

Numerical and Feasibility Study of Onboard MHD

Power Extraction on Supersonic Vehicle

Song Chai, Gang Meng, Runhui Wu, Jiaqi Liu, Xin Liu and Ruiqi Sun

Beijing Institute of Space Long March Vehicle, National Key Laboratory of Science and Technology on Test Physics and Numerical Mathematics, Beijing 100076, China

ABSTRACT: Within this paper, a concept model containing main features of on-board magnetohydrodynamic (MHD) generators has been constructed and its feasibility of power extraction on supersonic vehicle for a typical flight condition has been studied numerically. The results revealed that the MHD generator is capable of providing substantial energy output up to tens of kilowatts per square meter or even several hundred kilowatts if the alkali-seeded boundary layer has been coated.

I INTRODUCTION

There are two key elements of onboard MHD power extraction, high speed and high density plasma. It found that ^{[1][2]} under typical reentry flight conditions (height 45.80 km, speed 6 km/s ~ 7 km/s) with 0.1-1% mass fractions of alkali metal seed elements within a suitable magnetic field (0.1 T ~ 0.2 T), hundreds of kW to MW levels energy can be extracted from the per unit area of the aircraft surface. In the meantime, the wall heat and frictional resistance can be reduced effectively as well ^[3]. The traditional MHD power extraction was mainly used to reduce wall heat and frictional resistance in the reentry flight of aircraft. While in recent years, with the development of high-speed, long-hanging and reusable hypersonic vehicles ^[4], its advantages in power supply are gradually revealed. In this paper, efforts has been put on feasibility studies of onboard

MHD power extraction for supersonic vehicles. A simplified concept model containing main features of on-board MHD generators has been proposed and problems have been solved numerically for the purpose of providing preliminary guidelines for the design of external MHD generators on board hypersonic vehicles.

II CONCEPTUAL DESIGN

Figure 1 is a conceptual design diagram of the MHD power extraction device on the surface of the aircraft. Four band-shaped surface electrodes are uniformly distributed on the surface of the cone, and the magnetic field ($B \sim 0.1$ T) perpendicular to the cone surface is provided by a permanent magnet located below the surface of the electrode^{[5][6]}. Four alkali metal seed injection holes are provided at the head of the craft to increase the gas ionization degree^{[7][8]}.

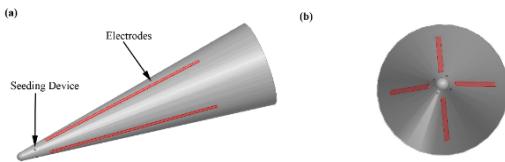


Figure 1 Conceptual design of onboard MHD power extraction device: (a) side view; (b) top view.

According to Faraday's law of electromagnetic induction, in the onboard MHD power extraction device, B is the magnetic intensity generated by the permanent magnet, and d is the distance between two electrodes. Plasma conductance is

$$\sigma = \frac{e^2 n_e}{m_e v_{eff}} \quad (1)$$

Then the power density P (unit is W/m^2) extracted per unit area can be expressed as

$$P = \frac{B^2 v^2 e^2 d n_e}{m_e v_{eff}} \quad (2)$$

Considering the collisions of free electrons in the atmosphere with each component ion (N, H, O, NO, N_2 and so on) and neutral atoms (including alkali metal atoms), the total effective frequency v_{eff} is the sum of the collision frequencies of the component. However, in the low-temperature weak ionization plasma, the electron density is much greater than the ion density, resulting in $v_{en} \gg v_{ei}$, so^[9]

$$v_{eff} \cong v_{en} = n_n \left(\frac{3kT_e}{m_e} \right)^{1/2} \sum_{i=1}^N M_i S_i \quad (3)$$

Where n_n is the number density of the neutral particle, M_i is the mass fraction of the air component, and S_i is the effective collision cross section of the component i ,

which can be obtained by looking up the table.

III SIMULATION AND ANALYSIS

Assume that a cone-shaped vehicle with a tail radius of 1.5 m and a half cone angle of 15 degrees can fly at a hypersonic speed of 5 km/s (Mach number ~ 15) in the atmosphere at a height of 50 km, and the surface electron density distribution can be obtained through simulation analysis of the ablation flow field around the aircraft, which is shown in Figure 2(a). The peak electron density is approximately $1 \times 10^{12} \text{ cm}^{-3}$, distributed near the vehicle head region, and decreases rapidly as the gas diffuses along the wall. We found that in the near wall surface, the electron density decreases and the atmosphere is thinner. Under the combined effect of the electron number density and the number density of the neutral particles, the effective plasma collision frequency (Figure 2b) gradually decreases outward from the wall and backward from the head. It can be known from the formula that the plasma conductivity is determined by the ratio of the density and the effective collision frequency as shown in Figure 2(c) without the auxiliary ionization of alkali metal: the plasma conductivity less than 10 S/m in the area where the surface electrodes are arranged, is much lower than the value, i.e. 100 S/m during reentry flight. Fig. 2(d) shows the contour plot of output power at per square meter, which is about 50 kW/m² in the head

region and reduced to $10 \text{ kW/m}^2 \sim 15 \text{ kW/m}^2$

at the tail.

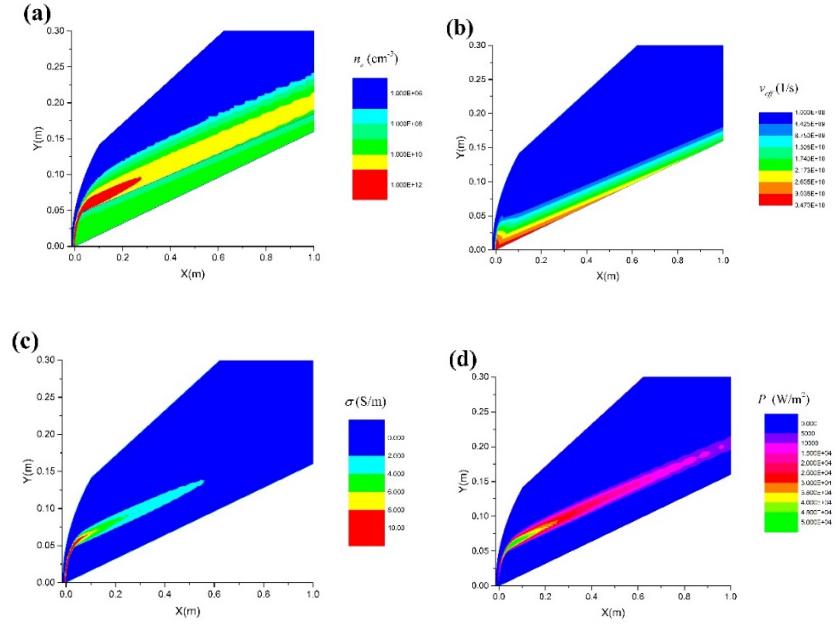


Fig. 2 Contour plots of (a) Electron density n_e , (b) Effective collision frequency v_{eff} , (c) plasma conductivity of the ablative flow field σ and onboard MHD extraction (d) power density P of a hypersonic vehicle without alkali metal ionization under the flight conditions: $v = 5 \text{ km/s}$ and $h = 50 \text{ km}$.

Fig. 3 shows the generated power densities at $X = 0.2 \text{ m}$ section (head) when the hypersonic vehicle is flying at 30 km , 50 km and 70 km altitude at a speed of 5 km/s in the absence of alkali metal-assisted ionization. The same point of these three curves is that the energy density peaks appear at about 2 cm from the wall surface. This requires that the designed magnetic field generator should maintain a high magnetic field strength at least 2 cm away from the wall surface. At a height of $h = 70 \text{ km}$, the power density is smaller because the air pressure and density gradually decrease as the flying height increases, resulting in a decrease in the electron density of the

thermally ionized electrons. At height $h = 30 \text{ km}$, the air density is too high, thus the number of neutral particles as well as the effective collision frequency of the plasma increases, as a result the electrical conductivity decreases, affecting the energy extraction efficiency.

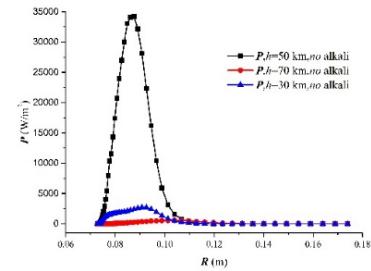


Fig. 3 Radial distributions of power density with alkali metal seeds at different flying heights (at cross section $X = 0.2$)

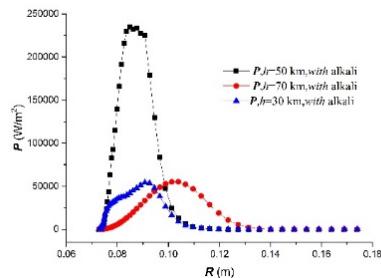


Fig. 4 Radial distributions of power density at different flying heights with ionization of alkali metal seeds (at cross section $X=0.2$)

Figure 4 shows the comparison of MHD power density at different flight levels with the addition of alkali metal seed assisted ionization. Obviously, after adding alkali metal as the seed element (auxiliary ionization means), the energy extraction power increases significantly up to 250 kW/m^2 , so it can be inferred that the electron number density generated by alkali metal ionization will be much higher than that caused by pure air component ionization.

IV CONCLUSION

In this paper, the conceptual design of the onboard MHD power extraction device is proposed and its feasibility is analyzed by establishing a numerical simulation model containing alkali metal seed elements. The main conclusions include: (1) The power of $30 \text{ kW} \sim 300 \text{ kW}$ can be obtained from the surface unit area of the hypersonic vehicle, which is generally considered as an effective way of energy generation; (2) At the flight altitude of about 50 km, the feasibility of MHD energy extraction is optimal; (3) Seeds Elemental assisted ionization will greatly

increase the efficiency of onboard power extraction and broaden its applications in various flight segments of hypersonic vehicles.

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