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MHD의 스크램제트 성능 개선과 전력 생산 잠재력

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Potential of MHD in Improving the Performance of and Generating Power in Scramjets

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ABSTRACT

Magnetohydrodynamics (MHD) devices have received considerable attention in recent years as a means to either improve the propulsive characteristics of hypersonic cruise missiles or as a means to generate power at low cost in drag and weight aboard scramjet powered vehicles. Based on more complete physical models than previously used, it is here argued that the use of MHD is not valuable in improving the performance of hypersonic propulsion systems through prevention of boundary layer separation or power bypass. This is due to the inevitable high amount of Joule heating accompanying MHD flow control having considerable undesired adverse effects on the engine performance. On the other hand, preliminary estimates indicate that MHD is likely to succeed in generating high amounts of power with little additional drag to feed megawatt-class energy weapons on-board scramjet engines.

초 록

스크램젯 비행체에서 극초음속 순항미사일의 추진 특성을 향상시키고 항력을 적게 발생하면서 전력을 생산하는 장치로써 MHD 장치가 최근 들어 큰 관심을 받아왔다. 이전에 보였던 것보다 보다 완전한 물리적 모델을 바탕으로 하면, 경계층 박리 억제나 파워 바이패스를 통해 극초음속 추진 시스템의 성능 향상을 하는 MHD의 쓰임새를 논의하는 것은 불필요한 일이 된다. MHD 유동 제어를 하게 되면 엔진 성능에 상당한 역효과를 미치는 불가피한 Joule 가열이 크게 발생한다. 하지만, 예비조사에 따르면 MHD는 약간의 항력만을 더 발생하면서 스크램젯 엔진을 장착한 무기에 메가와트 단위의 큰 전력을 생산해 낼 수 있을 것으로 여겨진다.

Key Words: MagnetoHydroDynamics(MHD), Supersonic Combustion ramjet(SCramjet), Joule Heating(Joule 가열)

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1. Introduction

Magnetohydrodynamics (MHD) has recently

been the focus of substantial interest as a means to improve the performance of hypervelocity flight vehicles. One possibility that MHD offers is the bypass of the flow kinetic energy from the inlet to the nozzle such as in project AJAX[1] or as in other derived concepts.[2] By bypassing some of the flow energy around the combustor, it is hoped that the flow speed can be reduced substantially while maintaining the temperature to a reasonable value. A decrease in the combustor flow speed can enhance significantly the amount of mixing and the amount of heat released which would translate into a higher thrust of the engine.

Other possible applications of MHD to hypersonic flight include the observed drag reduction over blunt bodies when an external magnetic field is applied to a conducting incoming flow, the suppression of boundary layer separation in the inlet and combustor of scramjets, or the control of the shock positioning in a scramjet inlet to achieve shock-on-lip condition over a relatively wide Mach number range while keeping the geometry fixed.[3]

There has also been a considerable interest in MHD as a means to generate electrical power aboard a hypervelocity flight vehicle similarly to power generation from rocket exhausts through a MHD generator.[5] Due to the very high kinetic energy of the flow, the latter can provide a low-weight and high-output power generator with little additional drag. Preliminary estimates show that a power of hundreds of thousands of megawatt per cubic meter could be produced in such a way.[5] The power could then be used for on-board flight navigation equipment or to feed a megawatt-class energy weapon.

Most of the preliminary studies performed so far have used simplified physical models which did not take into account losses originating from resistivity in the flow. This lead to overly optimistic conclusions for some applications of MHD to hypersonic flow. In this paper, we discuss the limitations of the previous studies and assess whether the previously proposed concepts are viable in light of a more accurate physical model.

2. Physical Model

A short overview of the equations governing the fluid and the electromagnetic fields is here given. The mass-conservation transport equations for the neutral molecules and the negative/positive ions is fixed to:

$$\frac{\partial}{\partial t}\rho c^k + \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\rho v_j c^k - \sum_{j=1}^{3}\frac{\partial}{\partial x_j}v^k\frac{\partial c^k}{\partial x_j} = \underbrace{W^k}_{plasma\,chemical\,source\,terms}$$

where W^k are the chemical source terms related to the plasma – that is, ion and electron creation and destruction as well as other chemical reactions taking place in air at high temperature. The momentum equation for the neutrals takes on the form:

$$\frac{\partial}{\partial t}\rho v_i + \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\rho v_j v_i - \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\mu\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\sum_{j=1}^{3}\frac{\partial v_k}{\partial x_k}\right) + \frac{\partial}{\partial x_i}P = \underbrace{(\vec{j}\times\vec{B})}_{\vee entz\ force}$$

Part of the Lorentz force term on the RHS is ~B the magnetic field vector and ~j the current vector.

A particularity of the relatively-low-temperature plasmas encountered in hypersonic propulsion systems is the non-equilibrium of the electron temperature and vibrational temperature with respect to the translational temperature of the neutrals. An example of the large degree of thermal non-equilibrium near an electrode can be seen in Fig. 1. This requires the solution of the nitrogen vibrational energy transport equations performed simulateneously to the total energy transport equation:

$$\frac{\partial}{\partial t}\rho e_V + \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\rho v_j e_V - \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\left(\kappa_{e_V}\frac{\partial T_V}{\partial x_j}\right) = \eta_V \underbrace{\frac{\vec{j}\cdot\vec{j}}{\sigma}}_{Electron\ Joule\ heating} + \frac{\rho}{\tau_{Vt}}\left(e_V^0 - e_V\right)$$

The "total" energy here refers to the energy of the neutrals and the ions excluding the energy of the electrons which is determined locally as a function of the effective electric field:

$$\frac{\partial}{\partial t}\rho E + \sum_{j=1}^{3}\frac{\partial}{\partial x_j}\left\{v_j(\rho E + P) - \kappa\frac{\partial T}{\partial x_j} - c^{N_2}\kappa_{e_V}\frac{\partial T_V}{\partial x_j} - \sum_{k=1}^{n_s} h^k v^k \frac{\partial c^k}{\partial x_j} - e_V v^{N_2}\frac{\partial c^{N_2}}{\partial x_j} - \sum_{i=1}^{3} v_i \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\sum_{k=1}^{3}\frac{\partial v_k}{\partial x_k}\right) - \mu_k \frac{\partial k}{\partial x_j}\right\} = \underbrace{\sum_{i=1}^{3}\left(\vec{j}\times\vec{B}\right)_i \cdot \vec{v_i}}_{electromagnetic\ work} + \underbrace{\frac{\vec{j}\cdot\vec{j}}{\sigma_e}}_{Joule\ heating} + q_b$$

The fraction of the Joule heating consumed in the excitation of the vibration levels of the nitrogen molecule, η_V, is obtained from the effective electric field in the electron frame of reference.

3. Energy-Bypass Around Combustor (project AJAX)

An alternative means to reduce the flow velocity while keeping the temperature to a reasonable level is through a MHD generator located in front of the combustor, such as first proposed by project AJAX[1-2].

The energy extracted from the flow is bypassed around the combustor and inserted back into the flow in the nozzle through a MHD-accelerator. In doing so, preliminary estimates based on an ideal-MHD model (excl. the effect of Joule heating) show that the flow speed can be reduced in the combustor while maintaining the temperature at the combustor entrance at an acceptable low value hence yielding better mixing and heat release.

4. Prevention of Boundary Layer Separation

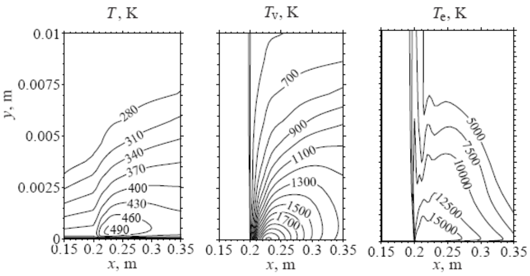

Fig. 1 The large degree of thermal non-equilibrium typical of cold plasmas can here be seen through the temperature, vibrational temperature, and electron temperature near an electrode as computated by Parent et al.[6]

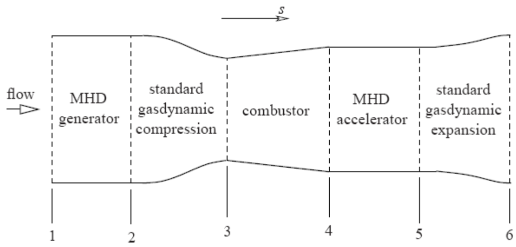

Fig. 2 Energy bypass scramjet (AJAX project).

MHD flow control has also been considered recently as a means to prevent boundary layer separation occurring in the scramjet inlet or combustor. In the scramjet inlet or combustor, the shock waves interact with the walls and create in the process high streamwise pressure gradients. Due to the boundary layer being of considerable thickness, these pressure gradients are generally sufficiently high to cause flow reversal which result in the separation of the boundary layer.

5. Generation of Power for Energy Weapons

Rather than being used to increase the scramjet performance through energy bypass or boundary layer control, a MHD generator can instead be used to power an energy weapon. Since the flow needs to be ionized for power generation to be possible, and since the temperature of the air in the combustor is not sufficiently high for self-ionization to occur, a seed (such as cesium or potassium) needs to be mixed with the combustion products or the latter need to be ionized through other means. Due to the very high kinetic energy of the flow (and hence total enthalpy) at hypervelocities, this would be sufficient to power a megawatt-class laser or microwave weapon installed on-board a scramjet.

6. Conclusions

The use of MHD is argued not to be valuable when trying to improve the performance of hypersonic propulsion systems through prevention of boundary layer separation or power bypass (AJAX). This is attributed to the low conductivity associated with cold-air plasmas inducing a high amount of Joule heating along with the MHD push force. In the case of the energy-bypass concept, the amount of energy waisted in Joule heating would offset the gains associated with power bypass. In the case of boundary layer control by an MHD accelerator, it is estimated that most of the power deposited would be in form of heat rather than push power, effectively encouraging boundary layer separation rather than suppressing it.

On the other hand, premilinary studies shed hope that MHD is likely to succeed in generating high amounts of power within scramjet engines. It is estimated that little additional drag would be imposed on the propulsion device to generate enough power to feed megawatt-class energy weapons.

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