noted that a transition from low-drag regime to high-drag one takes typically several milliseconds. So, one can say that for given lab-scale magnetic system there is a critical magnetic field which switches the low-drag flow structure to high-drag one. The jump relates with finite scale of magnetic system and with Hall effect. At small magnetic field, MHD interaction occurs mainly over the plate between conductors. As magnetic field increases, the flow decelerates. The base for MHD interaction diminishes, and zone of electric current flow moves away the magnet. So, real MHD interaction occurs at lower and lower magnetic fields as magnetic field increases (see Fig.2 and 3). For space-scale flow, Hall parameter is small enough because magnetic field magnitude is small enough. Transition from low-drag regime to high-drag one has a smooth behavior (Fig.4a, red line). For lab-scale flow, MHD interaction zone moves from high magnetic field zone (due to decelerated or even stalled flow) with, in general, high Hall effect to the lower magnetic field zone, where Hall effect is small. Transition from Hall effect dominated flow to those with small Hall effect is found to have a critical point. The demonstration lab-scale problem has been solved, in which the Hall effect was neglected. The drag curve is similar to that corresponding to the space-scale case.

Finally, Fig. 4b shows that both drag curves look similar if appropriate characteristic numbers are chosen to specify MHD interaction. As in [3], we take MHD interaction factor $S_1$ defined as $S_1 = \frac{\sigma_0 B_m L^*}{\rho U}$. Here, characteristic value of conductivity is chosen as $\sigma_1 = \frac{\sigma_0}{1 + \beta_0^2}$, $\beta_0$ is Hall parameter. $B_m$ is midpoint value of magnetic field defined above.

Conclusions
Possible aerospace application of the magnetohydrodynamic method for high-speed flow control known as the MHD parachute has been considered. The dramatic rise of aerodynamic drag has been demonstrated on the real-air flow corresponding to the Earth’s re-entry flight for two test models of different spatial size with the built-in magnetic system. It was shown that the drag can be increased by more than order of magnitude by inducing acceptable magnetic fields: ~2 T for the lab-scale model, and ~0.5 T for the space-scale model. Intensity of MHD deceleration can be characterized by the appropriate MHD interaction factor. This quantity seems suitable for both scales considered in the paper despite quite different behavior of the drag for lab-scale and space-scale models. Jump-like drag dependence for lab-scale case is a mutual influence of finite-rate chemistry, decelerated flow structure, and Hall effect in a spatially restricted magnetic field.

References
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