Plasma-Enhanced Hypersonic Performance Enabled by MHD Power Extraction

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This paper reviews work underway on the development of new technologies that will enhance the performance of hypersonic vehicles through plasma-related processes and the utilization of MHD to provide the large power levels that are required to drive these processes. Three technologies are discussed for plasma-enhanced hypersonic performance. These include: (1) the use of off-body plasmas for drag reduction, steering, and enhanced inlet performance; (2) the use of surface or near-surface plasmas for mitigating local heating and controlling separation; and (3) the use of electron beam and plasma processes for controlling combustion for enhanced performance inside the engine and for local heat addition applications in other regions of the flow path. For realistic scale vehicles, the energies required for these applications exceed the present capability of on-board auxiliary power units, and, therefore, will require power to be generated directly from the hypersonic air passing over the vehicle or through the engine. In the high Mach number regime characteristic of re-entry vehicles, there is sufficient heating of the air to allow MHD power extraction using equilibrium ionization of alkali vapor seed material. By replacing a portion of the vehicle surface with a hollow core truss structure containing an embedded magnet coil, hundreds of kilowatts of power can be extracted during re-entry and used for vehicle control or other applications. At lower Mach numbers, MHD power extraction can be done downstream of the engine, then the temperature of the exhaust can be high enough to allow conductivity to be achieved with alkali seeding. This MHD generated power extracted from the flow aft of the engine can be used for plasma control upstream of the engine as well as for engine performance enhancement. Some aspects of this reverse energy bypass concept are analyzed in the paper, including plasma heating of the inlet flow that would allow elimination of the isolator, snowplow surface arcs for boundary layer and separation control, and electron beam and microwaves for initiation and control of combustion.

I. Introduction

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The use of plasmas for vehicle performance enhancement and control will require significant power, more than can practically be stored on board the vehicle. For subsonic or low supersonic aircraft, power can be extracted from the engine flow path through the use of a turbine, but at hypersonic speeds this is not an option. MHD technologies may provide a solution to this problem. MHD has the capability of directly extracting electrical power from a moving fluid, which, in this case, is either the air surrounding the vehicle, the air passing through the engine duct, or the air and combustion products at the exhaust of the engine. In all cases the fluid must be sufficiently ionized for the large currents that must flow for the MHD process to be practical.

Sustaining the ionization is probably the most difficult challenge for the use of MHD processes in hypersonic vehicles. There is no flight regime where the air alone has sufficient conductivity to permit the extraction of large amounts of power. The bow shock of a re-entry vehicle achieves sufficient conductivity, but does not extend far enough along the vehicle to allow for the extraction of large power levels. If the temperature of the air is above approximately 2500 K, then adequate conductivity can be achieved by seeding the air with an alkali metal vapor, such as potassium, which has a low ionization potential. At temperatures below that level, the ionization must be sustained by external processes such as through electron beam injection or high voltage pulses. The high temperature regime occurs in the air surrounding re-entry vehicles, in the inlet of vehicles flying at speeds greater than ~Mach 12, and in the exhaust of the engine, whereas the low temperature regime occurs in the inlet below ~Mach 12 and in the air surrounding hypersonic vehicles at speeds below approximately Mach 15. In this paper we will examine two concepts for the extraction of power by MHD processes, both taking advantage of the high temperature of the air and conductivity enhancement by seeding with potassium vapor. In previous work we have examined the use of electron beams and high voltage pulses for creation of nonequilibrium ionization in cold air. Those approaches are useful when the high temperature alternative is not available, but they add heat to the flow, creating added entropy production and pressure loss. If thermal ionization is possible, it is preferable.

Once significant power has been generated, it can be used to improve the performance of the vehicle. Here four performance enhancement options are discussed: the reduction of drag and creation of lift for improved vehicle flight performance. Among them is the use of the power to reduce the drag and enhance the lift for improved vehicle flight performance by creating a plasma in the air in front of the vehicle. The flow configuration that was used to explore this option is

II. Drag Reduction and Lift Enhancement on Re-Entry Vehicles

Under support from DARPA, we have explored the use of MHD for power extraction from the high temperature air flow surrounding a re-entry vehicle, and the use of that power for drag reduction and lift enhancement. This program is a team effort. The modeling that has led to the flow results presented here was done together with Prof. Graham Candler at the University of Minnesota and is based on his thermochemical-nonequilibrium (11 species, two-temperature air model) hypersonic CFD code augmented with ionization and MHD equations (including Hall and ion slip effects) as described in Ref. 11. The development of the structure has been undertaken with Prof. Anthony Evans at the University of California, Santa Barbara and Prof. Haydn Wadley at the University of Virginia. The structure work is presented in Ref. 12. The two-dimensional modeling was done for a 12° half-angle wedge with nose bluntness radius of 10 cm, however the flight configuration for the vehicle is expected to be conical, as shown in Fig. 1. The results for the flight altitude and speed regime modeled are summarized in Fig. 2: the predicted power extraction per square meter of MHD panel from a 3-5 cm thick boundary layer at altitudes of 45-60 km and flight velocities of 6-7 km/s with a 0.2 Tesla magnetic field ranges from a few hundred kilowatts to well over a megawatt. For this performance, 1% seeding with an alkali metal vapor is required. Without seeding the power extracted falls by a factor of five or more, as shown in Fig. 3, where the power extraction versus seed fraction is shown for the nominal operational point of 7 km/s and 46 km altitude.

Once there is substantial power available on the vehicle, many new design and functional options are possible. Figure 1. Diagram of a re-entry vehicle with the MHD power extraction section between “fin” electrodes. Alkali seeding is accomplished upstream of the MHD section.¹¹
shown in Fig. 4. The configuration shows the static temperature field surrounding the two-dimensional wedge model with 800 kW of power extracted from the boundary layer by MHD and introduced into the flow two nose radii ahead of the vehicle. The manner by which this is accomplished is not addressed, but would most likely be through microwave-driven electrical breakdown of the air. Figure 5 shows the surface pressure along the top (leeward) and bottom (windward) surfaces with no MHD, with MHD alone, and with MHD and energy addition ahead of the vehicle. Note that there is a net reduction of surface pressure on both the leeward and windward sides. The location of the energy addition strongly affects this surface pressure profile, and that has not yet been optimized. Nevertheless, there is a 15% reduction in the drag and increase in lift-to-drag ratio. The total drag power for this configuration is 220 MW, so a 15% reduction corresponds to 32 MW reduction in drag power, or 41.5 times the actual power spent (800 kW). Thus, putting 800 kW in front of the vehicle is equivalent to adding 32 MW in thrust, a very efficient alternative if it can be accomplished. Moving the location of the plasma can further enhance the lift and provide a mechanism for rapid steering. What is, perhaps, more interesting is that the added heat increases the performance of the MHD power extraction by a factor of two because the air is more highly conducting.

Figure 2. MHD generated power per 1 m² of surface at various altitudes and flight velocities. The body is a 24° blunted wedge. The magnetic field at the surface is 0.2 T. Note that the simulations assumed a constant seed mass flow rate, thus, although the seed fraction in the 3-centimeter thick boundary layer is 1% at h=46 km, it is higher at higher altitudes.
Figure 3. MHD generated power per $1 \text{ m}^2$ of surface of the $24^\circ$ blunted wedge as a function of seed fraction in the 3-centimeter thick boundary layer. The flight velocity is 7 km/s, the altitude is 46 km, and the magnetic field at the surface is 0.2 T.

Figure 4. Static temperature contours for the case of flight at 46 km, 7 km/s, $B_0=0.2$ T, 1% seed fraction, with MHD on and no heat addition (left plot) and with MHD on and heat addition of the entire extracted power 20 cm (2 nose radii) upstream of the nose (right plot).
III. Reverse Energy Bypass Hypersonic Air Breather

Figure 6 shows the reverse energy bypass concept for a hypersonic air breather. The scramjet has no turbine with which to extract power and no compressor with which to control the inlet pressure. Those functions can only be performed in ways that do not bring the flow to stagnation, since the total temperature of the flow passing through the combustor is too high and the pressure losses associated with the entropy rise through shocks would be too great. While it has been proposed to use an MHD device in the inlet to optimize the performance of the engine, the lack of conductivity of the air makes that approach very costly. In flight regimes below approximately Mach 12, the temperature of the air in the inlet is so low that, even with alkali seeding, the conductivity is too low for power extraction or control. In order to overcome this low conductivity, external ionization is required either through the use of electron beams or through very high voltage short pulses. In either case, there is significant heating of the flow, leading to an increase in the flow entropy and pressure loss. In addition, the MHD process itself adds heat due to internal resistance to the current. Both of these processes occur at low temperature, further increasing the entropy and the pressure loss. On the other hand, if the power extraction is done downstream of the engine, then the temperature of the exhaust can be high enough to allow conductivity to be achieved with alkali seeding. The flow can be relatively easily seeded by adding an alkali to the fuel. That eliminates the heat associated with the external ionization. Furthermore, the heat arising from the internal resistance of the flow is deposited at high temperature, reducing the associated entropy and thus minimizing the stagnation pressure loss. The power extraction aft of the engine is, for the overall engine cycle, similar to that in the conventional turbine engine and provides a method for producing megawatts of power that can then be used for inlet flow control and combustion enhancement as well as for other applications. Figure 6 shows the applications we have examined and reported in various papers. Here we will address only those processes shown in the shaded callouts. These include the power extraction by MHD in the engine exhaust, and the use of that power for eliminating the isolator by volumetric energy addition inside the inlet, suppressing boundary layer separation by localized snowplow surface arcs, and for the enhancement of the performance of the scramjet engine by the deposition of energy into the flame zone by microwaves.
Directed energy steering and possible drag reduction

Magnetically-driven, high repetition rate, snowplow arcs for suppression of separation

E-beam sustained MHD shock angle control

Plasma generated virtual cowl lip

MHD power extraction

Microwave-enhanced flame propagation

Plasma energy addition for elimination of isolator for transient RAM mode operation

Figure 6. The reverse energy bypass concept for a hypersonic airbreathing vehicle.

A. Power extraction

Figure 7 shows the predicted profiles of flow parameters and the extracted power at the engine exhaust using a two-dimensional model of the flow, assuming a 1 meter long, 0.3 meter wide MHD duct. The model had the following attributes:

- 1D Euler equations plus Faraday/Hall MHD generation and body force.
- Hall and ion slip effects included.
- Chemically equilibrium flow computed with ASTRA thermodynamic program.
- Saha equilibrium ionization of potassium seed.
- Electron-molecule and electron-ion collision cross sections taken from literature.
- Calculations for hydrogen fuel, using typical scramjet exit conditions.

These calculations were carried out for both constant-area and expanding-area ducts. The specifications for the flow were based on typical scramjet engine exit conditions for an air breather flying at 95,000 ft, Mach 10 with an air/fuel equivalence ratio of 1 and a dynamic pressure of 2003.4 psf. The pressure at the exit was 21.6 psia, the temperature was 4907 K, the flow velocity was 2675 m/s corresponding to a Mach number of 2.56, the molecular...
weight of the gas mixture (nitrogen plus combustion products) was 23.85, and the specific heat ratio (gamma) was 1.15, indicating that the vibrational modes are activated. For the ideal Faraday MHD section, the magnetic field was assumed to be 1 Tesla, there was a 1% seed fraction of potassium vapor, and the load factor was 0.5. In the figure, results for a constant area (dotted line) and an expanding area (solid line) duct are presented. In the expanding area case, the duct width increases by a factor of 50% over the one meter path. Note that the MHD performance in the expanding area duct is better because the heating associated with the MHD process causes an increase in temperature and pressure in the constant area duct, leading to a much greater reduction in the flow velocity. The power extracted from the constant area duct is 18.7 MW per spanwise meter, whereas the power extracted from the expanding area duct is 22 MW/m.

Figure 7. Predicted profiles of flow parameters and the extracted power at the engine exhaust using a two-dimensional model of the flow, assuming a 1 meter long, 0.3 meter wide MHD duct with potassium seed and B=1 Tesla.  

\text{Faraday Generator with segmented electrodes}
B. Elimination of the Isolator

For ram/scram accelerator vehicles, an isolator diffuser is required to decelerate the flow before it enters the ramjet engine. The isolator must be long enough to allow weak oblique shocks to decelerate the flow so that the entropy increase (pressure loss) is not too great and there is no flow separation. Separation of the flow may lead to engine stall and catastrophic failure. In the scramjet regime, however, the isolator is no longer needed because the flow is not being decelerated to subsonic speeds. Nevertheless, since the isolator section constitutes a major portion of the flow path, it remains with the vehicle, adding weight, and, particularly, adding a significant cooling load. Since the surfaces of the isolator are all internal, there is no radiative cooling, so all surfaces must be actively cooled. If a method could be devised to eliminate the isolator during the ramjet stage of acceleration, then the scramjet portion of the vehicle flight path could be made significantly more efficient. This means that, even at the cost of some additional power drain at low Mach numbers, the overall payoff for the vehicle mission could be significant.

With this in mind, we have undertaken a joint effort with Dr. David Van Wie of Johns Hopkins University Applied Physics Laboratory to explore the possibility of reducing the Mach number of the flow entering the RAM engine by heating volumetric heating in the inlet. This heating must be done in the region downstream of the cowl lip so that there is no loss in mass flow. For these calculations the inlet was designed for shock-on-lip condition at Mach 7 with a dynamic pressure, q, of 1000 psf (about 0.5 atm), and the inlet flow field under the design condition is shown in Fig. 8. As an example, the off-design condition of Mach 5, q=1000 psf, is assumed. Under this condition there is significant spillage, as shown in Fig. 9, because the bow shock now misses the lower engine cowl and the stream-thrust-averaged Mach number at the throat is 1.85. Several cases were examined, each with energy added inside the inlet and apportioned in the core of the flow, as well as along the ramp and along the cowl to keep the pressure relatively uniform.

Figure 8. Contour lines of static temperature and Mach number, and flow streamlines in the Mach 7, q=1000 psf design case.
Figure 10 shows the density, temperature, and flow streamlines for the highest power examined (20 MW per meter in the spanwise direction) energy addition case. Here the average Mach number at the throat reduces to 1.15, which is compatible with the entrance to the ramjet combustor where the Mach number will be further reduced to subsonic by the heat released by the combustion. The cost of the energy addition in the inlet is only 8.5% of the enthalpy flux through the throat. Calculations\(^2\) showed that sufficient power levels can be extracted under these conditions from the flow downstream of the engine by MHD. Specifically, assuming that only 52% of the MHD-generated power can be transmitted and deposited into the flow, a 1-meter long MHD generator operating at B=3.3 Tesla and load factor k=0.9 with 1% potassium seed would be sufficient for the needed 20 MW/m heating. However, the penalty in thrust will be significant: the power extraction and Joule heating in the MHD duct reduce thrust by 11%, and the inlet flow heating results in further 5% thrust reduction, for a total of 16% thrust loss. Since this is an application of power that occurs only for a rather short time interval, that penalty might be sustainable in order to offset the weight and cooling load cost of the isolator. A more encouraging approach is to inject fuel into the inlet region and use the electrical power to control the location of the burning. That could be accomplished by using an electron beam to control the droplet vaporization and microwaves to initiate the combustion, as shown in Fig. 11. In this case, the energy would come mostly from the fuel, so that the only electrical demand is on the control and ignition devices.

C. Snowplow Arc for Acceleration of Boundary Layer

Separation of the boundary layer in supersonic flows leads to loss of lift, high surface heating, unstable loading, and engine stall. If a method can be developed to suppress or actively control the separation of the boundary layer, both vehicle performance and vehicle safety can be significantly improved. The snowplow arc may be able to accomplish this task. The arc is formed between two slightly divergent linear electrodes that are plated onto the surface such that the gap at the upstream end is closer than downstream. When a voltage is applied across the electrodes, an arc forms along the surface between the electrodes. This arc is localized in the high temperature boundary layer because the density there is lower than in the core region of the flow, so the breakdown potential is minimal. Once the arc is formed, it causes further heating and remains localized in that high temperature zone. Since the high temperature zone is locally associated with the bulk gas, it moves at the local flow velocity. When it passes beyond the electrodes, a new arc is formed at the upstream point and it moves again with the flow. Thus, when seen from the side, the region looks like a uniform glow discharge, but when observed with a fast exposure camera, the localized arc is evident. Figure 12 shows a 30-milliampere surface arc in a Mach 3 flow imaged with the camera shutter opened for 1, 10, and 50 microsecond exposures. The core flow velocity is 600 m/s. The speed of the arc found from this set of images is 425 m/s, indicating that it is located at a \(y/b\) of \(\sim\)0.1. Figure 13 shows the location of this arc as seen from downstream where it is also evident that the arc is localized near the surface. When a magnetic field is applied, the arc is accelerated by \(j \times \mathbf{B}\) forces. Figure 14 shows the 30 milliamp arc at 1, 10 and 20 microsecond exposures accelerated by a 1.5 Tesla magnetic field. The arc is moving a 1900 m/s, 4.5 times the local flow velocity. The higher speed arc also increases the arc repetition rate because the arc leaves the region between the electrodes more quickly. Note that the magnetic field induces a rotation of the arc, which can be related to the Hall effect. That leads to stretching of the arc and an increase in the voltage required to drive a 30-milliampere current through it. The question is whether the arc carries the bulk flow with it and accelerates the boundary layer.
Figure 10. Power deposition density, contour lines of static temperature and Mach number, and flow streamlines in Mach 5, 1000 psf off-design case. Total heating rate is 20 MW/m (8.5% of the enthalpy flux through the throat), consisting of 13 MW/m between the cowl and the compression ramp, 5.25 MW/m at the cowl, and 1.75 MW/m at the ramp.
Figure 11. Schematic of electron beam-induced fuel atomization and microwave-induced ignition for controlled energy addition.

Figure 12. 30-milliampere surface arc in a Mach 3 (600m/s) flow moving from right to left. The arc is imaged with the camera shutter opened for 1 (upper), 10 (middle), and 50 (lower) microsecond exposures. Measurement of the arc displacement over these times gives a speed of 425 m/s indicating that the arc is located near the wall at approximately 10% of the boundary layer thickness.
Figure 13. Surface arc as seen from downstream looking back up toward the Mach 3 slot nozzle during wind tunnel operation. The arc is located on the right at the wall of the tunnel.

Figure 14. 30-milliampere surface arc in the Mach 3 flow at 1 (upper), 10 (middle) and 20 (lower) microsecond exposures accelerated by a 1.5 Tesla magnetic field. Flow is from right to left. Measurement of the arc displacement over these times gives a speed of 1900 m/s, 4.5 times the local flow velocity.
Figure 15 shows preliminary measurements of the variation in surface Mach number with magnetic field. In each case the Mach number was determined using a 0.040” glass pitot probe against the wall and a static pressure tap in the wall of the wind tunnel. The measurements were long time-averaged and thus represent the overall effect of the high repetition rate snowplow arcs. They were taken with a glass probe to minimize the influence of the probe on the arc. The pitot probe was located at the end of the electrode segments approximately where the arc detaches as it moves downstream. Since the measurements indicate an increase in wall Mach number even with no magnetic field, there is remaining uncertainty about their significance. The increasing power required to drive the arc adds to the heating of the flow. In order to assess whether that alone could be affecting the measurement, the pitot pressure per Watt was determined and found to be increasing with magnetic field as well. This leads us to believe that the increase in Mach number of the surface flow with magnetic field indicates that the magnetic field driven snowplow arc is increasing the wall flow velocity. More measurements need to be made to definitively determine what is occurring, but if the wall velocity can be increased, then separation may be controllable with this concept.

![Figure 15](image)

**Figure 15.** Preliminary time-averaged measurements of the variation in surface Mach number with magnetic field (snowplow arc experiments) taken with a 0.040” glass pitot tube located at the wall just downstream of the arc and a static wall pressure tap at approximately the same location.

### D. Microwave-Driven Flame Speed Enhancement

Low flame speed, particularly associated with hydrocarbon fuel combustion, forces the utilization of recirculating flame holders and imposes a lower limit on the engine length for scramjet engines. Engine size adds weight and cooling loads to the vehicle, and flame speed may limit the minimum size of hydrocarbon-fueled vehicles. The possibility of increasing the flame speed significantly with the use of microwave power is enticing, particularly if that can be accomplished with power levels that are low compared to the power produced by the combustion process. In collaboration with RSI, Inc, we are exploring that possibility. Preliminary results show that of microwave power levels that are below the breakdown threshold, power can be coupled into the flame zone with the result that the flame speed is increased. Experiments were conducted in a microwave cavity as shown in Fig. 16. The co-flow burner was located at the center of the microwave channel where the microwave field is maximal. A flat plate at the top of the channel stabilizes the flame. As the microwave field is increased, the location of the flame moves toward the burner as shown in Fig. 17. Newer results on this technology utilize a high Q resonant microwave cavity and significantly reduce the microwave power required to achieve flame speed enhancement. Further enhancement in the performance may be possible using pulsed microwaves which may be able to induce instabilities into the flow, enhancing mixing and flame propagation.
Standing waves produce regions of maximum electric field.

Figure 16. Microwave cavity and burner configuration for studies of microwave-enhanced flame propagation.\textsuperscript{24}

Figure 17. Photographs of steady flame position in the experiments of Fig. 16 with methane-air mixture at a pressure of 1 atmosphere and equivalence ratio of 0.7.\textsuperscript{24}
IV. Conclusions

MHD power extraction has the potential of providing hypersonic vehicles with high power capabilities. Modeling efforts indicate that power levels on the order of megawatts per square meter of active panel area can be achieved on re-entry vehicle surfaces and in the exhaust region of hypersonic scramjet engines. These power levels will require that seeding with alkali metal vapor at a 1% level be incorporated, which, in these two regimes appears to be feasible. For the re-entry vehicles, the magnetic field only needs to be on the order of 0.2 Tesla, a level that can be achieved with electromagnets integrated into the surface structure. For the scramjet, the field has to be on the order of 1-3 Tesla, so superconducting magnets will most likely be required. Once those power levels are available, there are many uses that can be considered. Among those are the use of plasma heating of the flow or microwave and electron beam-controlled combustion in the inlet that would eliminate the isolator section, the use of surface snowplow arcs to suppress separation and control boundary layer phenomena, and the use of microwaves to enhance the performance of the scramjet engine.

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