

MHD Experiment on a Blunt Body in High-Enthalpy Argon Flow at the TennHET Arcjet Facility

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In this MHD flow control investigation, pressure sensors were used in conjunction with high-speed and infrared imaging to observe post-normal shock behavior. The blunt body test sample was designed and configured to act as a housing unit for permanent magnets, and was placed in a high-enthalpy Mach 11 argon flow in the TennHET arcjet facility. The acquired data allowed comparison of the magnetic and non-magnetic test cases, with pressure, temperature, and emission intensity being the metrics of focus. The non-magnetic case saw a 25.94% increase in post-normal shock emission intensity when compared to the magnetic case. Magnetic and non-magnetic pressure and temperature data showed no statistically significant changes across each test. The magnetic case showed a pressure spike at the start of each tunnel run, which was not observed in the non-magnetic case.

I. Introduction

Over the past several decades, researchers have investigated Magnetohydrodynamics (MHD) phenomena as a means of controlling flows in hypersonic environments [1]. MHD, as a method of flow control, has a wide range of potential applications, from reducing surface heating to changing pressure distributions on hypersonic vehicles during flight or re-entry. This technique requires strong magnetic fields, which often exceed one tesla, and highly ionized flows. While it is possible to achieve high-strength magnetic fields in a flight-weight vehicle, it is difficult, and as such, experiments have continued to investigate ways to improve efficiency. Past experiments have yielded success when using blunt or conical bodies with permanent and electromagnet configurations in ground-based hypersonic testing facilities [2, 3]. Ground testing of this phenomenon allows for improvement of existing numerical models, something that is essential for future use on flight vehicles. Researchers have used a combination of high-speed imagery and pressure transducers to observe the effects of MHD in ground-based arcjet tests [4]. Most of these experiments used an argon flow over the test samples due to its ease of ionization [5]. The advancement of such arcjet tunnels, like the TennHET facility at the University of Tennessee, has allowed smaller-scale testing to be affordable and achievable. Thus, enabling the quick development of scaled-down models to replicate flight-like conditions.

Ongoing efforts to improve facilities and material properties alike have allowed continued improvement of these systems. Despite these improvements, challenges persist in designing and testing a viable flight-weight vehicle. While high enthalpy, high Mach number facilities exist, it is difficult to simulate these conditions for long-duration testing. Arcjets, which have been around for decades, come in many different configurations, allowing a wide range of altitudes and mach numbers to test hypersonic vehicles during reentry and high altitude cruise conditions [6]. While they are versatile, there is a lack of knowledge on the levels of ionization present in these facilities, and as such, MHD experiments have proven difficult. Low ion count, highly conductive test section and nozzle materials, and rarefied air at high Mach numbers have all contributed to difficulties with recreating MHD experiments in arcjet tunnels [4].

This investigation focused on how to achieve flow control using MHD in a smaller arcjet facility. All testing was conducted in the TennHET 500 kW arcjet facility located at the University of Tennessee, Knoxville, which produced Mach 11 high-enthalpy argon flow as described in Sec.II.A. The test sample used a nylon 6/6 outer shell encasing three neodymium N45 magnets as described in Sec.II.B. Data was acquired using the high-speed and infrared cameras alongside the pressure transducers mentioned in Sec.II.C to investigate the MHD interaction in the freestream. The magnetic and non-magnetic results are analyzed and discussed in Sec.III, where the two different test cases are compared across the three unique measurement techniques. Future investigation concepts and concluding remarks are made in Sec.IV

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II. Experimental Setup

A. Tennessee High Enthalpy Tunnel

The Tennessee High Enthalpy Tunnel (TennHET), located at the University of Tennessee, Knoxville, is an arc-heated wind tunnel configured to produce high-temperature Mach 11 Argon flow as shown in Fig. 1 [7]. This facility was operated in pulsed mode with a typical test duration of 500 ms. The conditions were achieved using a converging-diverging nozzle that had conical geometry and an exit diameter of 85 mm. An alumina ceramic and stainless-steel plate was placed downstream of the plenum chamber to block upstream radiation from reflecting into the cameras. For these tests, one fast-opening solenoid valve was used to release a pure Argon (Ar) gas initially pressurized to 50 psia, into the arc-heater, set to the maximum power condition. The selected facility conditions are illustrated in Table 1. Kulite pressure sensors located in the plenum chamber and the free stream of the tunnel allowed stagnation pressure measurements to be recorded. Additionally, a Pitot probe was positioned in the core flow, which enabled post-normal shock stagnation pressure to be measured. The facilities free jet design enabled the flow to expand into the 750 mm diameter test section, set up with optical access perpendicular to the flow for high-speed imaging, and at an acute angle for FLIR imaging. The base of the test section is equipped with a multi-axis translation stage for precise positioning of the various model configurations in the free stream.

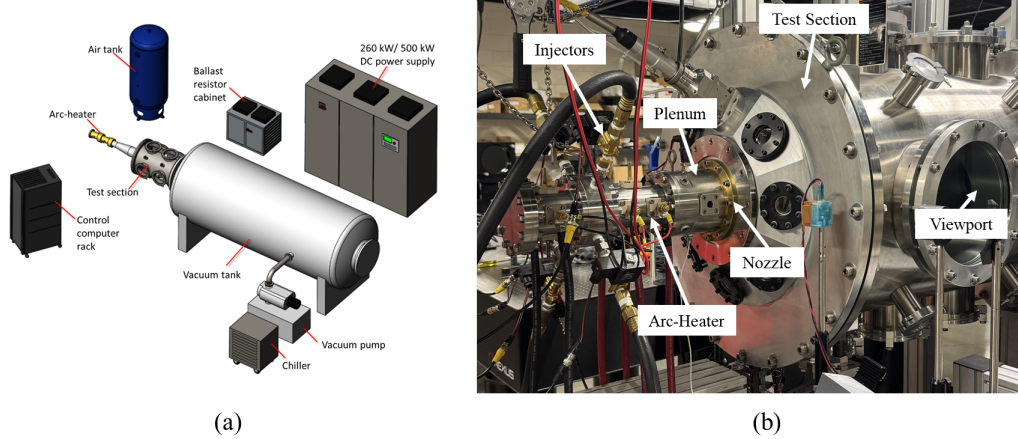


Fig. 1 (a) CAD overview of the TennHET facilities primary components. (b) Labeled image of the arc-heater and test section.

B. Magnetohydrodynamics Blunt Body Model

This work used a traditional cylindrical blunt body shape shown in Fig. 2, to produce the normal shock necessary for observation of the MHD phenomena. A fiberglass reinforced Nylon 6/6 outer shell with a coefficient of thermal expansion (CTE) of 4.86×10^{-5} 1/K was used for protecting the three disc-shaped neodymium magnets with outer radius, inner radius, and thickness of $1 \times 1 \times 0.25$ inch, respectively. The shell had an outer diameter of 1.5 inches, a front wall thickness of 0.2 inches, and a side wall thickness of 0.25 inch. A 0.05 inch orifice was drilled into the front-facing wall to allow stagnation pressure measurements in the free stream, while a 1 inch diameter cavity was machined in the shell, which allowed the magnets to be mounted inside. An aluminum piston was machined on a lathe to act as both a Kulite pressure sensor mount and a securing mechanism for the magnet-shell model. Two $1/8 \times 1/2$ inch dowel pins were inserted into the model perpendicular to the flow to secure the structure together. The pins were flush-mounted to the model's side to reduce unnecessary oblique shock formations. Tight tolerancing was used

Table 1 Selected Facility Operating Conditions.

Property	Stagnation Pressure	Mass Flow Rate	Arc Voltage	Arc Current	Flow Power
Values	89.25 kPa	12.85 g/s	126.7 V	367.6 A	46.58 kW

throughout machining to allow consistent magnet placement in the flow. The shell magnet system was secured into the tunnel on optical posts and aligned to the nozzle's centerline using two laser levels.

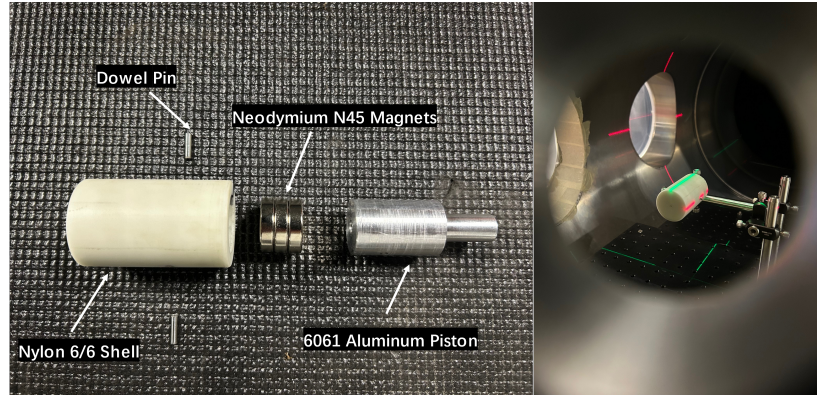


Fig. 2 Blunt body MHD model components shown on left, with the fully assembled model shown in the test section on the right.

The shell's outer diameter was selected to fit inside the calculated steady core flow diameter of at least 50.8 mm. This was defined by measured stagnation enthalpy and pressure values that remained constant along the flow's free-stream centerline [8]. The model was inserted on a sting arm perpendicular to the flow for all tests and was routinely checked for shell ablation and magnetic strength.

C. Experimental Setup

High speed fluorescence imaging, infrared thermography, and stagnation pressure measurements were acquired for each test case as shown in Fig. 3. For all tests, facility conditions were acquired at 10 kHz by a DAQ system. A Photron Nova S16 high-speed camera, equipped with a 100 mm Macro 2 $\times$ lens, was mounted outside the test section perpendicular to the flow centerline. The test section view-port in front of the camera was equipped with an uncoated fused silica 4 inch window, which allowed efficient transmission of emission between 185 and 2100 nm. The pixel resolution was set to 384 $\times$ 384. A capture rate of 500 Hz was used, with time averaging done during post-processing to produce the images shown.

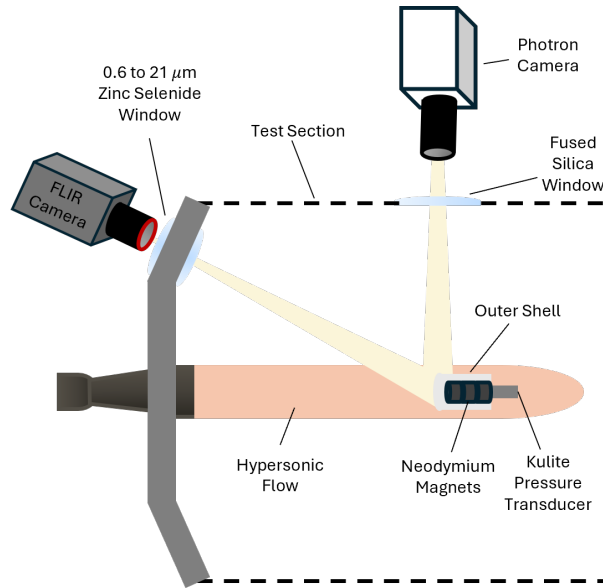


Fig. 3 Data acquisition setup used for free stream flow control observations.

A FLIR A8581 camera system equipped with a lens f-number of 2.5 and a wavelength range of 3.0 to 5.0 μm , was mounted outside the test section at an acute angle to the centerline of the blunt surface for infrared data acquisition. The Zinc Selenide window used in front of this camera had a wavelength range of 0.6 to 21 μm , allowing IR wavelengths to pass through. An ambient starting temperature of 21° C and a camera range of 10 – 90 °C at a capture rate of 30 Hz allowed for observation of the surface heating for each of the 500 ms test durations. A linear temperature scale across this set range provides consistent color gradients throughout testing. Post-normal shock stagnation pressures were recorded by the DAQ system using a Kulite pressure transducer.

III. Results

A. High Speed Imaging

The images provided in Fig. 4 highlight the visible radiation of three different time steps for both the magnetic and non-magnetic test cases. The first image represented on the left corresponded to a tunnel operating time of $t_0 = 300$ ms. Subsequent images increase in increments of $\Delta t = 100$ ms, for both the magnetic (top) and non-magnetic (bottom) cases. Both rows of images showed no major variation in intensity or shock structure despite unsteadiness in the surrounding flow, thus allowing for a time-averaged analysis and comparison of the MHD effects caused by the magnetic and non-magnetic models.

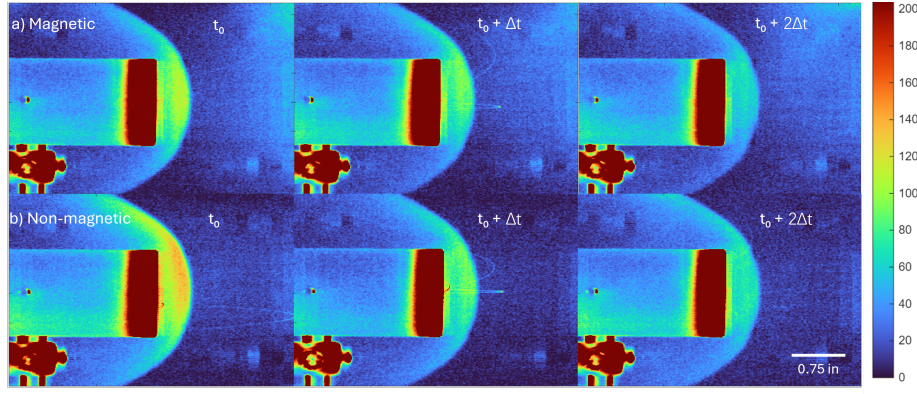


Fig. 4 Three high speed camera images from two separate tests, the top images being the magnetic case and the bottom images being the non-magnetic case, with t_0 and Δt being 300 ms and 100 ms respectively.

These two test cases, magnetic and non-magnetic, were chosen to investigate the effect the magnetic field has on ionized argon gas (Ar). Illustrated in Fig. 5 are time-averaged images from $t = 300$ ms to $t = 500$ ms for both the magnetic case (left) and the non-magnetic case (right). Both images had sufficient contrast and intensity for comparisons to be made.

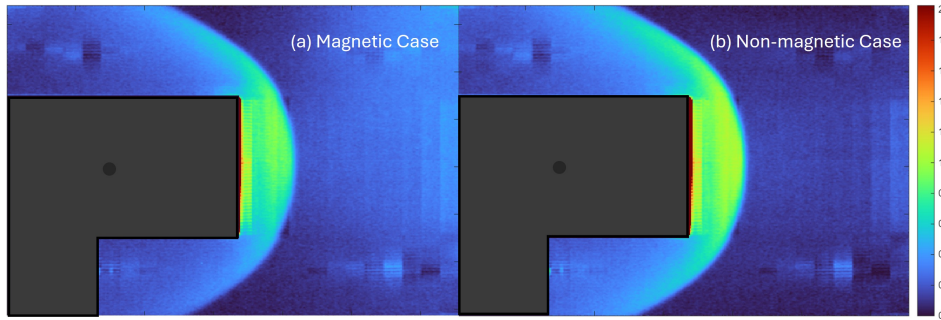


Fig. 5 (a) Time-averaged image from $t = 300$ ms to $t = 500$ ms for magnetic test case. (b) Time-averaged image from $t = 300$ ms to $t = 500$ ms for non-magnetic test case.

In both cases, a clear bow shock boundary was visible, marked by the sharp intensity drop-off seen in the images.

During the selected time range, the magnetic case had a lower overall intensity when compared to the non-magnetic case, as seen in Fig. 6.

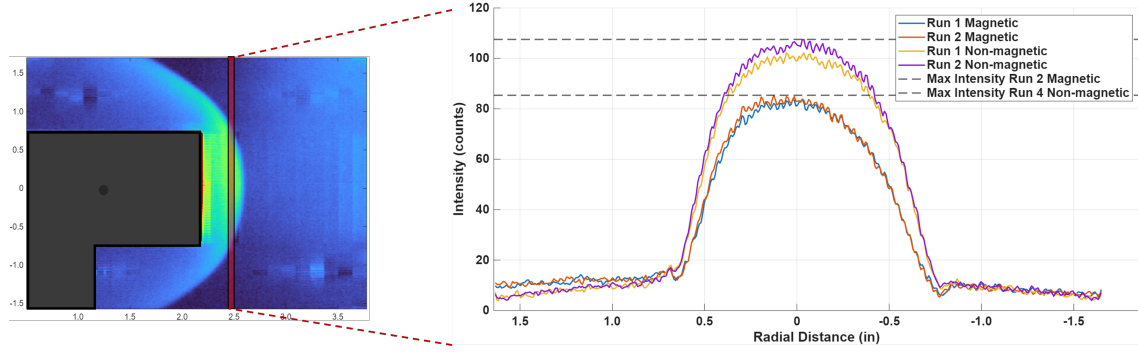


Fig. 6 Post-normal shock intensity vs radial position of both magnetic and non-magnetic tests in the highlighted region of the MHD image.

A numerical analysis was performed to obtain all intensity values in a defined region, as presented in Fig. 6, in the form of intensity vs. radial position, with the 0-inch position representing the centerline of the blunt body. The non-magnetic case was observed to have a 25.94% higher intensity value. Despite no noticeable change in shock standoff distance between the two test cases, a discrepancy was measured in the emission intensity behind the shock front that can suggest minor impacts from the induced magnetic field on the surrounding flow.

B. Infrared FLIR Imaging

IR images were acquired at an acute angle to the front of the sample to investigate surface heating in both magnetic and nonmagnetic cases. The selected frame rate allowed for time-resolved tracking of the surface heating throughout each test duration. Post-processing was performed to refine the images shown in Fig. 7, with the top and bottom rows of images representing the non-magnetic and magnetic case respectively.

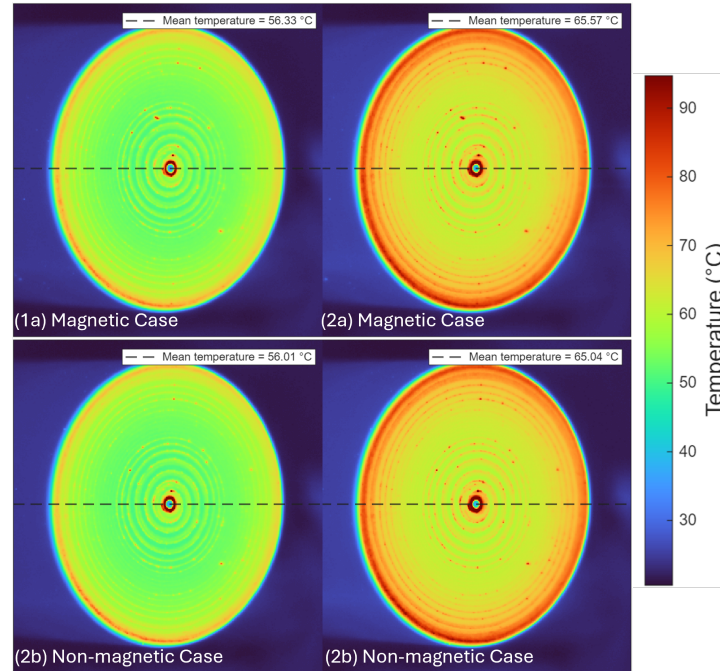


Fig. 7 (1a) and (2a) FLIR images of magnetic case at $t = 330$ ms and $t = 463$ ms respectively. (1b) and (2b) FLIR images of the non-magnetic case at $t = 330$ ms and $t = 463$ ms, respectively.

Both test cases showed localized maximum heating that exceeded 90 °C at the edges of the centerline hole, where heat transfer was expected to be greatest due to the higher effective surface area in this region. The next local maxima were along the outer edges of the leading surface, where the shock front was closest to the material surface. Uniform surface heating was seen in both the magnetic and non-magnetic cases. High intensity regions could be seen scattered throughout each sample; these locations corresponded to grooves made during the sample's machining process. No statistically significant temperature differences were observed between the two test cases.

C. Stagnation Pressure Measurements

Stagnation pressure was acquired for each test using a Kulite pressure transducer mounted on the sample's centerline. The acquired data for each of the two test cases was displayed below in Fig. 8. Both the non-magnetic and magnetic cases showed no major changes in stagnation pressure for all steady-state testing. The slower response rate seen by the non-magnetic test case was attributed to the model's configuration and was not a result of any MHD interaction. A noticeable pressure spike was observed at the start of each magnetic model run.

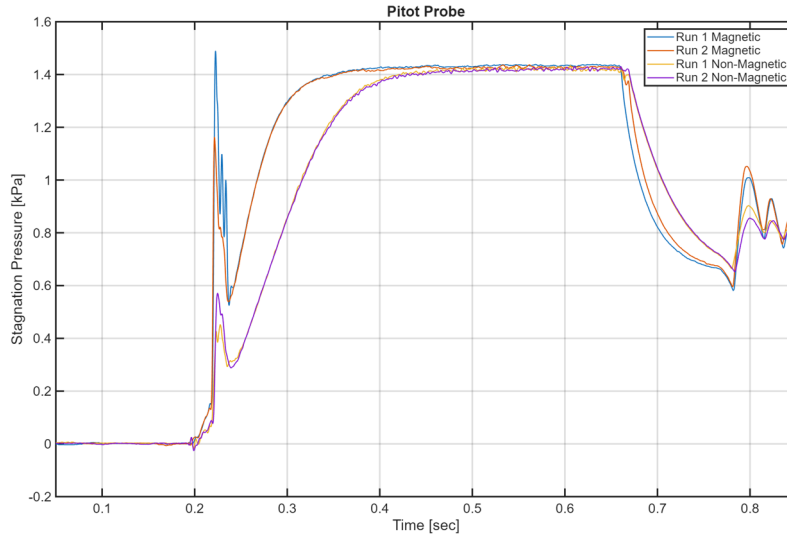


Fig. 8 Stagnation pressure measurements on the centerline of the MHD model for both magnetic and non-magnetic test cases.

These measurements allowed for the calculation of the free stream Mach number by using the ratio between the free stream stagnation pressure, p_s , and the plenum chamber stagnation pressure, p_o . The normal shock relation,

$$\frac{p_s}{p_o} = \left[\frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2} \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{(\gamma + 1)}{2\gamma M^2 - (\gamma - 1)} \right]^{\frac{1}{\gamma - 1}} \quad (1)$$

was applied to derive the Mach number. A specific heat ratio (γ) value of 1.67 for Argon gas was used with the p_s/p_o ratio of 0.0159, which corresponded to a Mach number of $M = 10.94$.

IV. Conclusion

An MHD flow control investigation was performed in the TennHET arcjet facility to observe a magnetic field's effect on pressure, surface heating, and post-normal shock intensity. The high enthalpy Mach 11 argon flow, when paired with a magnetic model, reduced the post-normal shock intensity by 25.94%. Both the magnetic and non-magnetic temperature and pressure data did not show significant deviations from one another.

Discrepancies in expected and actual test results can likely be attributed to facility setup and capabilities. Previously successful tests, such as that in [4], utilized a non-conductive lower Mach number nozzle to prevent a significant reduction in the number densities of ions during the expansion phase. The brass nozzle used in these experiments is both conductive and designed to produce Mach 6 conditions with a working gas of air, which leads to much more rarefied flow conditions ($M = 10.94$) with a pure argon working gas. On top of the highly conductive nozzle materials, the

stainless steel test section also served as a conductive body to dissipate charged particles. Therefore, the high Mach number observed in the flow and the existing facility setup is unlikely to produce electron densities close to 3.5 %, the amount that a previous experiment proved to be sufficient to observe an MHD interaction in argon flow [2].

These three test characteristics were the major sources of error identified in this experiment. To pursue further MHD interactions, a new nozzle will be machined from fiberglass-reinforced nylon 6/6 to produce a lower Mach number and a less conductive surface. The existing nozzle produced free stream flow densities that were less than 0.4% of those in the plenum chamber. Decreasing the flow speed of the free stream to Mach 6 would result in a free stream density of 2.1% of the density of the plenum chamber, ideally increasing the MHD interaction in this region. An additional precaution to help limit the loss of charged particles from the flow would be to use Teflon sheets in the test section to cover any stainless steel surfaces and prevent the premature loss of charged particles from the flow. Attempts will also be made to change the delivered flow power in order to increase the electron density in the free stream to maximize the MHD interactions observed.

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