EXPERIMENTAL MHD INTERACTION IN HYPERSONIC FLOW

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ABSTRACT

An experimental investigation on the effect of the MHD interaction with the plasma of the shock layer above a wedge immersed into a hypersonic argon flow was carried out with the Mach 6, partially ionized flow obtained from the high-enthalpy arc-heated wind tunnel of Alta-CPR (Pisa). The tests were conducted with total pressures of 0.65, 0.85, and 1 bar, and magnetic fields in the range of 0.15-0.35 T. The diagnostics included electrostatic probes on the model surface, an optical multi-channel analyser, and a fast shutter CCD camera. Due to the MHD interaction an increase of the shock distance from the body surface was observed, although the MHD interaction effect was reduced by the low conductivity of the plasma in the boundary layer above the test body surface.

1. INTRODUCTION

The use of MHD-interaction in the hypersonic flight has recently received an increasing interest: typically it is foreseen as a way to reduce the incoming surface heat flux on re-entry vehicles, modifying the fluid-dynamic field through strong magnetic fields, or for control of the shock wave position in the inlet of the thruster of a single stage to orbit (SSTO) vehicle. During the last few years several studies on the interaction of hypersonic flows with plasmas and with the MHD process have been performed (Bobashev, 2000 - Vuillermont, 2000 – Lineberry, 2001 – Borghi, 2004), regarding in particular the control of the fluid dynamic phenomena in the region between the shock front and the surface of the vehicle (Shang, 2001-2002). When flying at high altitudes and high speeds, the gas-dynamic bow-shock causes a compression and a strong heating of the gas with temperature reaching values over 10000 K. Close to the surface the temperature is sufficient to cause gas ionization, and to sustain a significant level of the MHD interaction process, when the magnetic flux density is of the order of 1 T. Hence it is conceivable to generate forces which can modify the fluid dynamic configuration and, for example, move the shock front away from the vehicle surface, causing a decrease of the thermal flux toward the wall and resulting in thermal protection of the vehicle.

The first experimental investigation on the MHD interaction at high velocities has been performed in the hypersonic wind tunnel of the TsAGI Institute near Moscow with air as operating gas (Bityurin, 2003 – Lineberry, 2003). A second investigation, supported by the Italian Space Agency (ASI), was performed in Italy, coordinated by the University of Bologna, and is described in this paper. The experiments were carried out in the hypersonic wind tunnel of Alta S.p.A. in Pisa using Argon as working fluid, due to the fact that Argon is a mono-atomic gas which is sufficiently ionized at the conditions reached in the wind tunnel.

2. THE FACILITY

Alta’s High-Enthalpy Arc-heated Tunnel (HEAT) is a pulsed hypersonic wind tunnel operative since 1996 (Scortecci, 1997-1998), that can produce Mach 6 flows in the low to medium Reynolds number range (10\(^{4}\)-10\(^{6}\)). In the wind tunnel settling chamber the gas is heated by means of an arc discharge powered by a 260 kW DC power supply and delivering arc currents up to 630 A with running times of 20-300 ms. Total specific enthalpies up to 6 MJ/kg can be reached, with stagnation pressures up to 9 bar. The gas heater can be operated with air, nitrogen, argon, CO\(_2\) in a pulsed or quasi-steady mode. One of two possible converging-diverging nozzles can be mounted at the end of the settling chamber with a typical core flow diameter of about 50 mm. The arc heater scheme is shown in Fig. 1.

![Figure 1. Arc heater scheme](image-url)
The flow characteristics are obtained by means of pitot probes (Passaro, 2001) provided with fast miniaturized piezo-resistive pressure transducers, and stagnation temperature probes, provided with fast coaxial thermocouples or thin-film gauges. The pressure in the settling chamber is measured by fast pressure transducers, while in the vacuum vessel by capacitive manometers. For all the pressure signals accuracies of about 3% are obtained. The flow total enthalpy can be estimated from the arc discharge power balance, or measured by the stagnation temperature probes in the test section. The total enthalpy error is ±5-10%.

### 3. TEST CONDITIONS AND EXPERIMENT SETUP

For the present activity the used gas was Argon (Ar) and a short Mach 6 conical nozzle with an effective exit test section of a diameter of about 50 mm, was designed and installed on the tunnel.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$I_{arc}$ [A]</th>
<th>$V_{arc}$ [V]</th>
<th>$M$</th>
<th>$p_{tot}$ [bar]</th>
<th>$H_{tot}$ [MJ/kg]</th>
<th>$T_{tot}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>618</td>
<td>76</td>
<td>5.72</td>
<td>1.02</td>
<td>1.41</td>
<td>2713</td>
</tr>
<tr>
<td>2</td>
<td>613</td>
<td>68</td>
<td>5.70</td>
<td>0.85</td>
<td>1.81</td>
<td>3483</td>
</tr>
<tr>
<td>3</td>
<td>610</td>
<td>60</td>
<td>5.68</td>
<td>0.65</td>
<td>2.10</td>
<td>4041</td>
</tr>
</tbody>
</table>

*Table 1. Flow characteristics in the settling chamber*

A series of ignition tests allowed to identify the best conditions for the arc discharge showing how, for all test conditions, the arc discharge voltage drop is below 100 V in Argon. Three typical test conditions were identified with total pressure ranging between 0.65 and 1 bar (see Table 1). Pressure fluctuations were observed for lower pressure levels due to the turbulent conditions created in the settling chamber, while the flow was steady for pressure levels greater or equal than 0.6 bar. The gas properties at the nozzle exit for the three test conditions are summarized in Table 2.

### 3.1. The model and magnetic circuit

A Macor® model was placed directly in front of the nozzle exit: the model shape is a ramp, inclined of a 12.5 deg angle with respect to the flow mean direction. Eight copper electrodes are buried flush on the ramp in order to short-circuit the Faraday component: a crucial point that has to be taken into account when designing an experiment on MHD interaction in low pressure plasmas is the high value assumed by the Hall parameter, due to the reduced collision rate between electrons and heavy particles.

In a two dimensional geometry, assuming the reference system shown in Fig. 3, where the gas velocity $u$ and the magnetic flux density $B$ lie on the $x$-$y$ plane, while electromotive force $u \times B$ is directed along the $z$-axis, the generalized Ohm’s law is:

$$ \mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) $$

where the conductivity tensor, in the two dimensional geometry considered, has the following expression:

$$ \sigma = \frac{\sigma}{1 + \beta z^2} \begin{bmatrix} 1 + \beta z^2 & \beta z & \beta z & \beta z \\ \beta z & 1 + \beta z^2 & -\beta z & -\beta z \\ -\beta z & -\beta z & 1 & \beta z \\ \beta z & \beta z & -\beta z & 1 \end{bmatrix} $$

and:

$$ \beta_z = B_z/B = \mu_z B_z, \quad \beta = B_z/B = \mu_z B_z $$

Assuming then a velocity $u$ in the $x$ direction, and a $B$ field in the $y$ direction, and the Faraday component of the electric field $E_z$ equal to 0, Ohm’s law yields:
As a matter of fact, a Hall parameter higher than unity can easily impair the MHD interaction, as the conductivity is approximately reduced by a factor. So, in order to maximize the current density \( J \) and, consequently, the MHD body force, the current density \( J_x \) should be set equal to zero (i.e. imposing \( E_x = -\beta \mu B \)), thus obtaining the maximum Hall field.

Thus, it is possible, in principle, to experiment an adequate MHD interaction even in plasmas with a high Hall parameter. The electrode configuration was designed to exploit the Hall component of the current density in the plasma. Sets of electrostatic probes were placed on the test body surface, at the inlet and at the outlet of it, and between adjacent electrodes, in order to measure plasma characteristics on the surface.

An iron core magnet, placed within the vacuum chamber, created a B field roughly perpendicular to the test body surface exposed to the flow. The power for the magnet was supplied by a capacitor-inductance Pulse Forming Network which produces current pulses up to 5 kA for 5 ms, obtaining a magnetic flux density up to 0.35 T on the test body surface (Fig. 4).

\[
\begin{align*}
  j_x &= \frac{\sigma}{1 + \beta_x^2} (E_x + \beta_x u B) \\
  j_x &= \sigma E_x \\
  j_x &= \frac{\sigma}{1 + \beta_x^2} (-\beta_x E_x + u B)
\end{align*}
\]

3.2. Non-intrusive diagnostics

In order to study the MHD interaction, imaging of the shock by means of a fast shutter PCO SensiCam SVGA CCD camera was performed (Fig. 5).

Spectral intensities were observed by means of a 30 mm focal length collector focused at the nozzle exit on the flow axis. The collector was coupled with an Avantes optical multi-channel analyzer (OMA), with a resolution of 1.2 nm. In order to obtain signal significantly larger than noise, all spectra are the average of 10 exposures of 5 ms. Time resolved emission spectroscopy has been also performed by means of a Jobin Yvon monochromator with a coupled with a 460mm focal length and a focal ratio of F5.3.

4. Results

4.1. Hypersonic Plasma Flow

Assuming that the ionization may decrease on some extent during the expansion due to recombination, \( 10^{-5} \) would then be the maximum value of ionization degree one may expect to have in the reservoir. This electron concentration is however orders of magnitude higher than the equilibrium concentration that would be estimated in the reservoir at the measured temperature and pressure. These experimental data disagree with the common assumption that the plasma in the reservoir is in local thermodynamic equilibrium (LTE). These conditions are usually true for neutral mixtures, but for weakly ionized gases, especially in plasma jet expansion, non equilibrium conditions, produced in the discharge chamber, can survive along all the nozzle. In these conditions it is not possible to experimentally estimate the degree of non-equilibrium at the nozzle inlet, although it is reasonable to assume that the electron temperature in the discharge is much higher than the gas temperature and that metastable states are in equilibrium with the electron gas.

To investigate the phenomena described above, the quasi one dimensional model of the plasma expansion developed by the National Research Council (CNR) group of Bari was used (Colonna, 1998-2001-2003).

4.2. Spectroscopic Measurements

Spectroscopic observations were performed in the gas flow at the exit of the nozzle in front of the test body. The measurements were done by means of the optical multi-channel analyzer described above. The intensities of the lines of neutral argon (ArI) and of singly ionized argon (ArII) were detected. The Boltzmann plots of ArI and of ArII obtained from the measurements, when the
magnetic field is not present, are shown in Fig. 7, for test condition 1 ($p_{\text{tot}} = 1.02$ bar).

The presence of ionized argon is shown by the experimental observations. This confirms the assumption of non-equilibrium made in the previous paragraph. Indeed in the LTE assumption at the gas temperatures reached, ionization of Ar would be very low. Two different values of the population temperature ($T_p$) for ArI and ArII are obtained: $T_p = 1.86$ eV for ArI and $T_p = 1.36$ eV for ArII. This is in agreement with the electron energy distribution obtained from the CNR simulations: the predicted presence of a plateau between 15 and 20 eV is also observed in the determination of the ArI lines population temperature. This effect is less relevant for the population of the levels of ArII, which are at higher energies.

The time resolved measurement has been performed utilizing a monochromator 0.523nm bandwidth for all the lines except than for Argon II, which has been measured with a 0.342nm bandwidth. Light has been collected from the shock region at the position of the first electrode. By means of time resolved spectroscopy it is evident a changing in plasma properties when the B field is switched on. Argon I line intensity can both rise or being depressed, indicating a modification of the population levels. In Fig. 7, the emissions at 603 nm, 420 nm and 763 nm wavelength are shown. These emissions are caused by de-excitation from excited levels of 15.1 eV, 14.5 eV and 13.1 eV respectively. As can be easily noted, the emission caused by de-excitation with a higher upper level decrease when the magnetic field is on, while emission with a lower upper level increase. For Argon II the behaviour is different, seeming to indicate that there could not to be an influence of the magnetic field.
4.3. Shock front Imaging

In order to investigate the influence of the MHD interaction on the shock created by the test body in the argon flow at Mach 6, images of the shock with and without the magnetic field are compared. In Fig. 8 two images are superimposed: both images are obtained in condition 3 ($p_{\text{tot}} = 0.65$ bar), with $B = 0.35$ T for the shock with magnetic field. The MHD interaction causes a visible increase of the shock front angle.

![Figure 8. Superimposed shock images with and without magnetic field: $p_{\text{tot}} = 0.65$ bar, $B = 0.35$ T when used](image)

Figure 8. Superimposed shock images with and without magnetic field: $p_{\text{tot}} = 0.65$ bar, $B = 0.35$ T when used

In Fig. 9 the comparison regards test condition 2 ($p_{\text{tot}} = 0.85$ bar). In this case the increase of the shock front angle on the test body surface caused by the MHD interaction is less evident. However, when the magnetic field is on, at the leading edge of the ramp the shock appears to be much broader and the shock surface less defined.

![Figure 9. Images of the shock with and without magnetic field for test condition 2 ($p_{\text{tot}} = 0.85$ bar).](image)

Figure 9. Images of the shock with and without magnetic field for test condition 2 ($p_{\text{tot}} = 0.85$ bar).

4.4. Electrical Measurements

Hall voltages were measured between the 1$^{\text{st}}$ and the 8$^{\text{th}}$ electrode: the measured values are very low for all experimental conditions and the Hall voltage decreases when the magnetic field increases. By means of the electric probes the electric field on the ramp surface can be determined, as shown in Fig. 11 for condition 2 with a magnetic field of 0.25 T. Although a zero Faraday electric field should be expected, at all investigated conditions the Faraday field is different from zero. Plasma resistance was also measured: for test condition 2, the measured value was 0.8 k$\Omega$. Assuming a cross section of the plasma current of $5 \times 10^{-4}$ m$^2$ and a distance of 0.10 m from the upstream and the downstream electrode, a plasma conductivity of 0.20 S/m was derived.

![Figure 10. Hall voltages measured between the 1$^{\text{st}}$ and the 4$^{\text{th}}$ electrode.](image)

Figure 10. Hall voltages measured between the 1$^{\text{st}}$ and the 4$^{\text{th}}$ electrode

![Figure 11. Floating potential distribution on the test body surface for test condition 2 and $B = 0.25$ T.](image)

Figure 11. Floating potential distribution on the test body surface for test condition 2 and $B = 0.25$ T

5. DISCUSSION AND CONCLUSIONS

A new experimental campaign was conducted in Pisa with the aim to investigate about the MHD interaction effect on the flow field around a wedge immersed in a hypersonic flow. The experimental setup was defined in order to maximize the MHD effect obtaining the maximum possible Hall field. Nonetheless, a Faraday field different from zero was observed in all the
experimental conditions, indicating that the electrodes failed to shorten the electric field in the z direction, as shown in Fig. 11 by the diagonal pattern of the equipotential lines. At the same time, a relatively low Hall voltage was measured: as can be seen from Eq. 1, a Faraday electric field produces a decrease of the current density in the z direction, which is responsible of the MHD body force.

At the same time, the electrical conductivity, that was estimated on the basis of the measured electrical resistance of the plasma, with a 0.20 S/m value, is substantially different from the conductivity obtained from calculations, that is in the order of 10 S/m.

The mentioned disagreement may indicate that the boundary layer is constituted by a plasma with a low electrical conductivity. This layer would be responsible of the high resistance between the test body and the core flow. On the other hand, the low conductivity layer would also prevent the shortening of the Faraday component of the electric field, hence causing a reduction of the effect of the MHD interaction. These observations indicate that the MHD interaction is probably weakened by the effect of low conductivity of the plasma in the boundary layer of the test body.

Nonetheless, the experimental results show how the effect of the MHD interaction resulted in an increase of the shock distance from the body surface. The effect of the interaction was also observed by an array of electrostatic probes on the test body and a significant magnetic-field-derived variation in the ArI spectral lines was observed.

6. ACKNOWLEDGMENTS

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7. REFERENCES


