FEASIBILITY STUDY OF MHD CONTROL OF COLD SUPERSONIC PLASMA FLOWS

Peter Palm, Rodney Meyer, Andrew Bezant, Igor V. Adamovich, J. William Rich

Nonequilibrium Thermodynamics Laboratories
Department of Mechanical Engineering
The Ohio State University, Columbus, OH 43210

and Sivaram Gogineni

Innovative Scientific Solutions, Inc., Dayton, OH 45440

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Abstract
The paper presents preliminary results of an experimental study of MHD effects in low-temperature ionized supersonic flows. The main objective was to determine whether the Lorentz force produced in nonequilibrium plasmas can affect the supersonic flow separation and the intensity of turbulent fluctuations in the supersonic boundary layer. The results show that a combination of the transverse RF and transverse non-self-sustained DC discharges can be used for generation of stable ionization in supersonic flows and for sustaining transverse current to produce Lorentz force in the presence of the magnetic field. The results also show that plasma flow visualization can be used for straightforward diagnostics of separation of low-temperature supersonic MHD flows. Finally, the results show applicability of the use of miniature microphones for measurements of pressure fluctuations spectra in low-temperature supersonic plasma flows in the presence of electric and magnetic fields. The results have not shown any detectable effect of the Lorentz force on the supersonic flow separation or on the pressure fluctuation spectra since these preliminary measurements have been done at the fairly low electrical conductivity and transverse DC currents.

1. Introduction
The use of magnetohydrodynamics for supersonic flow control, supersonic air-breathing propulsion, and for development of novel hypersonic ground testing facilities has recently attracted considerable interest [1-5]. The most serious challenge in developing these applications is creating and sustaining electrical conductivity in the airflow sufficient to produce substantial MHD effects. The conductivity required to produce significant changes in the flow enthalpy can be estimated from the magnetic interaction parameter,

1 Copyright ©, American Institute of Aeronautics and Astronautics. All rights reserved
2 Post-Doctoral Researcher, Member AIAA
3 Undergraduate Research Assistant, Student Member AIAA
4 Post-Doctoral Researcher
5 Associate Professor, Department of Aerospace Engineering and Aviation, Associate Fellow AIAA
6 Ralph W. Kurtz Professor, Associate Fellow AIAA
7 Associate Fellow AIAA
\[
I = \frac{\text{Lorentz force}}{\text{Inertia force}} = \frac{\sigma B^2 L}{\rho U} \sim 1, \quad (1)
\]

where \( B \) is the magnetic field, \( L \) is the length of the MHD channel, \( \rho \) is the flow density, and \( U \) is the flow velocity. Assuming \( B \sim 10 \) T, \( L \sim 1 \) m, \( \rho \sim 0.01-0.1 \) m\(^3\) (for a room temperature flow at \( P \sim 0.01-0.1 \) atm), and \( U \sim 1000 \) m/s, one obtains \( \sigma \sim 0.1-1.0 \) mho/m. Recent experimental and computational results suggest that such values of electrical conductivity in low-temperature supersonic flows can be achieved using efficient nonequilibrium ionization methods, such as high-energy electron beams [6,7]. The above estimate also suggests that noticeable MHD effects in cold supersonic flows can be produced only using powerful, large-scale superconducting magnets. Indeed, Eq. (1) shows that for less powerful rare earth permanent magnets (\( B \sim 1.0-1.5 \) T) the required conductivity increases up to \( \sigma \sim 10-100 \) mho/m. However, this leaves open a possibility of using such low-cost, relatively lightweight magnets for supersonic flow control applications that may be realized at much lower values of the interaction parameter and consequently electrical conductivity. Qualitatively, such applications might include control of turbulent transition in the supersonic ionized boundary layer and supersonic flow separation control, which both critically affect aerodynamic drag and heat transfer on a hypersonic vehicle.

Boundary layer transition control seems to be a promising application of the MHD supersonic flow control concept, because relatively weak actuating forces are needed for instability control. The delay or acceleration of transition can be achieved by the suppression or enhancement of initial instability waves at the early stage of the boundary layer flows for the purpose of drag and heating reduction, or for the purpose of fuel mixing enhancement. Since the disturbance waves are initially very weak, their control by magnetic forces may require relatively weak electromagnetic fields and/or fairly low electrical conductivity in the gas flow. Similar qualitative argument can be suggested with regard to the flow separation control since the flow momentum in the vicinity of the separation and reattachment points is rather low and affecting it might not require a significant Lorentz force.

Recent modeling calculations using a high-order MHD / compressible Navier-Stokes flow code developed at UCLA [8] suggest that stability and transition in a hypersonic ionized boundary layer can be significantly affected by Lorentz force. These predictions are consistent with the experiments in a salt water turbulent boundary layer [9], which demonstrated the possibility of both reduction and amplification of the turbulence intensity by Lorentz force produced by permanent magnets. These results also show the need for an experimental study of the feasibility of a supersonic boundary layer control using MHD body forces, which constitutes a primary objective of the present paper.

2. Experimental
The experiments have been conducted at the supersonic nonequilibrium plasma wind tunnel facility at Nonequilibrium Thermodynamics Group. This facility generates stable, diffuse supersonic flows of nonequilibrium plasmas at \( M = 2-4 \), with run durations from tens of seconds to complete steady state [10-12]. Previously, the plasma wind tunnel has been used for studies of shock wave modification by nonequilibrium plasmas [10-12]. The schematic of the experiment is shown in Fig. 1. A high aspect ratio, rectangular cross section supersonic nozzle made of transparent acrylic plastic is connected to a gas supply system and to a 150 ft\(^3\) ballast tank.
pumped by a 150 cfm Stokes vacuum pump. The nozzle throat dimensions are 7 mm x 3 mm. To reduce the effect of the side wall boundary layers on the supersonic inviscid core flow, the side walls of the nozzle are slightly diverging at an angle of 1.5°. The nozzle cross section in the test section 10 cm downstream of the throat is 40 mm x 6 mm. During the wind tunnel operation, static pressure in the test section is monitored using a pressure tap in the nozzle side wall, as shown in Fig. 1.

Ionization in the supersonic test section (with electrical conductivity of 0.1-1.0 mho/m) is produced by a transverse RF discharge sustained between 24 mm x 5 mm strip copper electrodes embedded in the nozzle side walls 5 cm downstream of the throat, as shown in Fig. 1. Both RF electrodes are placed inside the C-shaped rectangular quartz channels flush mounted in the walls to prevent secondary electron emission, which would result in the discharge collapse into an arc. The RF electrodes do not extend to the top and bottom nozzle walls, which was done to prevent excessive flow heating and hot spot formation in the boundary layers. The RF voltage is applied to the electrodes using ENI 13.56 MHz, 600 W RF power supply. This allowed sustaining a stable, diffuse, and uniform transverse discharge in nitrogen and helium flows.

A 45 MGOe, 1.4 T, 2x2x1 in. Nd-Fe-B epoxy coated permanent magnet is flush-mounted in the nozzle side wall 1.5 cm downstream of the RF electrodes as shown in Fig. 1. The magnetic field measured on the magnet surface is 0.45 T (perpendicular to the surface). The magnetic field in the test section can be approximately doubled by placing a second magnet in the opposite nozzle wall. In the present study, a single magnet configuration was preferred since it provided optical access to the flow. A second nozzle of the same geometry is equipped with a non-magnetized Nd-Fe-B block of the same dimensions to provide reference data in the absence of magnetic field. Low-temperature plasmas produced by the transverse RF discharge are ideally suited for the use with these low-cost permanent magnets whose maximum operation temperature does not exceed 100° C.

The transverse DC electrical current in the supersonic flow pre-ionized by the RF discharge was sustained by applying a DC field (up to ~100 V/cm) to two copper electrodes flush mounted in the top and bottom nozzle walls, perpendicular both to the flow velocity and to the magnetic field direction, as shown in Fig. 1. At these conditions, the estimated reduced electric field does not exceed E/N~2.0⋅10^{-16} V⋅cm^2, which precludes self-sustained ionization by the DC discharge. In the present measurements, conducted at the relatively low RF power (50-100 W) the DC current density did not exceed ~0.1 A/cm^2, which corresponds to the conductivity of ~0.1 mho/m. The DC field was applied using two different power supplies available at the Nonequilibrium Thermodynamics Group. One of them (Thorn EMI 3000R) is current-limited at only 5 mA, while the other (Sorensen DCR 600 - 4.5 B) is capable of sustaining much higher currents, up to 1 A. The electrical conductivity of the flow can be considerably increased by raising the RF power. In our previously plasma wind tunnel experiments [11,12], the stable RF discharge in M=2-3 flows was sustained at RF powers up to 300 W.

Note that sustaining the transverse DC current using the external electric field has a significant advantage over the current induced by convective motion of electrons in supersonic ionized flows in magnetic fields. Indeed, the drift velocity of electrons in the DC discharges in N2 and He at E/N~1.0⋅10^{-16} V⋅cm^2 reaches 20-40 km/sec [13], while the convective flow velocity is only
0.5-1.0 km/sec. This fact significantly increases the $\mathbf{j} \times \mathbf{B}$ force for the same electrical conductivity. In the present experiment, this suggests a possibility of observing MHD effects similar to the ones predicted in the boundary layer of a high stagnation temperature hypersonic flow in the absence of external electric field [8], but at a much higher flow conductivity (100 mho/m compared with ~1 mho/m attainable at the present facility). In particular, the goals of the present study are to detect the effect of the MHD forces on (i) supersonic ionized flow separation and (ii) spectrum of turbulent fluctuations in a supersonic ionized boundary layer.

The present measurements have been done in helium and nitrogen at two plenum pressures of $P_0$=1/3 atm and 1 atm. These two gases are chosen primarily because they both produce an extended visible afterglow downstream of the RF discharge, which allows straightforward plasma flow visualization [10-12]. High-resolution still images of the flow, as well as movie clips, were taken by a Nikon digital camera. At plenum pressure of 1 atm, test section pressures were $P_{\text{test}}$=6 torr in nitrogen and $P_{\text{test}}$=8 torr in helium, indicating Mach numbers of $M$=3.8 and 4.0, respectively. At $P_0$=1 atm, the steady flow in nitrogen is sustained for about 60 seconds, in helium for about 20 seconds. The estimated test section Reynolds numbers based on the distance from the throat are $Re_\infty$=10$^5$ and $Re_\infty$=10$^4$, respectively.

The pressure fluctuation spectra in the supersonic flows are measured using a miniature microphone located in a plastic tube recessed from the flow by 5 to 10 cm and an HP 35665A dynamic signal analyzer, as shown in Fig. 1. An attempt to place the grounded microphone flushed in the nozzle wall considerably improved the signal-to-noise ratio. However, in this case a rather significant current flowed between one of the DC electrodes and the microphone, thereby eventually destroying it. To avoid this problem, a grounded metal fitting was also placed in a plastic tube a few cm before the microphone. To prevent strong interference with the microphone signal, the RF electrodes were shielded using a grounded copper mesh. For the same reason, a 1 MHz high-frequency cutoff filter was placed between the microphone and the spectrum analyzer, which somewhat decreased the signal-to-noise ratio. The fluctuation spectra were averaged over 20 snapshot spectra taken by the spectrum analyzer during the run, which took 5-7 seconds.

3. Results and Discussion

3.1. Flow separation

As was mentioned in the previous section, the use of the transverse RF discharge to ionize the supersonic flows also produced convenient flow visualization technique. Figure 2 shows steady-state $M$=4 flows of helium and nitrogen at $P_0$=860 torr and 730 torr, respectively, visualized by a 100 W RF discharge in the absence of both magnetic field and the transverse DC field. One can clearly see oblique shocks originating where the N$_2$ supersonic flow turns a corner. The oblique shocks in He flow are less distinct, primarily due to the higher viscosity.

At a lower stagnation pressure of $P_0$=1/3 atm in helium, the flow became unsteady after about 10 seconds due to the gradual rise of the back pressure (see Fig. 3) and partially separated from the nozzle walls, which was observed using the plasma flow visualization (see Fig. 4). The location of the flow separation points (upstream of the RF electrodes), as well as the reattachment points is clearly visible in Fig. 4. In particular, the location of the separation points is indicated by the extent of the bright visible glow upstream of the RF electrodes produced by the counterflow of
the plasma excited between the electrodes. As the back pressure rises during the run, the separation region size increases while the separation points are moving upstream toward the nozzle throat and the reattachment points are moving downstream (see Fig. 4). After about 50-55 seconds, the flow in the test section seizes to be supersonic and becomes completely separated, which can also be seen in Fig. 4.

The experiments also showed that the location of the flow separation points in the two nozzles of the same geometry (one with a non-magnetized Nd-Fe-B block, and the other with a Nd-Fe-B magnet) was different for the same flow parameters (helium, $P_0=250$ atm, RF discharge power 100 W, $t=50$ sec). Figure 5 compares the flow fields visualized by the plasma for these two cases. It can be seen that in the nozzle with the magnet the separation points are located further upstream from the RF electrodes.

To verify that this effect was not due to small differences in the nozzle geometry, we made three control runs using the same nozzle (with the magnet): (1) with only RF field turned on, (2 and 3), with both RF and DC field turned on. In cases 2 and 3, the bottom and the top DC electrodes were kept positive, respectively, i.e. the direction of the $j \times B$ force was reversed. Figure 6 compare frames taken from the movie clips for the runs (2) and (3), i.e. for the opposite directions of the Lorentz force, for the same moment $t=52$ sec. Again, it can be seen that the locations of the flow separation points (upstream of the RF electrodes) for these two runs are somewhat different. Obviously, there remains a possibility that this effect might be due to the run-to-run flow field variation. Additional experimental data are needed to completely rule this out.

The experiments with the combined transverse RF and transverse DC discharges showed that both discharges were diffuse and stable, with no sign of arc filaments. These measurements have been done using a high-current DC power supply (Sorensen DCR 600 - 4.5 B). A few bright sparkle-like spots visible across the face of the magnet in Fig. 6 were sometimes generated near small nicks and scratches in the epoxy coating of the magnet. Also, there was no visible interaction between the two discharges so that the current would flow between the RF electrodes and the DC electrodes. Leaving the negative DC electrode floating resulted in current flowing from the positive DC electrode downstream to the grounded ballast tank through the low-pressure flow region rather than to one of the powered RF electrodes upstream. In these runs, the measured DC current was 15-20 mA at the DC voltage of 100 V and the RF power of 100 W. Experiments with higher DC voltages and/or RF powers were postponed until the completion of the pressure fluctuation spectra measurements. These preliminary results suggest that a combination of the transverse RF and transverse non-self-sustained DC discharges can be successfully used for producing stable ionization of supersonic flows and sustaining transverse current to produce Lorentz force.

3.2. Pressure fluctuation spectra
In the present study, all pressure fluctuation spectra have been measured in the magnetic nozzle at the same stagnation pressure of $P_0=1$ atm since the steady-state flow run time considerably increases at high stagnation pressures. Figure 7 shows the measured amplitude of the pressure fluctuations in helium and nitrogen $M=4$ flows (in arbitrary units) as functions of frequency (with both DC and RF discharges turned off). One can see that in nitrogen, the high-frequency
fluctuation intensity is higher. This is expected since the Reynolds number is the nitrogen flow is higher than in helium by about an order of magnitude (mainly due to a much higher viscosity of helium). A similar result was observed comparing fluctuation spectra measured in argon and in helium.

Figure 8 shows the pressure fluctuation spectra in He and N₂ plasma flows ionized by the RF discharge, with and without DC discharge drawing the transverse current. These measurements have been done using a low-current DC power supply Thorn EMI 3000. Spectra for both DC discharge polarities, with high voltage applied to the top and to the bottom electrode, are shown. Switching the DC discharge polarity reverses the direction of the Lorentz force vector. It can be seen that the data show no detectable effect of the DC field on the spectra, which is not surprising, since the transverse DC current in both cases did not exceed 5 mA, which corresponds to a very low flow conductivity of ~0.01 mho/m. Our initial efforts to obtain similar results at higher DC currents using the high-current power supply (Sorensen DCR 600 - 4.5 B) were unsuccessful because of the rather high-intensity noise produced by this power supply in the external circuit (even at rather small currents of a few mA) and picked up by the microphone. Measurements at higher DC currents would require the use of a high-current, low-noise DC power supply.

During the progress of the experiments, better shielding of the RF electrodes greatly reduced RF interference with the microphone, which allowed measuring the pressure fluctuation spectra without using a 1 MHz high-frequency cutoff filter placed between the microphone and the spectrum analyzer. Figure 9 shows several pressure fluctuation spectra measured in a M=4 nitrogen flow without plasmas, (i) with the microphone recessed from the flow by a plastic tube about 10 cm long, (ii) with the tube shortened by 3 cm (both spectra taken with the cutoff filter), and (iii) with the cutoff filter removed. One can see that both shortening the recess tube and removal of the filter substantially increased the microphone signal intensity and greatly improved the signal-to-noise ratio.

The last series of measurements was done without the use of the cutoff filter. Figure 10 shows the pressure fluctuation spectra in M=4 nitrogen flows, with and without RF ionization and transverse DC current (again using a low-current DC power supply). Again, it can be seen that in this series there is virtually no difference between the spectra taken in the non-ionized flow, in the flow ionized by the RF discharge, and in the RF-ionized flow with the low transverse DC current of 3 mA. Further spectra measurements at higher DC currents, using a new high-current, low-noise DC power supply are planned in the immediate future. An encouraging conclusion inferred from the data of Figs. 8 and 10 is that in the present experiment the pressure fluctuation spectra measured by a microphone are not affected by either RF or DC discharges sustained in a strong magnetic field (with proper shielding). This shows applicability of the present method for further straightforward measurements of pressure fluctuations in low-temperature ionized supersonic MHD flows.

4. Summary
The present preliminary results suggest that a combination of the transverse RF and transverse non-self-sustained DC discharges can be successfully used for generating stable ionization of supersonic flows and sustaining transverse current to produce Lorentz force in the presence of
magnetic field. The results also show that nonequilibrium plasma flow visualization can be used for straightforward diagnostics of separation of low-temperature supersonic MHD flows. Finally, the results show applicability of the use of sensitive miniature microphones for measurements of pressure fluctuations spectra in low-temperature ionized supersonic plasma flows in the presence of strong electric and magnetic fields. These preliminary studies did not show any detectable effect of the \( j \times B \) force on the supersonic flow separation or on the pressure fluctuation spectra since so far the measurements have been done only at the fairly low electrical conductivity and transverse DC currents. Continuing these measurements using a high-current, low-noise DC power supply and a second Nd-Fe-B magnet to increase the magnetic field in the test section up to 1 T may well result in experimental observation of MHD effects on supersonic flow separation and intensity of turbulent fluctuations in supersonic ionized boundary layers.

5. Acknowledgements
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6. References
Figure 1. Schematic of the experiment
Figure 2. Photographs of steady-state supersonic flows in the test section (top, helium, $P_0=860$ torr, $P_{test}=8.1$ torr, $M=4.0$; bottom, nitrogen, $P_0=730$ torr, $P_{test}=6.0$ torr, $M=3.8$) visualized by a transverse RF discharge in the test section (RF power is 100 W, no magnetic field).
Figure 3. Test section static pressure as a function of time in nozzle 1 (without a magnet) and nozzle 2 (with a magnet). Helium, $P_0=250$ torr.

Figure 4. Photographs of an unsteady supersonic flow in the test section. Helium, $P_0=250$ torr, RF power = 100 W, with magnetic field
**Figure 5.** Comparison of the flow separation in the test section for the two nozzles of the same geometry. Helium, $P_0=250$ torr, RF power = 100 W, $t=50$ sec.

**Figure 6.** Comparison of the flow separation in the test section of the same nozzle (with the magnet), for different DC discharge polarities. Helium, $P_0=250$ torr, RF power = 100 W, $t=52$ sec. Left, bottom electrode is positive; right, top electrode is positive.
Figure 7. Pressure fluctuation spectra in $M=4$ helium and nitrogen flows without plasmas. Magnetic nozzle, $P_0=1$ atm.

Figure 8. Pressure fluctuation spectra in $M=4$ helium (left) and nitrogen (right) RF-ionized plasma flows with and without transverse DC current. Magnetic nozzle, $P_0=1$ atm.
**Figure 9.** Pressure fluctuation spectra in a M=4 nitrogen flow without plasmas for different signal collection approaches. Magnetic nozzle, $P_0=1$ atm

**Figure 10.** Pressure fluctuation spectra in M=4 nitrogen flows with and without RF ionization and transverse DC current. No high-frequency cutoff filter used. Magnetic nozzle, $P_0=1$ atm