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Scramjet Inlet Flow Control Using Combined Magnetohydrodynamics and Glow-Discharge-Plasma Effect

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Introduction

THE realization that conventional aerodynamic control surfaces might not possess sufficient potential to satisfy all of the performance requirements of future hypersonic vehicles has led the aerodynamics community to seek new, unconventional high-speed flow control approaches. The proposed approaches include those applicable to external aerodynamics as well as internal flows in scramjet engines. Broadly, the flow control methods aim to achieve improved 1) external flows leading to increased vehicle aerodynamic performance and 2) internal flows through engines, including scramjet inlets leading to better engine performance particularly under off-design conditions.

Two unconventional methods have recently been proposed to address the goals just listed, both of which employ charged particle action on the gas: glow discharge plasma (GDP)[1–3] and magnetohydrodynamics (MHD).[4–11] The concept of flow control by GDP has been applied primarily to external flows, whereas most of the MHD control research has been directed to the flows in scramjet and ramjet engines.

Glow discharge plasma can be a convenient tool for localized heat addition into the flow. It was proposed to use GDP as a method for heat addition upstream of a shock wave.[2] In other studies, a weakening of bow shocks was observed when heat was added using GDP that formed between the body and the bow shock.[3] The results of these studies demonstrated the potential of the plasma technology in high-speed aerodynamics. The exact nature of plasma-shock-wave interaction is not clearly understood. However, there is broad agreement that the observed phenomena are associated with plasma electrons acquiring energy from the external electric field and transferring it to the gas in interactions with the molecules.[12]

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Previous studies of the application of MHD to engine inlets have shown that the MHD action increases flow compression and mass flow rate.[4,8,9] However, the resulting improvements in flow parameters were incremental. It was also proposed to use MHD to decelerate the flow in front of the combustion chamber of the scramjet engine, with subsequent acceleration of the flow after the chamber.[13] Calculations for a Mach number of $M = 6$ showed that this scheme can increase the scramjet specific impulse. To the best of our knowledge, GDP has not been considered to date for the improvement of scramjet flows.

In this report, we investigate the possibility of enhancing the MHD control of scramjet inlets by simultaneously applying GDP. We present sample results of an analysis, which shows that MHD and GDP can be applied in a complementary fashion to further enhance the benefits that could be gained by applying MHD or GDP alone in the inlet duct. This is because the effectiveness of MHD and GDP vary with the local flow conditions. That is, the local benefit of each action varies from region to region in the inlet flow, and the optimum location for GDP application is, in general, different than that for MHD for a given set of local flow parameters.

MHD and GDP Effects on Flow

Both MHD and GDP flow control mechanisms rely on the relatively small number of charged particles, which are either formed within the gas flow or introduced into it. The ionization level in both cases usually does not exceed 10^{-5}. The actions on the neutrals are caused by the interaction of the charged particles with the external magnetic (in the case of MHD) or the electrical (in the case of GDP) field. The physical mechanisms of these interactions are different. This leads to the fact that the ranges of the flow parameters (velocity, density, local Mach number, etc.) where the GDP and MHD actions are optimal do not necessarily overlap. Therefore, these actions can be complementary rather than competing, and using both MHD and GDP actions in an appropriate sequence can lead to a more significant effect on the flow than that by a single action.

MHD Action

Figure 1 shows a Faraday MHD generator in a channel where the gas flows from left to right. We assume that the gas is made electrically conductive with conductivity of σ. The external magnetic field $\boldsymbol{B}$ is directed normal to the flow, along the z axis as shown. The electric charges (electrons and ions) moving with the flow with velocity u experience an equal but opposite force, which causes the charges to separate. Separation of the charges creates an electric field $\boldsymbol{E}$. When the electrodes on the opposite sides of the flow are not connected, this field is simply $\boldsymbol{E} = -[\boldsymbol{u} \times \boldsymbol{B}]$, which is along the y axis. When the electrodes are linked up through a load resistor R_L, as shown in the figure, the electric field has both x and y components, and the current is induced in the circuit determined by $\boldsymbol{j} + \mu[\boldsymbol{j} \times \boldsymbol{B}] = \sigma \cdot ([\boldsymbol{u} \times \boldsymbol{B}] + \boldsymbol{E})$, where μ is the permeability of the gas. For an ideally segmented Faraday MHD generator, the current has only a y component (as in Fig. 1). The magnitude of the current density is found from $j_y = -\sigma u B(1 - k)$, where $k = E_y/uB$ is the load factor determined by the load resistor R_L (such as $k = 0$ when $R_L = 0$). The magnetic field exerts a Lorentz force $\boldsymbol{F} = [\boldsymbol{j} \times \boldsymbol{B}]$, on the charged particles that acts in the direction opposite to the velocity vector. Thus the magnetic field tends to decelerate flow in the

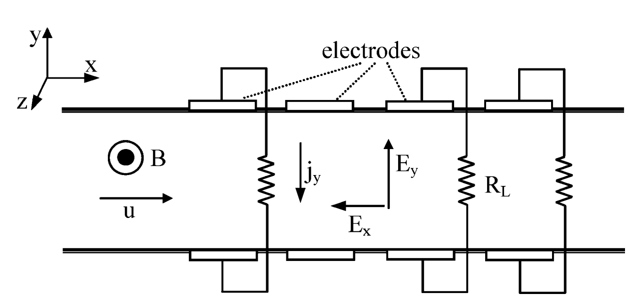

Fig. 1 Segmented electrode Faraday generator.

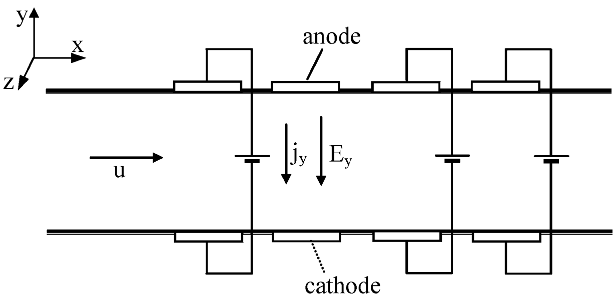

Fig. 2 Segmented electrode transverse glow discharge.

configuration shown in Fig. 1. The magnitude of this force is given by $F = -(1-k)\sigma u B^2$. Hence, the work done by the Lorentz force per unit time on the unit volume of gas is $\dot{w} = (\boldsymbol{F} \cdot \boldsymbol{u}) = -(1-k)\sigma u^2 B^2$. In addition to exerting a force on the flow, MHD action adds or removes energy from it at the rate $\dot{q} = (\boldsymbol{j} \cdot \boldsymbol{E}) = -k(1-k)\sigma u^2 B^2$. For an MHD generator because $k < 1$, energy is removed from the gas. In the case of MHD accelerator, the force will be along the flow direction with $k > 1$ resulting in energy deposition into the gas. In sum, the MHD action on the flow is dual: a force and an energy exchange. The magnitude of the force and the amount of added or removed energy are both proportional to square of the magnetic field. The ratio between the energy extracted from (or deposited into) the flow and the work done on (or by) the gas is the load factor k. The work and the energy added to the flow are both proportional to the square of velocity u. Therefore, the MHD action in the scramjet inlet becomes progressively less effective (and less efficient) as the flow is decelerated near the combustor.

GDP Action

In this case, the charged particles are formed because of the electrical breakdown of gas that is subjected to external electric field. The electrons acquire energy from the field and deposit it to the gas in collisions with neutral molecules. Figure 2 shows the electrode configuration for a transversely excited (TE) glow discharge formed in a channel. TE discharge is an appropriate choice for controlling the flow in the scramjet inlet because it can be achieved essentially in the same electrode arrangement as that of an MHD generator shown Fig. 1. The only difference is that the resistive load is replaced with an electric power source. Otherwise the GDP generator is technically much simpler than the MHD generator because it does not require an external source of ionization such as an electron gun, or doping of the gas with alkali metal, and, more importantly, it does not need external magnetic field.

The principal effect of glow discharge plasma is heat addition to the flow, and the rate of heat addition per unit volume of the gas can be approximated by $\dot{q} = jE$. The electric field established in the GDP is a function of the gas density only. In a self-sustained glow discharge, the parameter E/N (where N is the gas number density) is greater than in any discharge that requires an external source of ionization, such as in the MHD generator plasma. In addition, electric field in GDP adjusts automatically to changes in gas density so that E/N essentially remains constant. Hence, the heat addition into the gas increases with increasing gas density. Thus, the effect of GDP action is stronger further downstream in the scramjet inlet, near the combustor where the gas velocity is smaller and the density is larger. This is contrary to the situation with the MHD generator, as just discussed. Therefore, the ranges of flow parameters where the MHD and GDP effects are most efficient do not overlap.

Combined MHD and GDP Approach

In the proposed application to scramjet inlets, the MHD generator serves to reduce the flow velocity. This reduction in flow velocity is accompanied by certain reduction in the total enthalpy. By contrast, the GDP increases the total enthalpy, which results in a reduction of the local Mach number. The simplest and technologically feasible combination is a serial arrangement. The governing equations for the steady one-dimensional supersonic flow subjected to MHD action can be written in the form

$$\rho u A = \text{const}, \qquad p = \rho R T$$

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}p}{\mathrm{d}x} = (\boldsymbol{j} \times \boldsymbol{B})_x, \qquad \rho u \frac{\mathrm{d}[h + (u^2/2)]}{\mathrm{d}x} = \boldsymbol{j} \cdot \boldsymbol{E}$$

Here p is the static pressure, ρ is the density, T is the temperature, and h is the enthalpy of the gas while A is the duct cross-sectional area and R is the gas constant. The current density and the electric field are determined by the magnetic field and load factor, and the boundary conditions are defined at the upstream edge of the magnetic field region, $x = x_0$, as $P = P_0$; $u = u_0$; $\rho = \rho_0$.

In the GDP region, the continuity and state equations remain the same while the right-hand side of the momentum and energy conservation equations are modified as follows:

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}P}{\mathrm{d}x} = 0, \qquad \rho u \frac{\mathrm{d}[h + (u^2/2)]}{\mathrm{d}x} = j_p E_p = a j_p \rho = cb \frac{j_p}{u}$$

Here E_p and j_p are the electric field and current density in the GDP, $c = E_p/\rho$ is a constant for a given gas, and b is determined by the cross section of the channel. The boundary conditions are defined at the upstream edge of the GDP region, $x = x_1$, as $p = p_1$; $u = u_1$; $\rho = \rho_1$. These are the outflow parameters for the MHD region if MHD is first applied in the scramjet inlet.

The momentum and energy equations in the MHD and GDP actions delineate the effect of each action on the flow. There is essentially no body force in the GDP while it contributes to the total enthalpy by volumetric heat addition in the energy equation. This enthalpy addition is directly proportional to the density and inversely proportional to velocity of the gas. On the other hand, the right-hand sides of the momentum and energy equations for the MHD region are directly proportional to the square of velocity.

Sample Results

To assess the effectiveness of using MHD and GDP simultaneously in scramjet engine inlets, we carried out a study by numerically solving the one-dimensional model just presented. The hypersonic flow is subjected to MHD and/or GDP action in a duct with constant cross section. A set of representative calculations are presented in Figs. 3 and 4. Figure 3 compares the normalized deceleration length L, obtained by the MHD action alone with that obtained by the GDP action alone. The normalization factor for L is $\rho_0 c_p a_0 T_0 / \sigma u_0^2 B^2$ for MHD and $\rho_0 c_p a_0 T_0 / j_p E_p$ for GDP. Here, a is the speed of sound, and c_p is the specific heat at constant pressure. Subscript 0 refers to the beginning of the plasma zone. In both cases, the flow Mach number decreases from an initial value of $M_0 = 7$ to its final value of M. The volumetric energy input in the GDP zone is set equal to the work done by the Lorentz force per unit volume at the beginning of the MHD zone (i.e., $\dot{q} = \dot{w}_0$). The combined MHD + GDP action is shown in Fig. 4. Here the flow is first decelerated in the MHD region from the initial Mach number of $M_0 = 7$ to a certain intermediate number M_1 and then subjected to GDP action where

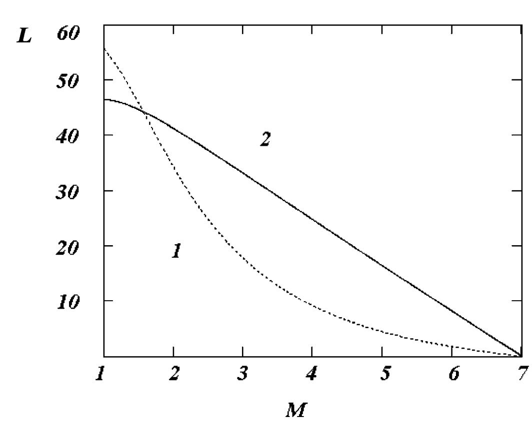

Fig. 3 Deceleration lengths vs the final Mach number: (1) MHD and (2) GDP (The initial Mach number is $M_0 = 7$.)

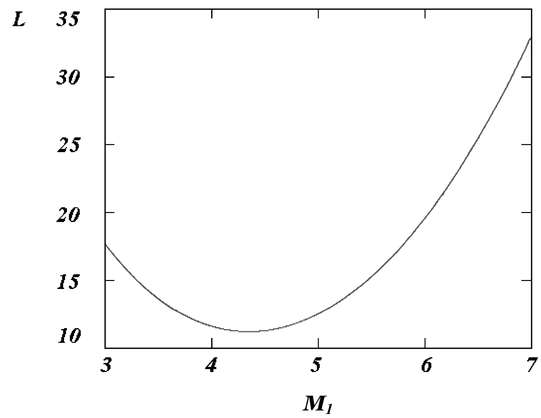

Fig. 4 Deceleration length vs transition Mach number in an MHD + GDP combination. (The initial and final Mach numbers are $M_0 = 7$ and $M = 3$.)

the Mach number is reduced from M_1 to its final value of $M = 3$. The combined value of the energy input by GDP and the Lorentz force work used for flow deceleration by MHD is kept constant and equal to that in Fig. 3. Length L is the total normalized length over which the MHD and GDP actions are applied. The L vs M_1 dependence features a minimum, and this minimum value is significantly smaller than the deceleration length of the single MHD or GDP action using the same total input power (see Fig. 3). The calculations we have carried out for a range of initial Mach numbers showed that, for a given inlet length, the Mach number can be reduced by the combined action to a value which is up to three times smaller than that for the single action of GDP or MHD, with the same input energy. A reduction in the Mach number can lead to a decrease in the total pressure loss and increased specific impulse.[6] Therefore, the presented study demonstrates that the simultaneous application of GDP together with MHD can enhance scramjet performance.

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Studies on Advanced CL-20-Based Composite Modified Double-Base Propellants

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I. Introduction

PROPELLANTS and explosives are the obligatory energy delivering systems of weapons. The development of propellants and explosives technology is focused on the enhancement of the lethality of weapon systems and improvement of the range of missiles. Research in this direction brought into focus the concept of high-energy dense materials (HEDMs). Hexanitro hexaazaisowurtzitane (HNIW or CL-20),[1] the most powerful HEDM of today, has emerged as a viable high velocity of detonation alternative to cyclo trimethylene trinitramine (RDX) and cyclo tetramethylene tetranitramine (HMX). The HEDMs such as CL-20 have also evoked interest as a powerful replacement for ammonium perchlorate (AP) for realizing the eco-friendly high-performance, I_{sp}, propellants for futuristic missiles and space missions. Potential applications of CL-20 include boost propulsion of strategic missiles or space launchers as well as high-lethality warheads for SMART and light weapons.[2]

Golfier et al.[3] reported that CL-20 propellants offer 7% superior I_{sp} (251 s) compared to corresponding RDX-based formulations. Weiser et al.[4] found that the CL-20/glycidylazide polymer-(GAP) propellants exhibit burning rates twice those of HMX/GAP propellants. Attempts have been made to ballistically modify CL-20 formulations, but specific information about the modifiers is not available.[3]

The present study was undertaken to evaluate CL-20 as the HEDM component of composite modified double base (CMDB) propellant. Because the technology of CL-20-based systems is in a transitional state, the data generated during this study are envisaged to provide inputs for weapon designers. Slurry cast CL-20 incorporated CMDB propellant containing 17.5% aluminium (Al) was selected in view of the optimum I_{sp} level of ~ 265 s obtained by theoretical calculation using NASA CEC71 program (Table 1). The effect of ballistic modifiers on the burning rates of CL-20 propellants was assessed. Copper chromite (CC) found effective during earlier work[5] in RDX-based compositions, which like CL-20 belongs to the nitramine class, was selected in this work. The effect of Fe_2O_3 was also assessed. Bis-dinitropropylformal/acetal (BDNPF/A) and low molecular weight GAP were evaluated as coplasticizers with NG as a substitute for the inert phthalate plasticizer with the aim of augmenting the ballistics. The NG-free trimethylolethanetrinitrate-triethyleneglycoldinitrate (TMETN-TEGDN) plasticized propellant was also investigated to achieve low vulnerability. The thermal studies were undertaken to gain insight into the chemical processes occurring in the condensed-phase during combustion.

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