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EXPERIMENTAL INVESTIGATION OF A 2-D MHD SLIPSTREAM ACCELERATOR: PROGRESS REPORT

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ABSTRACT

An experimental study of the magnetohydrodynamic (MHD) effects of partially dissociated and ionized flow over a wedge with a 2 Tesla electromagnet is presently being undertaken in the Rensselaer Polytechnic Institute 24-inch Hypersonic Shock Tunnel. The wedge provides a 0- to 20-degree flow turning angle into the 2-inch by 3-inch MHD channel. The selected flow freestream conditions are 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 a similar wedge in the same flow were investigated to determine the conductivity of the flow through the MHD channel. The generator results have been verified. The next phase of study involves the establishment of an electric discharge between the electrodes of the new model to enhance conductivity and accelerate the plasma. calculations have revealed that at least 30 kW of energy must be added to the flow to see a 1 psia increase in impact pressure behind the MHD channel. The initial testing of the model's major components (electromagnet and exploding wire) are the subject of this paper.

INTRODUCTION

In the 1960's the interaction of high velocity plasma with a magnetic field was actively investigated by a number of researchers, including

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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, 1999, Gurijanov et al, 1996). Myrabo 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 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

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schlieren and luminosity photographs confirmed this flow deceleration due to energy extraction in the 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, another slipstream accelerator model with 2-D geometry, a single open-top MHD channel, and a 0.3T permanent magnet was constructed. Only the MHD generator characteristics of this model were investigated, however, because the ambient conductivity behind the upper wedge shock wave is too low to initiate an unassisted discharge. For this reason, an exploding wire has been chosen to provide the initial conductivity to start a discharge in future experiments; a new 2-D MHD wedge model with a more powerful electromagnet is being designed with this purpose in mind. The 2-D MHD accelerator model testing preparations are the subject of the present paper.

EXPLODING WIRE CONCEPT

At 3000 K static temperature the equilibrium conductivity of air is negligible. Many methods, therefore, have been envisioned to artificially increase the flow conductivity. These methods include seeding, exploding trigger wires, high voltage discharges, and laser- or microwave-induced breakdown. For the next phase of the MHD wedge accelerator investigation, exploding trigger wires are to be used to drastically increase conductivity and to create a "T-layer" or "paddle," as described by Myrabo et al. (1995), to essentially push the air through the MHD channel.

Although the MHD accelerator design calls for a laser- or microwave-induced line breakdown, the trigger wire is a good simulator of this event. The trigger wire concept has a number of distinct advantages over the others mentioned. It is simple and lends itself well to the current model design. The power supply and timing circuit are easily configured with the Hypersonic Shock Tunnel's current setup. Finally, the conductivity is expected to increase drastically as vaporized metal particles are entrained by the flow. Figure 1 is a schematic representation of what the exploding wire is expected to look like in a static environment.

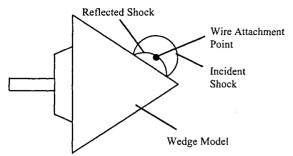


Fig. 1 Schematic of Exploding Wire Concept

When considering such an experiment, however, one has to take into account the many influences presented. Once a high current discharge has been established through the use of a trigger wire, an acceleration of the air due to the MHD effect is sure to ensue. How does one distinguish the pressure increase due to the MHD acceleration from that due to the added mass and possible shock wave contributions of the wire itself? A baseline can be established by simply exploding the wire without the magnetic field present.

While proper wire size and composition is being decided upon, some estimates of mass can be made. A 5.4 cm long, one-half milligram wire may add significantly to the calculated mass flow rate of 15.8 g/s. Copper wire could prove an interesting choice, as the excited vaporized copper atoms may interact with the copper vapor laser beam in some uncertain way. It could either absorb energy, leaving a dark spot on the schlieren photos, or possibly serve as a short, one-pass amplifier to overexpose portions of the photos. It is for these reasons that copper may also not be the best choice for wire material. For the experiments described within, 0.013 inch steel wire was used primarily because of its availability. It will be interesting to compare the performance of this ferrous wire with its nonferrous counterparts in future tests.

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 (RPI HST) facility. Figure 2 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, Meloney, 14 2000).

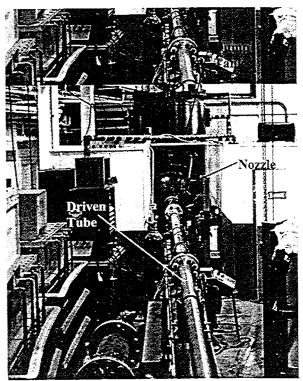


Fig. 2 Rensselaer Polytechnic 61-cm Hypersonic Shock Tunnel

For the present investigation, the tunnel was operated in the equilibrium interface mode near ambient temperature (Minucci¹³ et al., 1994), using argon as the gaseous piston (Nascimento 15, 16 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 a minimum electrical conductivity of air flowing behind the attached shock wave that stands around the model during the 2 ms of useful test time.

Historically the RPI HST has been an aerodynamic research facility. Recently, however, research has changed focus to aero-electromagnetic interaction phenomena—this has required a major change in laboratory setup and equipment. Much work has been dedicated to this changeover effort.

Power Sources

A multitude of power supplies have been developed for different experiments over the years, thus furthering lab capabilities. For low current, high voltage needs, a simple series-parallel circuit of 540VDC Eveready batteries, producing 1080VDC

total can be quickly attached to the system, and is capable of producing approximately 2A for short For moderate current, low voltage requirements, a Miller welder has been used to provide 600A at 70VDC continuously, and much more in the initial transient. For high voltage, high current requirements, a Maxwell capacitor bank can be used to deliver pulses of 10kV and up to 100kA. Most recently, a large array of lead-acid automotive batteries (Fig. 7) has been assembled to provide moderate-voltage, high current, clean and steady The supply can be power for experiments. provide any parallel-series reconfigured to combination of 20 batteries necessary. experiments presented within have been run with pure series combinations of 10, 15, or 20, 12.6VDC, 1000A batteries.

Power is delivered from any power supply to the test section through a high-power coaxial conduit mounted to the capacitor bank (Fig. 3). Changing power supplies is achieved by simply rearranging copper shorting bars in a locked interface box at the head of the conduit. The coaxial conduit enters the test section through a dedicated, isolated vacuum feedthrough plate.

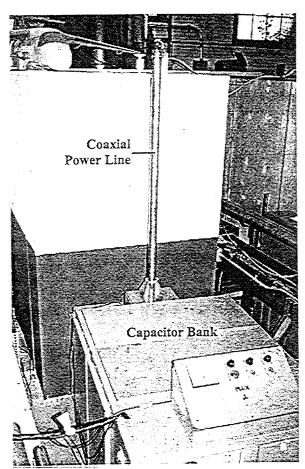


Fig. 3 Maxwell Capacitor Bank and Coaxial Power Line

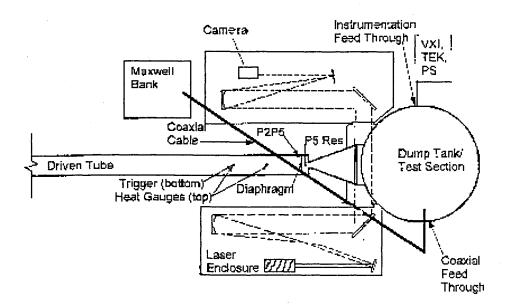


Fig. 4 Layout of the Shock Tunnel and Instrumentation

Data Acquisition

Tektronix VXI and Test Lab data acquisition systems record pressure data from PCB piezoelectric transducers, shock tunnel heat transfer gauge signals, and the electric current and voltage readings from the power supply discharge. Most data is acquired at 200 kHz, though limited channels are available for up to 12.5 MHz sampling rates. A computer code written for LabVIEW™ software serves as the interface between researchers and the acquired data and acquisition equipment.

As part of the aforementioned changeover effort, the PCB pressure sensors currently used in all experiments are being phased out in favor of optical fiber pressure sensors. These sensors consist of a tiny Fabry-Perot etalon attached to an optical fiber that feeds back to a signal conditioner. They are impervious to the EMI-generated noise that has plagued high-power electric interaction experiments in the past.

Image Acquisition

Flow visualization capabilities in the RPI HST have recently been improved. A Cordin model 350 framing drum camera, on loan from the NASA Marshall Space Flight Center is used to capture multiple images at up to 35,000 fps for self-luminous events; the same camera has also been modified to serve as a high-speed open-shutter drum camera for schlieren imaging at up to 4,600 fps. Figure 4 shows

the Z-path schlieren system and some of the basic instrumentation of the RPI HST.

Schlieren photographs are laser-illuminated with an Oxford Lasers 10W copper-vapor unit. An Oxford Lasers 'n-Shot Controller' properly times the pulses from the laser; each 10 ns pulse exposes a frame on the camera drum as the drum rotates. Presently, the maximum schlieren imaging rate of 4,600 fps is limited by the capabilities of the camera, but a new camera is being designed that will take pictures at rates up to the limit of the laser: 30,000 fps.

Self-luminosity photographs are taken on Ilford Delta 3200 film (ASA 3200) and push-processed to ASA 12500. Schlieren images are taken on Kodak Plus-X Pan (ASA 125) and developed normally. Standard developers, stop baths, and fixers are used in all developing, and all negatives are scanned in a Polaroid SprintScan 4000 negative scanner at 4000 dpi. These scanned images can then be enhanced, reduced, and used to make movies as necessary.

EXPERIMENTAL APPARATUS

Earlier work in MHD power generation was performed in the RPI HST with an 80-degree included angle wedge equipped with a permanent 0.3T magnet. Details of this model can be found in previous papers (Minucci¹⁷ et al., 2000, Meloney¹⁸ et al., 2000), but the important characteristics will be summarized here.

Wedge Models

The wedge material is Delrin, and the upper and lower surfaces are each a 40-degree flow turning angle (Fig. 5). The two electrodes in the upper surface are each 3 inches long, 0.75 inches high, and 0.125 inches thick; they form the walls of a 2-inch by 3-inch channel, the base of which is formed by the magnet.

The magnet is epoxied into a machined pocket in the top of the wedge and then covered with a layer of epoxy to prevent arcing through the magnet. After installation in the wedge, the magnetic field was surveyed and the results tabulated. Figs. 6a and 6b present the magnetic field intensities at 0mm and 6.35mm above the wedge surface; notice that the field is generally uniform except near the electrodes where its intensity drops off quickly.

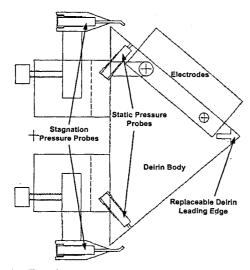


Fig. 5 MHD Slipstream Accelerator Wedge Model

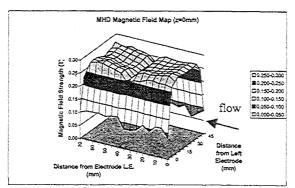


Fig. 6a Magnetic Field Strength over MHD Channel Area at z=0mm

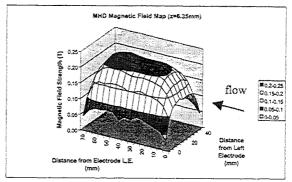


Fig. 6b Magnetic Field Strength over MHD Channel Area at z=6.35mm

A second wedge model, identical in all respects except for the exclusion of a magnet, has been machined for comparison experiments. This second model is used to study the exploding wire phenomenon in the absence of a magnetic field.

Power Supply Details

The lead-acid battery supply has been slowly growing since its original inception. It now consists of 20 batteries, and for this experiment, they were all wired in series to provide 249VDC at up to 1500A in the transient. This level of power can present a hazard to the experimentalists, so a system has been designed to allow wiring to be done with the circuit 'cold'. With the system door open, each battery is isolated, limiting the maximum possible potential to 12VDC. Figure 7 is a photograph of the battery box in the open position.

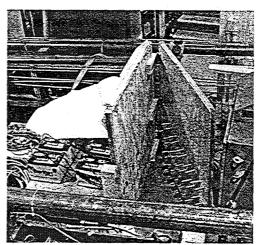


Fig. 7 Lead-Acid Battery Box

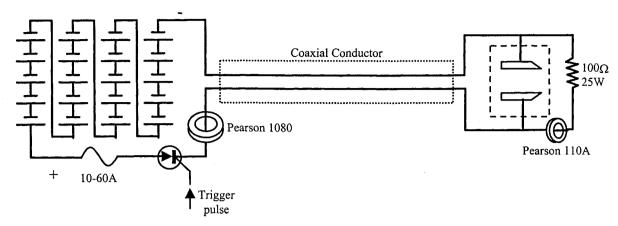


Fig. 8 Schematic of Electrode Power Supply and Delivery System

To switch the battery supply, a combination of solid state devices and one-time fuses are used. A silicon-controlled rectifier (SCR) is triggered by a time delay through a ferrite core tranformer. Once the SCR is closed and current is flowing, however, it continues to flow until the fuse breaks the circuit. The time-current curves of a number of fuses were studied, and experiments were performed to come up with the present system. Fuse values of 10A to 60A are used to provide pulsewidths of 2ms to approximately 6ms, depending on current.

Current and voltage is monitored using Pearson current monitors and minimal external circuitry. Figure 8 is a schematic of the system circuit, wired in pure series, including all instrumentation. Even at the test static pressure, 249VDC is not enough to arc across the 2-inch wide MHD channel unassisted. Because this problem was expected. 1mm holes were drilled approximately 0.5 inches behind the leading edge of each electrode, 0.375 inches above the surface of the model to allow a trigger wire to be installed. The trigger wire used in every experiment to date is 0.013-inch diameter steel, cut to length and pulled taut between the two copper electrodes. The high current discharge that ensued during some tests did melt a small portion of the sharpened leading edge of the cathode; when this was the case, the leading edge was carefully filed to approximate the original shape before the next test.

RECENT WORK

Present efforts are focused on working out the complications of the magnet and electric arc systems. While working out these systems the expected flow conditions must be kept in mind. The new wedge model will provide a flow turning angle of 0 to 20 degrees, which translates to a static pressure of 0.02 psia to 1.5 psia for the given flow conditions. All tests to date have been done at either atmospheric pressure, for simplicity, or at 0.02 psia.

Electromagnet Investigation

A small 12-turn coil was constructed and calibrated for measuring magnetic field intensity, and a variety of large electromagnet configurations were tested. The best performance of a magnet to date was obtained with a 48-winding coil of 16-gauge magnet wire on a 3-inch by 4-inch plywood core, driven by 20 batteries in series for a total open-circuit voltage of 249VDC. The magnetic field intensity on axis in the center of this magnet reached a maximum of 814 mT in steady state.

Of course, in such an impulse facility as the RPI HST, timing of such an inductive circuit is important. While increasing the number of windings will increase the available steady-state field strength, it will also increase the inductance and hence time to reach this maximum intensity. Figure 9 is a plot of magnetic field intensity against time for the described configuration. Notice that, for this configuration, the time to peak field intensity is more than 4 ms.

The maximum current realized during this test was only 650A. This leads to the conclusion that the magnetic field is presently resistance-limited. Future work will be in the direction of decreasing both this resistance and the time to peak field intensity.

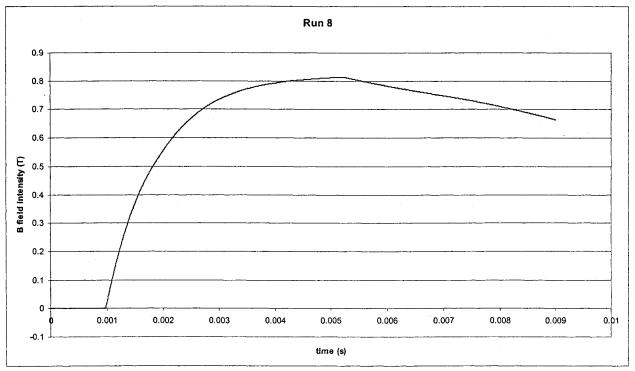


Fig. 9 Magnetic Field Intensity vs. Time

Electric Arc

Tests on an exploding wire-initiated electric arc have been conducted using two electrode geometries, with and without magnetic field, and both at atmospheric pressure and at 0.02 psia in the RPI HST test section.

Initial tests were conducted without a wedge model at all, but with a simple pair of tungsten electrodes 1/16 inch in diameter between which the exploding wire was strung. This is actually the same model that was used by Bracken¹⁹ et al. (2001). Later tests were conducted with either of the two wedge models—either with or without the 0.3T permanent magnet. In all cases current and voltage were monitored as previously described, and photographs were taken through the test section's 10-inch diameter windows.

A 0.013-inch diameter steel wire 2 inches in length was used in each test case. The exact resistance of this wire varied slightly from test to test

depending on how the electrodes were aligned and how tight the wire was pulled. For the tungsten electrode tests the circuit resistance, including the wire, was usually 2.1 ohms, while the circuit resistance increased to 3.3 ohms with the wedge model installed. The wire has a listed resistivity of $15.19\Omega/ft$.

In all cases, the current and voltage vs. time curves of the exploding wire phenomenon were similar, though they differed quantitatively based on resistance. In addition, there was never a test at atmospheric pressure during which an arc ensued after the wire exploded; the current trace of Figure 10 is for the characteristic exploding wire. In the low-pressure cases, after the explosion, an arc of up to 1100A was ignited in every case except that with magnetic field. Figure 11 is typical of an arc following the wire explosion. All current and voltage traces were very consistent from test to test.

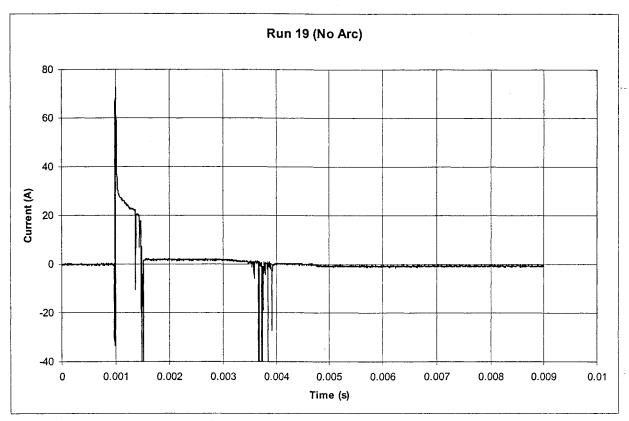


Fig. 10 Current vs. Time for Exploding Wire, No Arc

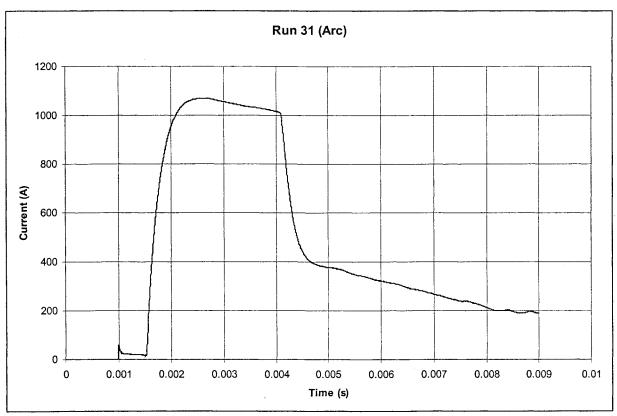


Fig. 11 Current vs. Time for Exploding Wire with Arc

The energy density deposited in the wire before explosion was fairly consistent from run to run, and averages 0.126 J/cm. In the 0.02-psia cases, the arc resulting from this explosion was as expected for both the tungsten electrodes and the copper wedge electrodes. Self-luminosity photos were taken at 20 kfps of the tungsten electrodes both on axis and perpendicular to the arc. Figures 12 and 13 are representative photos from these tests—they are taken near the peak current in each case.

The photographs of wires exploding over the wedge models were the most interesting of the group. For reference, Figure 14 is a photograph of a wedge model in the RPI HST test section oriented as it is during the tests. The copper electrodes can be easily seen in this picture. The arc over the magnetless model exposed 150 frames of film at 20 kfps; some representative frames, in order, are shown in Figure 15. Notice that the arc seems to be relatively diffuse during most of its lifetime. After the last picture at 750 µs, the discharge does not change significantly before extinguishing. The peak current during this arc was 1100A, and the arc did melt a small mass of the cathode.

The photographs of the wire exploding over the magnet model help provide some insight into why no arc formed even at low pressure. Although the wire itself is not nearly as luminous as an arc, it was bright enough to expose approximately 30 frames at 20 kfps. In these frames, due to the Lorentz force, the wire stretches forward as current starts to flow; the magnetic field strength at the center of the wire is approximately 180mT. Figure 16 is a series of photographs from this test that show this phenomenon.

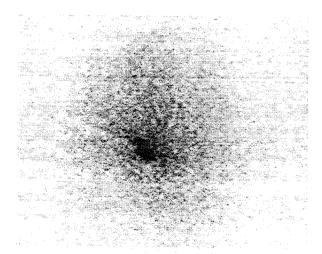


Fig. 12 Axial Self-luminosity Photo of Arc Between Tungsten Electrodes

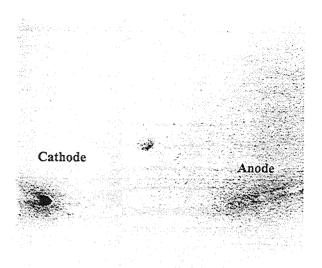


Fig. 13 Perpendicular Self-luminosity Photo of Arc Between Tungsten Electrodes

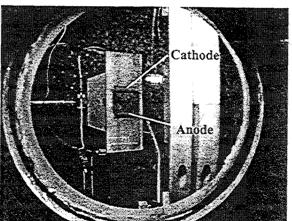


Fig. 14 Photograph of Wedge Model in the RPI HST Test Section Prior to Test

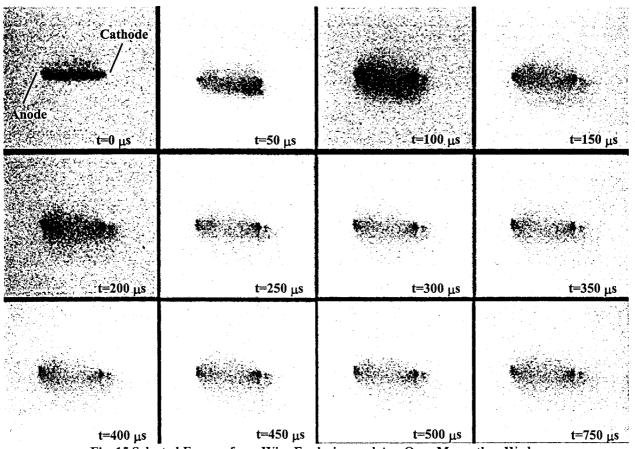
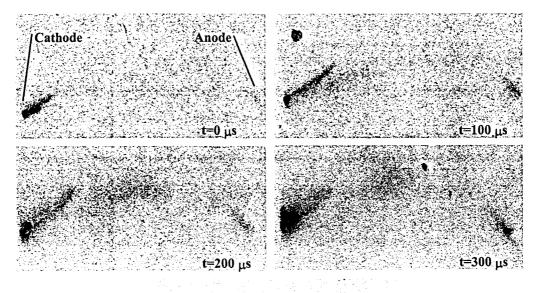


Fig. 15 Selected Frames from Wire Explosion and Arc Over Magnetless Wedge



 $_{\mbox{\scriptsize t=400}~\mu s}$ Fig. 16 Selected Frames from Wire Explosion Over Magnet-equipped Wedge

FUTURE WORK

Various methods for reducing the resistance of the electromagnet are to be tested within the coming months. The maximum field strength expected is approximately 2T. Hopefully a single power supply will be able to power both the magnet and the arc, thereby reducing problems associated with timing.

Different wire materials and different magnetic field strengths are to be tested for the electric discharge. Perhaps the time to explode the wire could be adjusted by changing the gauge of the wire. Though an arc did not strike during the one magnetic test performed, perhaps a weaker magnetic field, as that likely to be produced by the electromagnet during ramp-up, would be more appropriate. All of these details require further investigation.

Calculations show that at 100% efficiency, an applied power of 30.2 kW should create a 1-psia impact pressure increase in the MHD channel flow. The current in this case should be as high as possible: at least 400 amps assuming, again, 100% efficiency. Of course, we cannot expect anywhere near 100% efficiency, but this gives us some estimate of our power requirements.

Twenty, 1000 amp lead-acid batteries will provide 63 kW at anywhere from 1 kA to 5000 kA. With this sort of power supply, the new "T-layer" approach, and a redesigned model, we expect to see useful MHD accelerator results.

SUMMARY AND CONCLUSIONS

- A new test model is being built to utilize an electromagnet and exploding wire to accelerate air using the MHD effect.
- Experiments are being performed to characterize the electromagnet and exploding wire to be used with this model.
- More wire sizes and materials must be tested before a good choice of wire can be made.
- An extremely useful tool for studying fast transient events has been developed: schlieren movies at 4.5 kHz can be created with a drum camera, 30 kHz Cu-vapor laser, and controllers. In addition, self-luminous events can be recorded at rates of up to 35 kHz.
- Fiber optic transducers will likely be required to obtain data of satisfactory quality with negligible noise.
- A high current, moderate voltage, stable DC source has been assembled of lead-acid batteries.

- The next stage in experimentation is the testing of MHD slipstream accelerators that employ pulsed "T-layers."
- The T-layer approach maximizes the percentage of input energy used to accelerate the flow by minimizing the energy used to simply enhance flow conductivity.
- This concept has been traditionally proposed for laser and microwave Lightcraft.

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