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EXPERIMENTAL INVESTIGATION OF A 2-D MHD SLIPSTREAM GENERATOR AND ACCELERATOR WITH $M_\infty = 7.6$ AND $T_0 = 4100$ K

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An experimental study of the magneto-hydrodynamic (MHD) effects of partially dissociated and ionized flow over an 80-degree included angle wedge with a 0.3 Tesla permanent magnet is presently being undertaken in the Rensselaer Polytechnic Institute 24-inch Hypersonic Shock Tunnel. The selected flow freestream conditions were approximately Mach 7.6, 4100 K (7380 R) stagnation temperature, and 780 psia stagnation pressure. In the initial part of the study, the power generation characteristics of the flow were investigated to determine the conductivity of the flow through the MHD channel. The external resistance between the electrodes was varied, resulting in different potentials, currents, and powers being extracted; the electrical-generation characteristics seem to change between three distinct regimes. Finally, a current was established between the electrodes to accelerate the 4100 K stagnation temperature flow through the MHD channel, resulting in a relatively consistent doubling of the impact pressure at the channel exit.

INTRODUCTION

In the 1960's the interaction of high velocity plasma with a magnetic field was actively investigated by a number of researchers, including Rosa,[1] 1962, Nagamatsu & Sheer,[2] 1961, Nagamatsu[3] *et al.*, 1962, Way[4] *et al*, 1961, and Steg & Sutton,[5] 1960. This interest in magneto-hydrodynamic (MHD) phenomena arose from applications in thermonuclear reactions, astrophysics, electric power generation, space propulsion, and the magneto-aerodynamic control of ICBM nose cones (Ericson[6] *et al*, 1962) and the Apollo re-entry capsule. Until recently, numerous analytical but only limited experimental papers were published on hypersonic MHD phenomena.

Presently, interest in MHD for aerospace applications has been renewed by the need to drastically decrease the cost of launching payloads to space (Covault,[7] 1999, Gurijanov[8] *et al*, 1996). Myrabo[9] et al. (1995) have proposed that laser or microwave beams could power a MHD slipstream accelerator to propel vehicles, called Lightcraft, to an orbital Mach number of 25 and potentially reduce launch costs by a factor of 100 to 1000, as compared to today's chemical rocket launchers.

The interest in developing a hypersonic MHD airbreathing propulsion system motivated the present investigation. Two different geometries for hypersonic MHD and slipstream accelerators have recently been investigated in the Rensselaer Polytechnic Institute 24-inch Hypersonic Shock Tunnel. The first model, which is axisymmetric and fitted with 24 peripheral open-top MHD channels and two pulsed Bitter-type electromagnetic coils (Fig. 10b), was successfully tested at Mach 7.8 (Kerl[10, 11] *et al*, 1999). The test program was designed to first demonstrate MHD power extraction from the hypersonic inlet flow, then MHD acceleration of the inlet flow. The Shock Tunnel generated the 4100 K (7380 R) and 780 psia reservoir of air necessary for adequate electrical conductivity behind the conical shock wave. The first tests indicated that the hypersonic airflow past the channels was indeed decelerated because of the interaction of the high speed, high temperature airflow in the channels and the perpendicular pulsed magnetic field. Laser based schlieren and luminosity photographs confirmed this flow deceleration due to energy extraction in the

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MHD channels. The extracted voltage was also recorded as a function of the external electrical load. Unfortunately, due to model complexity and the lack of a suitable electrode power supply, acceleration of the conducting airflow past the MHD channels could not be attempted. To overcome this problem, therefore, a second slipstream accelerator model with 2-D geometry, a single open-top MHD channel, and permanent Nd-Fe-B magnets is presently being investigated in the RPI facility (Fig. 10a). The 2-D MHD accelerator model testing results are the subject of the present paper.

RPI 61-CM HYPERSONIC SHOCK TUNNEL

The 2-D MHD Slipstream Accelerator model tests are being conducted in the Rensselaer Polytechnic Institute 61-cm Hypersonic Shock Tunnel. Fig. 1 is a photograph of the Hypersonic Shock Tunnel. A detailed description of the tunnel facility can be found elsewhere (Minucci,[12] 1991, Minucci[13] *et al.*, 1994).

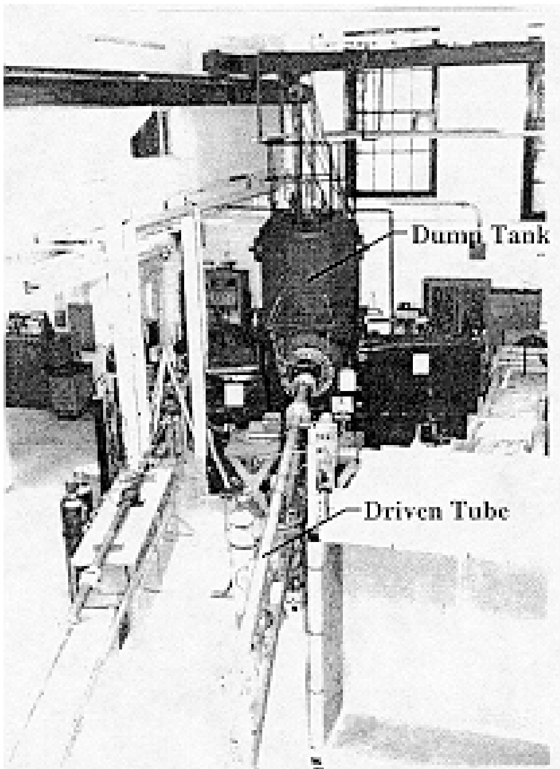

Fig. 1 Rensselaer Polytechnic 61-cm Hypersonic Shock Tunnel

For the present investigation, the tunnel was operated in the equilibrium interface mode near ambient temperature (Minucci[13] *et al.*, 1994), using argon as the gaseous piston (Nascimento[14, 15] *et al.*, 1997,1998), helium as the driver gas, and air as the test gas. In this mode of operation, the RPI facility can generate high enthalpy reservoir conditions—4100 K temperature and 780 psia pressure—upstream of the nozzle entrance for approximately 2 ms. By selecting the appropriate throat diameter, a free stream Mach 7.6 airflow is produced in the test section. The combination of high enthalpy reservoir conditions and free stream Mach number, in turn, assure the minimum necessary electrical conductivity of air flowing behind the attached shock wave that stands around the model during the 2 ms of useful test time.

The Maxwell capacitor bank in Fig. 2 was donated by the U.S. Army to the RPI Hypersonic Laboratory and provided the high current, high voltage pulse that drove the two Bitter-type coils inside the axisymmetric MHD slipstream accelerator model[10]. The authors' original intentions were to use this same capacitor bank as the high-voltage power supply needed to drive the flow-accelerating current between the wedge accelerator model electrodes.

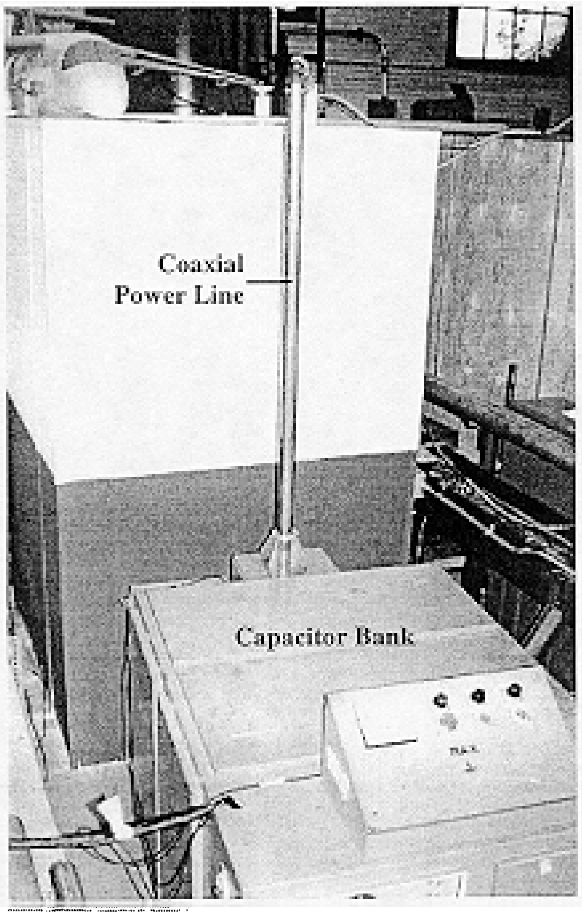

Fig. 2 Maxwell Capacitor Bank and Coaxial Power Line

Tektronix VXI and Test Lab data acquisition systems record pressure data from PCB piezoelectric transducers, shock tunnel heat transfer gage signals, voltage data from the model electrodes, and the electric current reading from the electrode power supply discharge. A computer code written for Labview™ software serves as the interface between researchers and the acquired data and acquisition equipment. Fig. 3 is a schematic drawing of the end of the Hypersonic Shock Tunnel driven section indicating the apparatus described.

EXPERIMENTAL APPARATUS

The electrode power supply is connected to the shock tunnel test section via a copper coaxial power line (Fig. 2). An in-house designed and built ceramic feed-through plate enables the power line to pass, isolated, through the test section steel wall before connecting to the model (Fig. 4). During the axisymmetric MHD model tests, the coaxial line was connected to the two Bitter coils, while for the 2-D flow accelerator wedge model tests, it is connected to the two copper electrodes. An electronic controller, developed in-house, provides two properly timed pulses to the 15 W copper vapor Oxford Laser and operates the camera's mechanical shutter to take a single schlieren photograph. The same controller can also pulse the laser at up to 30 kHz to take a sequence of photographs. The laser and the camera are part of a single pass schlieren system designed for flow visualization inside the test section through two 9-inch diameter circular windows. Either open-shutter photography or high-speed photography, using a recently acquired Beckman & Whitley Inc. model 350 framing drum camera, is used to record the luminous airflow around the model and the shock wave altered by the MHD interaction.

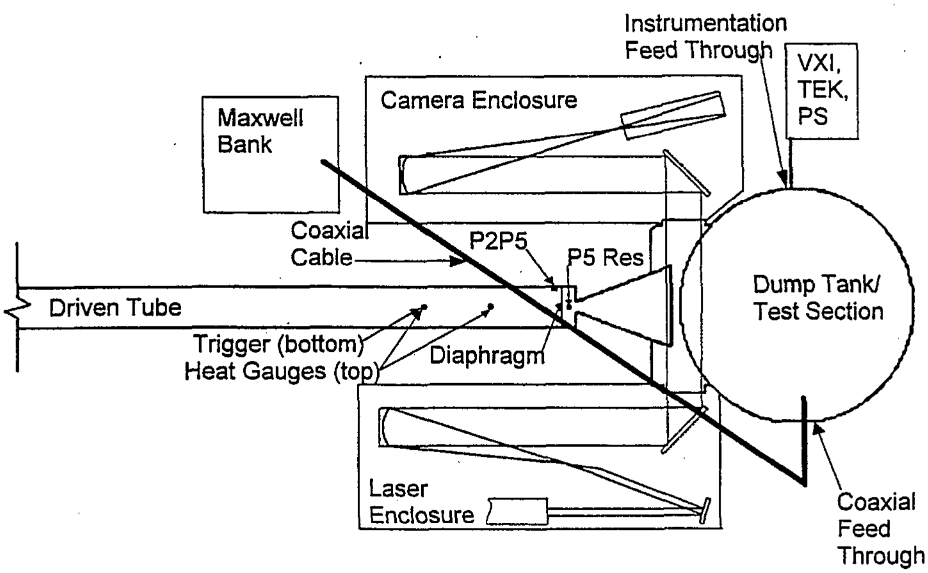

Fig. 3 Layout of the Shock Tunnel and Instrumentation

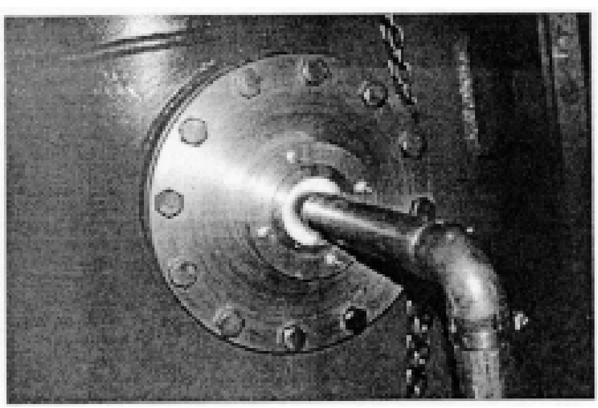

Fig. 4 Test Section Power Feed Through

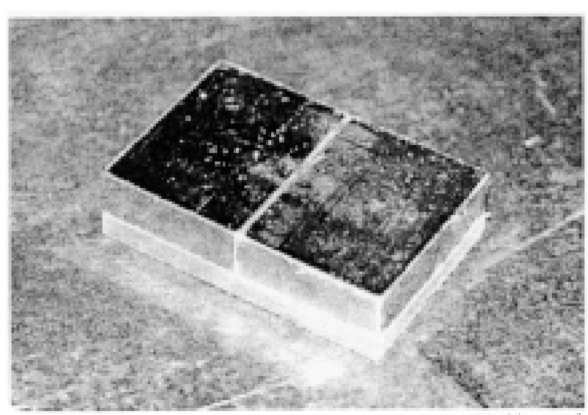

Fig. 5 Permanent Magnet Assembly

The axisymmetric inlet model is inherently complex; a large number of MHD channels (24), complex inlet flow, a low degree of ionization provided by the conical shock wave, a low-strength magnetic field (0.15 Tesla), and the lack of an additional power supply to accelerate the hypersonic air flow made the analysis of experimental results difficult. A new MHD model, therefore, was designed and constructed without these complexities. This new model is of a much simpler design that enables rapid evaluation of the MHD channel inlet flow conditions. It can be regarded as the 2-D version of one of the 24 channels existing in the axisymmetric MHD model. By using stronger, 0.3 Tesla permanent magnets, no power supply is necessary for the energy extraction experiments. Each one of the neodymium-iron-boron magnets measures 2.0 in. X 1.5 in. X 0.5 in.; they are commercially available from Edmund Scientific. Two such magnets were glued together to create the bottom of the MHD channel, which measures 2 in. wide by 3 in. long. They were then mounted on a cold rolled steel back plate 0.25 in. thick and epoxied into a pocket machined in the wedge top surface, between the two electrodes. Figure 5 shows the two-magnet assembly prior to its installation into in the wedge model.

An effort to survey and characterize the magnetic field is currently under way in the Hypersonic Laboratory. Although the entire field has yet to be mapped, preliminary results are available. At its greatest intensity near the surface of the wedge model, the magnetic field is 0.3 Tesla, and at all levels, the field strength remains roughly constant over most of the surface of the MHD channel but drops off sharply near the electrodes. Figures 8a and 8b are contours of the magnetic field strength over the MHD channel area at two heights above the wedge model surface.

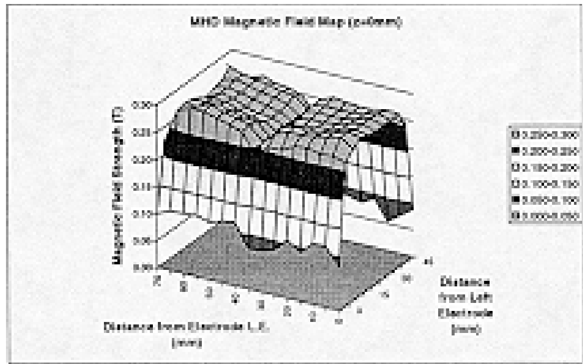

Fig. 8a Magnetic Field Strength over MHD Channel Area at z=0mm

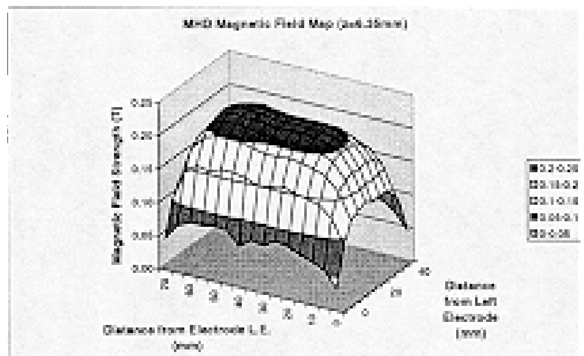

Fig. 8b Magnetic Field Strength over MHD Channel Area at z=6.35mm

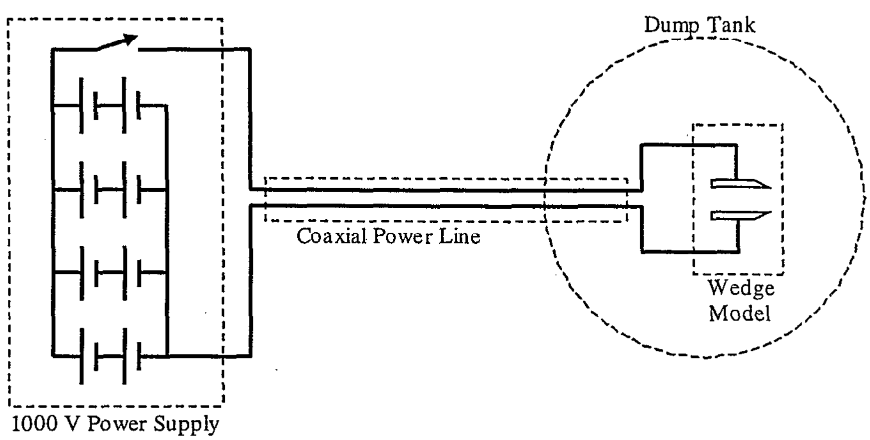

Fig. 9 Schematic of Electrode Power Supply and Delivery System

Since no power is required to drive these magnets during flow deceleration and acceleration investigations, the existing capacitor bank was available to power the two solid copper electrodes. However, the discharge characteristics of the capacitor bank were determined to be too intense for the experiment at hand. Instead, a high-voltage, low current, low noise power supply was assembled using four or eight 500 V Eveready type 497 batteries (Fig. 9) connected to the coaxial power line. Because the 2-D model consists of a 10 in. wide wedge with a 40-degree flow deflection angle, the Mach 7.6 oblique shock wave produces a higher degree of ionization than does the oblique shock for the axisymmetric model case. Because the model is symmetric with respect to the nozzle exit horizontal plane and the permanent magnet and two electrodes are installed only in the upper surface (Fig. 10a), it is possible to observe both the MHD disturbed (top) and undisturbed (bottom) wedge flows in each experiment.

The MHD slipstream decelerator and accelerator wedge model is shown in Fig. 10a. The axisymmetric MHD model is also shown in Fig. 10b for comparison. The centerline of the exit region of the MHD wedge model is instrumented with two surface pressure taps and two impact pressure probes, as diagrammed. The two impact pressure probes can be adjusted vertically to help determine the dynamic pressure distribution downstream of the MHD channel centerline. The impact pressure probes are mounted symmetrically with respect to the nozzle exit horizontal plane so that both dynamic pressures, downstream of the MHD channel (top wedge surface) and downstream of the unaffected oblique shock wave (bottom surface), can be measured simultaneously. A third impact pressure probe, located outside the model, measures the free stream pitot pressure necessary to determine the nozzle exit flow conditions. The wedge material is Delrin™, and due to its relative softness, the model was fitted with a removable Delrin™ leading edge, to allow the edge to be replaced after excessive erosion. After more than seventy runs, however, erosion of the original leading edge is still not apparent.

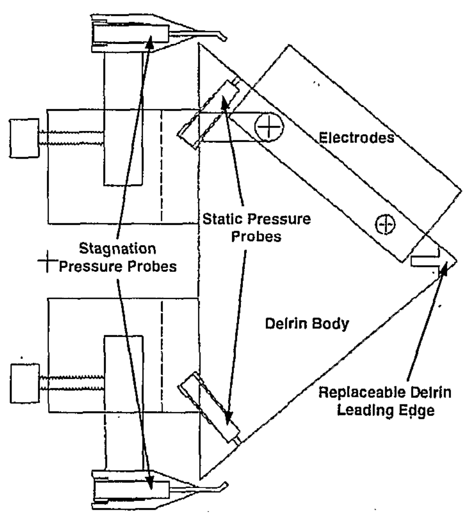

Fig. 10a MHD Slipstream Accelerator Wedge Model

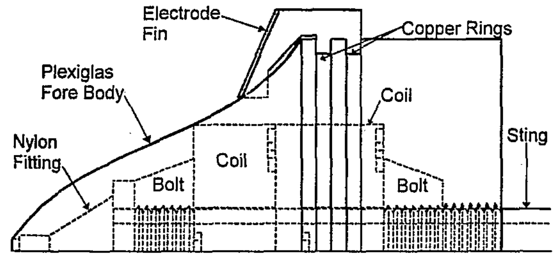

Fig. 10b Axisymmetric MHD Model

As in the axisymmetric inlet model, PCB model 112A22 piezoelectric pressure transducers were used in all model probes and surface pressure taps. A hollow stainless steel shaft connects the model to the test section main sting support system and carries the pressure transducer cables to a vacuum feed-through plate. For the energy extraction experiments, different external load resistors were connected between the two electrodes, via short copper bus bars. The voltage across the resistor was monitored via electric leads connected to the resistor terminals.

The rectangular electrodes are 0.75 in. X 3 in., 2 in. apart, and are removable to allow different electrode shapes and concepts to be tested. To minimize flow disturbances, the electrodes have sharp leading edges and the ramp surfaces face the channel's outside. Two small, 1mm diameter holes near the electrode leading edges allow the use of a copper fuse wire to start the discharge during the flow acceleration attempts, although experiments have proven the use of such a wire unnecessary. Solid threaded copper rods, under the wedge top surface, connect the electrodes to the cables that bring power from the 1000 V power supply.

An actual photograph of the 2-D model before its installation in the Hypersonic Shock Tunnel test section is shown in Fig. 11. The upper and lower impact pressure probes and the main pitot pressure probe are visible in this photograph.

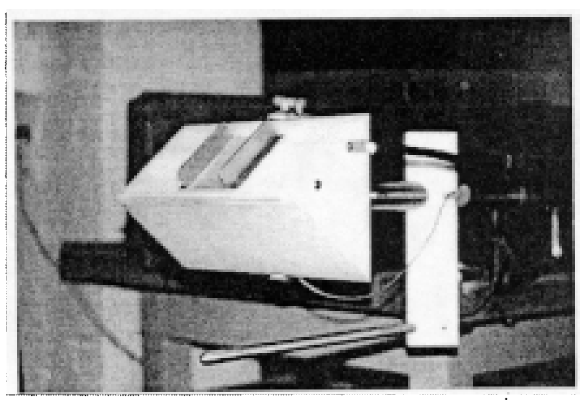

Fig. 11 2-D MHD Slipstream Accelerator Model outside the tunnel test section

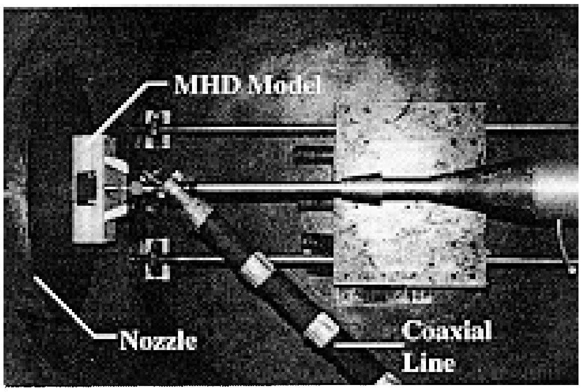

Fig. 12 2-D MHD Slipstream Accelerator Model installed in the Shock Tunnel Test Section

Figure 12 shows the model installed in the RPI facility test section. The coaxial power line that is used to deliver the high voltage pulse to the copper electrodes can also be seen in this figure.

AIR PLASMA CHARACTERISTICS

An iterative solver has been developed in FORTRAN by previous graduate students (Minucci,[12] 1991, Messitt,[16] 1999) to determine both the reservoir and freestream conditions from initial data for each run in the RPI facility. As mentioned previously, the RPI HST has been operated to produce 4100 K stagnation temperature and 780 psia stagnation pressure in the reservoir section for the present investigation. These reservoir conditions are sufficient to produce between 6 ms and 8 ms of Mach 7.6 flow in the test section. After expanding through a conical diverging nozzle, the flow static temperature and static pressure are 450 K (810 R) and 0.020 psia, respectively.

Another graduate student developed a second FORTRAN program to determine the flow conditions after deflection through a given angle; while the program takes into account real gas effects, it neglects boundary layer effects. As a first approximation, however, the boundary layer in the present experiment is assumed to be negligibly thin, as Mach number and flow deflection angle are both relatively high. The MHD accelerator wedge model turns the flow through 40 degrees, compressing and heating the air behind the attached shock wave to static temperatures and pressures of approximately 2500 K (4500 R) and 0.85 psia, respectively. The average Mach number of the parallel flow behind the attached shock is 2.28.

The Chemical Equilibrium with Applications (CEA) computer code (Gordon & McBride,[17] 1994) was used to determine gas composition at the conditions behind the oblique shock wave. For the given conditions, the major constituents of the hot test gas, in order of decreasing abundance, are N_2, O_2, O, NO, Ar, CO_2, CO, and other, less abundant particles, including free electrons.

EXPERIMENTAL RESULTS

Initial tests with the 2-D MHD Slipstream Accelerator to determine plasma conductivity have been completed. Peak voltages exceeding 11 volts have been extracted from the high velocity air plasma flowing between the electrodes with an external load of 762.2 kΩ. Figure 13a is a schlieren photograph taken during one of these tests for the indicated conditions. In addition, Fig. 13b is a schlieren photograph taken during a "cold run", and is presented for comparison. The low enthalpy, "cold run" test conditions were 780 K (1404 R), 265 psia, and Mach 10 flow.

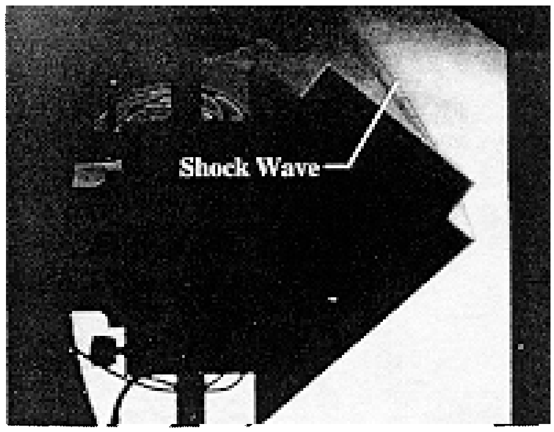

Fig. 13a Schlieren Photograph of the Mach 7.6 Airflow with Power Extraction for $T_5' = 4100$ K

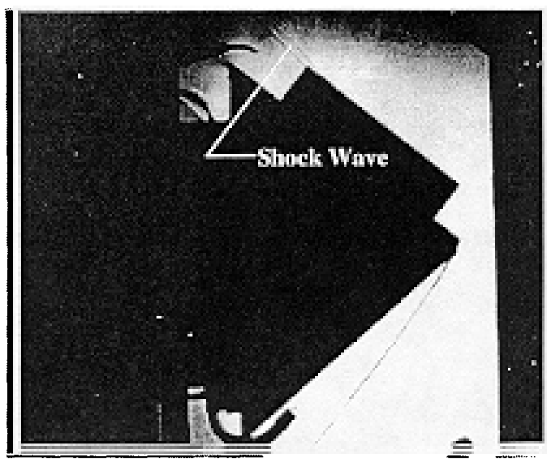

Fig. 13b Schlieren Photograph of Mach 10 Airflow (No Power Extraction) for $T_5' = 780$ K

The results of the power extraction phase of the experiment are presented in Fig. 14a through 16.

They reveal behavior similar to that of a generator: the potential decreases as current increases. All four figures, however, indicate three distinct regimes, between which the generator's behavior changes dramatically; this corresponds to the findings of Kerl[10, 11] *et al.* (1999). Similar nonlinear characteristics of the electrical conductivity for MHD power generation with room temperature electrodes have been observed by Nagamatsu[18] *et al.* (1999), and the ionic conductivity behavior at the electrode has been proposed in Ref. 19 for electric current extraction with room temperature electrodes. The stagnation temperature of 4100 K is on the threshold of dissociating and ionizing the flow, and as a result, only slight ionization of the gases takes place. The performance of the MHD generator, therefore, is conductivity-limited. Other limiting factors include the strength of the magnetic field and, to a lesser extent, the velocity of the plasma flow.

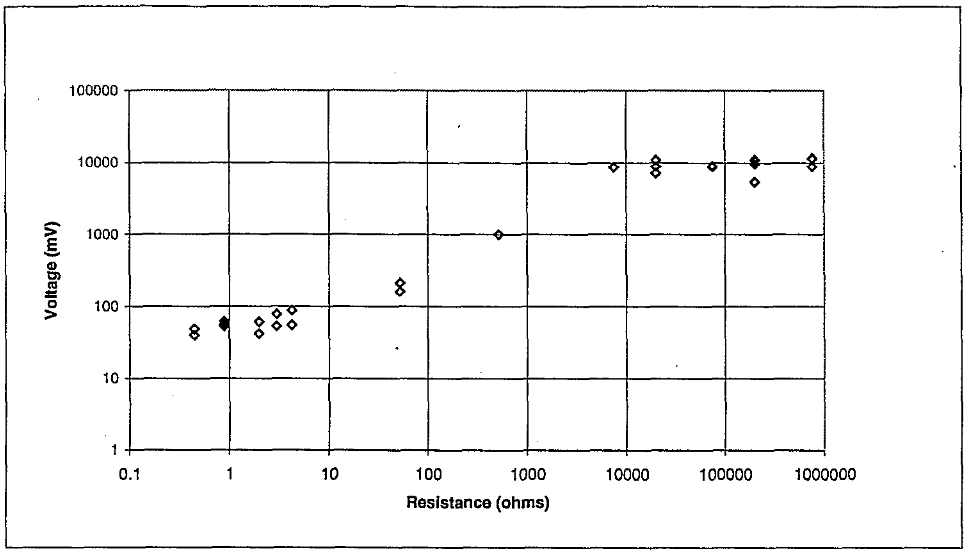

Fig. 14a Potential Across Electrodes as a Function of External Resistance

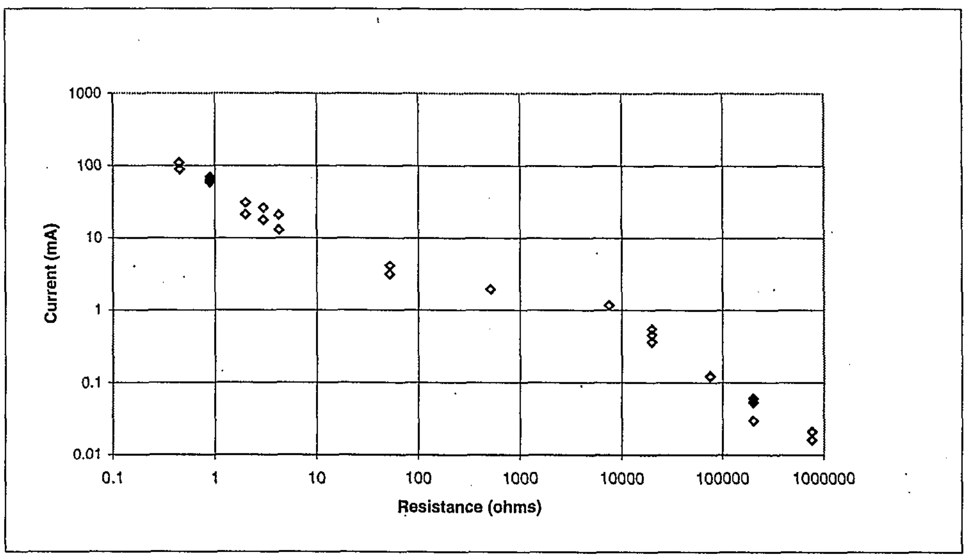

Fig. 14b Electric Current Output as a Function of External Resistance

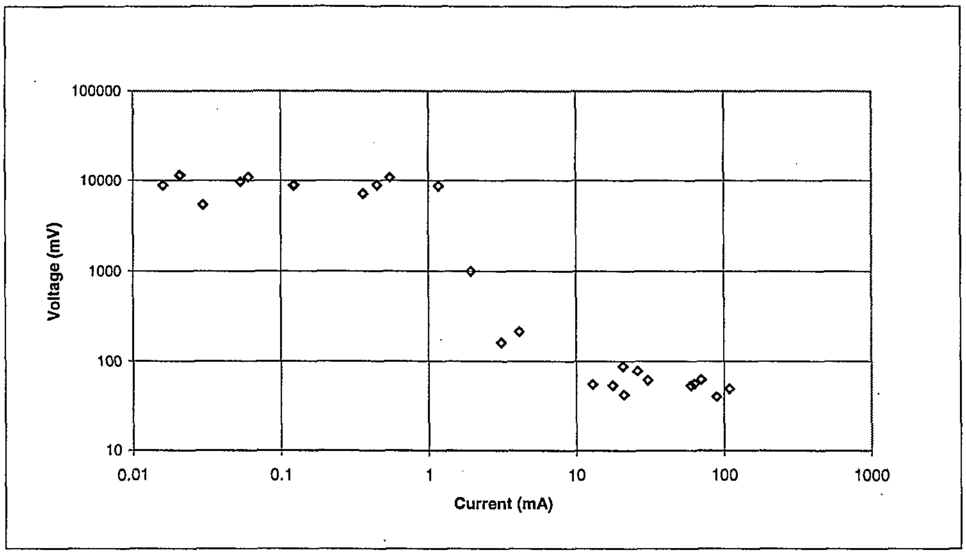

Fig. 15 Potential across Electrodes as a Function of Electric Current Output

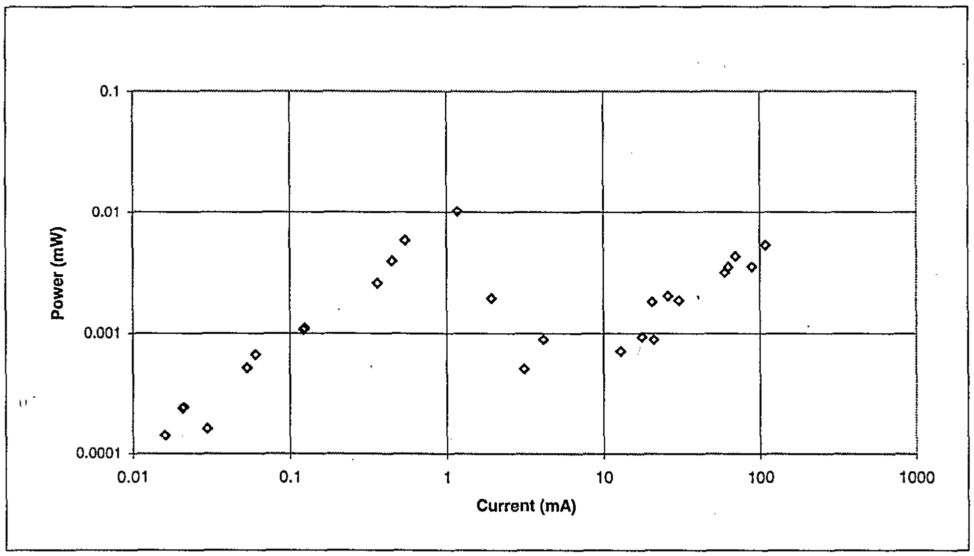

Fig. 16 Power Output as a Function of Electric Current Output

Figure 17 is a schlieren photograph of one of the flow acceleration runs made at 4100 K and 780 psia. Although the data has yet to be quantitatively analyzed, initial qualitative observations have revealed a consistent doubling of the impact pressure across the upper, MHD accelerated surface (Fig. 18 and Fig. 19a) accompanied by a severely weakened upper shock wave, as compared to that of the power extraction case shown in Fig. 13a. In addition, the pitot and bottom impact pressures are shown in Fig. 19b and 19c for comparison. Note that the model was inverted in the test section prior to the run presented in Fig. 17; as a result, the accelerated flow appears in the lower portion of the figure.

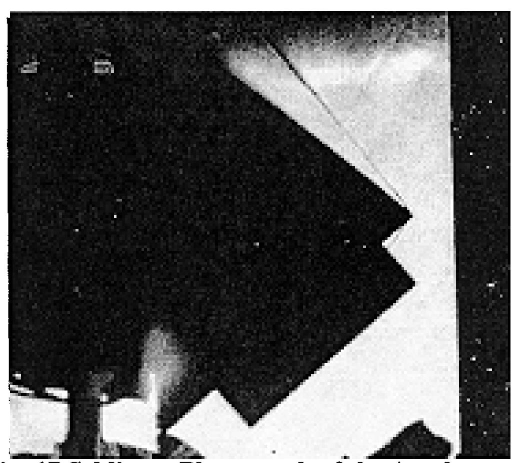

Fig. 17 Schlieren Photograph of the Accelerated Airflow Past the Model for $T_5' = 4100$ K

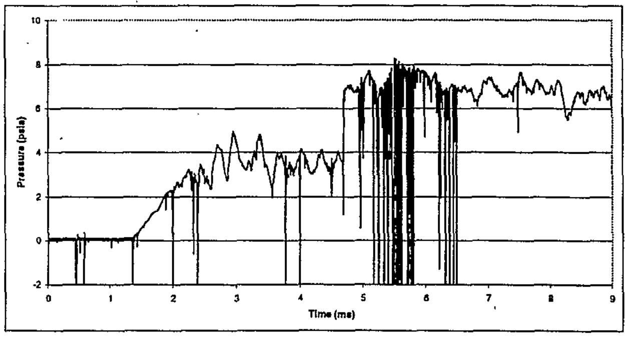

Fig. 18 Top Wedge Impact Pressure Trace from Flow Acceleration Run 46

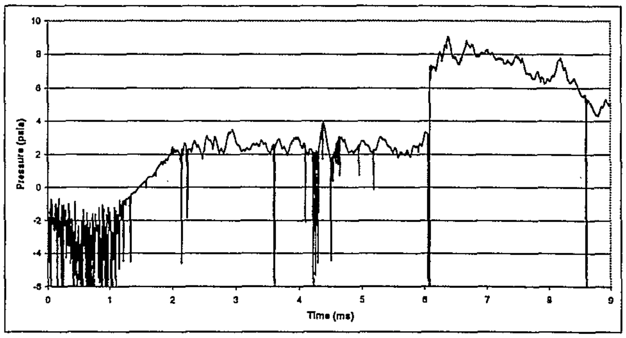

Fig. 19a Top Wedge Impact Pressure Trace from Flow Acceleration Run 61

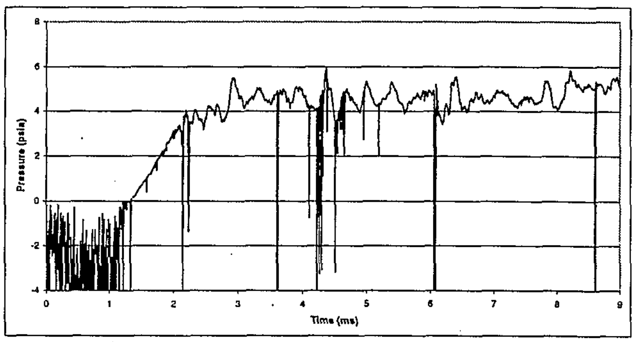

Fig. 19b Bottom Wedge Impact Pressure Trace from Flow Acceleration Run 61

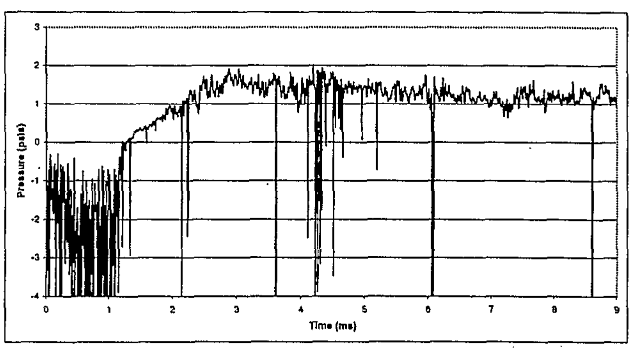

Fig. 19c Freestream Pitot Pressure Trace from Flow Acceleration Run 61

DISCUSSION OF RESULTS

The open circuit voltage, V_0, can be determined experimentally as the measured electromotive force that is induced with the highest external load. The experimentally determined open circuit voltage for the MHD wedge generator model in a Mach 7.6, 4100 K stagnation temperature, 780 psia stagnation pressure flow is 11.6 volts with an external load of 762.2 kΩ.

Theoretically, this open circuit voltage can be determined with the following relation (Blake,[20] 1999):

$$V_0 = \frac{U_2 BL}{10^8} \tag{1}$$

where U_2 is the plasma velocity in cm/sec, B is the magnetic field strength in gauss, and L is the electrode separation distance in cm. The theoretical value of open circuit voltage thusly determined is 32.2 volts.

Although the difference between the theoretical and experimental values of this voltage is significant, the order of magnitude is the same. The theoretical model does not account for boundary layers over either the wedge or its electrodes, electrode sheaths (Schneider[21], 1999), or the variation in the magnetic field strength with perpendicular distance from the surface. Considering these additional physical phenomena, all of which decrease the induced voltage, the theoretical open circuit voltage agrees fairly well with the observed open circuit voltage.

Conductivity was determined experimentally using the same method as Blake[20] (1999). The plasma resistance, R_p, without any external load, can be found from the following equation:

$$V = V_0 - IR_p \tag{2}$$

where V is the measured potential between the electrodes, and the induced current, I, is found using Ohm's Law:

$$I = V/R_{ex} \tag{3}$$

where R_{ex} is the external load. The conductivity, σ, of the plasma in a channel with electrode area A and separation distance L can then be determined by

$$\sigma = \frac{L}{AR_p} \tag{4}$$

The average plasma conductivity for the present investigation, determined by this method, is 6×10^{-4} mho/cm.

In generator mode, the 2-D MHD wedge model seems to operate in three different regimes. These regimes are apparent in Fig. 14, 15, and 16. In the first region voltage is not a function of current, while in the second region voltage depends nonlinearly on current. In the third region, voltage seems to approach a linearly decreasing function of current—much like a battery or generator. The reason for this strongly nonlinear behavior is still unclear. Further testing to determine the responsible physical phenomenon remains.

In accelerator mode, the 2-D MHD wedge model is capable of accelerating the hypersonic flow by applying a current perpendicular to both the flow direction and the magnetic field. This acceleration is indicated by the apparent doubling of impact pressure just beyond the electrodes' exit plane. This mode of operation is currently being further investigated in the RPI facility.

SUMMARY

- A permanent magnet for the MHD channel to extract power or to accelerate the weakly ionized Mach 7.6 plasma with stagnation temperature of 4100 K has yielded interesting and useful information for the MHD phenomena.
- For Mach 7.6 flow with a stagnation temperature of 4100 K it was not necessary to seed the flow in the RPI 61-cm Hypersonic Shock Tunnel to either extract power or accelerate the flow over an 80-degree wedge.
- There seem to be three distinct regimes between which the characteristics of the current extraction change. For currents of 0.016 mA to 1.2 mA, the voltage across the electrodes is over 10 volts. For a current range of 1.2 mA to 20 mA the voltage decreases by 9.3 volts, and for currents of 20 mA to 100 mA the voltage decreases by 40 mV. The effects of the boundary layers on the electrodes and the thick anode and cathode sheaths are significant, as discussed in Ref. 21.
- For a Mach 10 perfect gas flow with stagnation temperature of 780 K, there was an insignificant effect of the magnetic field on the flow, as indicated by the schlieren photograph and the surface and impact pressures for the wedge upper and lower surfaces.
- To accelerate the flow in the MHD channel with an electric current, it was not necessary to use a copper trigger wire across the electrodes to initiate the current flow. There was enough electrical conductivity in the 4100 K stagnation temperature Mach 7.6 flow after 40-degree flow deflection by the wedge model.
- With the current flowing across the MHD channel, the strength of the shock wave over the wedge surface with the magnetic field was decreased due to acceleration of the plasma flow.
- During flow acceleration, impact pressure increased downstream of the MHD channel from approximately 3.5 psia to 6.5 psia on average.

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