MAGNETOHYDRODYNAMIC FLOW NEAR A STAGNATION POINT

by

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SUMMARY

Some interaction effects of a plasma flowing around a blunt body in the presence of a strong magnetic field have been investigated. A one inch circular shock tube was used to provide the plasma during a testing time of approximately 30μsec. The required magnetic field strength was produced by discharging a 0.238 F electrolytic capacitor bank through a coil. The coil axis was parallel with the axis of the shock tube, generating a purely axial magnetic field of 60,000 Gauss, over a period of 4 msec, at the stagnation point. The blunt nosed model was a 3/8" d. hemishpere-cylindrical body made of lucite plastic and was mounted at the center of the coil.

Interaction effects of the plasma with the applied magnetic field have been observed in the form of an appreciable change in stand-off distance of the bow wave. The behaviour of the induced currents and the induced flux density have been examined by using three pick-up coils placed around the shock tube. This arrangement also made it possible to gain some more information about the available testing time and the values of the effective electrical conductivity of the argon plasma.

Calculations covering a shock Mach number range from 9 to 19 have been presented and a simple theory, was worked out for the particular magnetic field configuration.

The validity and the significance of the calculations and experiments are discussed together with some proposals for further work.
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FIGURES
NOTATION

a  speed of sound

v

velocity components in the r and \( \theta \) directions respectively

c  radius of spherical bow shock

x

d  shock tube diameter

y

e  unit vector

e_{r}, e_{\theta}, e_{\varphi}  unit directional vectors in spherical coordinates

f (r)  function of radial distance introduced by the velocity vector

f_{l} (x, r)  function of radial magnetic flux distribution due to unit axial magnetic flux density

f_{i} (x, r)  induced magnetic flux density due to unit induced current density

i  current

e  current density vector

kB  Boltzmann constant

k  Hall current parameter

l  half-length of coil

m  mass flow

mA  mass of argon atom

n  number of turns per meter of the coil

p  pressure

\[ \left( \frac{4L}{C} - R^2 \right)^{1/4} \]

q  radial coordinate of spherical coordinate system

rb  body radius

v
velocity vector

\( V_r, V_\theta \)
velocity components in the r and \( \theta \) direction respectively

\( x \)
shock tube length measured from diaphragm to test section

\( z \)
development distance of the boundary layer from shock wave to contact surface

\( A \)
area

\( B \)
magnetic flux density vector

\( B_0 \)
reference value of magnetic flux density

\( B_0 \)
absolute value of the applied magnetic flux density

\( C \)
capacitance

\( E \)
Electrical field intensity vector

\( E \)
voltage

\( F (R) = \frac{f(z)}{\sqrt{c^2}} \)
functions of Mach number defined in chapter (3.3.1)

\( F (M) \) and \( G (M) \)
functions of Mach number defined in chapter (3.3.1)

\( M_s \)
shock Mach number

\( N \)
total number of turns of the coil

\( L \)
Inductance in chapter II, or typical length in chapter III

\( P \)

\( = \frac{\varepsilon \rho}{\xi \sqrt{V^2}} \)
non-dimensional parameter associated with pressure on the body

\( -P (x) \)
total braking pressure in the x direction

\( Q_{in} \)
effective ion-neutral collision cross section

\( Q_{en} \)
effective electron-neutral collision cross section

\( R \)
resistance

\( Rem \)
magnetic Reynolds number = \( \sigma \mu \sqrt{L} \)
$S_c$ magnetic interaction parameter based on shock radius $c$

$S_s$ magnetic interaction parameter based on stand-off distance $\Delta$

$S_L$ magnetic interaction parameter based on a typical length $L$

$T$ absolute temperature

$T_{\text{max}}$ time to reach maximum current

$V$ fluid velocity parallel to axis of shock tube

$X, T$ similarity parameters introduced in (3.3)

$Z$ compressibility factor

$\alpha$ degree of ionization

$\beta$ ion slip coefficient $= 2 \omega_i \tau_i \omega_i \tau_i$ introduced in section (4.1) and (4.2)

$\gamma$ boundary layer parameter in section (3.3)

$\gamma = \frac{C_f}{C_v}$ ratio of specific heats

$d$ boundary layer thickness

$\varepsilon$ density ratio across standing bow shock $= \varepsilon_2/\varepsilon_3$

$\mu_0$ magnetic permeability

$\mu$ viscosity

$\nu$ mean collision frequency

$\rho$ density

$\tau_p$ Prandtl number

$\tau_0$ scalar electrical conductivity

$\tau$ testing time

$\tau_i$ ion collision period

$\tau_e$ time required to reach equilibrium

vii
mean electron collision period = \left[ \frac{1}{T_{e1}} + \frac{1}{T_{en}} \right]^{-1}

\omega_e

electron cyclotron frequency

\omega_i

ion cyclotron frequency

\Delta_0

stand-off distance without magnetic field interaction

\Delta

stand-off distance with magnetic field interaction

\phi

magnetic flux

\psi

ponderomotive force density

Subscripts

w

evaluated at the wall

s

evaluated at the shock

s_t

standard conditions: atmospheric pressure at 300°K

\{ \rho \}

spherical components

1

region ahead of the moving shock

2

region between the moving wave and the contact surface

3

region between bow wave and blunt body surface

(\_)_s

quantity right behind the shock

(\_)_n

quantity normal to the shock

(\_)_t

quantity tangential to the shock

(\_)_b

quantity evaluated at the body

[ ]

jump in quantity through shockwave (\_)_2 - (\_)_s
I. INTRODUCTION

The interaction between a hypersonic flow and a strong magnetic field has been the subject of a number of theoretical and experimental studies.

In Ref. 1 Kemp studied the problem in simple spherical geometry assuming a dipole magnetic field configuration and no conductivity ahead of the shock wave. The result of this paper and of the other papers quoted here, all indicate that the aerodynamic flow is modified. The effect of the magnetic field tends to reduce the stagnation point velocity gradient, to increase the stand-off distance and therefore to reduce convective stagnation point heat transfer. The same was suggested by Rosa (Ref. 2) Patrick (Ref. 3) and Resler and Sears (Ref. 4). Neuringer (Ref. 5) and Meyer (Ref. 6) concluded that the application of a magnetohydrodynamic interaction as a means to reduce surface heating can be of practical interest in air if there is a way to increase the electrical conductivity of the gas artificially or to apply extremely strong magnetic field strengths. In the experiment reported in this paper, argon was used as the test gas and a relatively high conductivity was obtained by heating the gas in a shock tube by strong shock waves. Since the ionization potential of argon is relatively low (15.7 ev) a high electrical conductivity may be obtained at reasonable shock Mach numbers.

By making use of a large electrolytic capacitor bank, and a compact coil, high field strengths can be obtained and in this way interactions of appreciable magnitude could be obtained.

For hypersonic flow over a blunt body, the Reynolds number is usually large, but the magnetic Reynolds number is small. The smallness of the magnetic Reynolds number, owing to a low value of the conductivity of the plasma and the small geometrical dimensions allows the assumption to be made that the magnitude of the magnetic field due to the induced currents is negligible compared to the imposed field. As a result, complicated wave propagation effects characteristic of magnetohydrodynamics at large magnetic Reynolds numbers do not enter into the problem.

The general features of the flow field can be seen in Fig. 1, in which the blunt body is sketched. Region 1 represents the undisturbed stationary argon gas, ahead of the shock wave. The strong shock wave travelling at supersonic speed \( M_s > 9 \) heats the argon in the region 2, and accelerates this test gas to supersonic speeds \( M_z \approx 2 \). This supersonic flow develops a stationary bow shock around the stagnation point at distance \( \Delta \). The high temperature, ionized shock layer 3 is the electrically conducting fluid upon which the magnetohydrodynamic forces are exerted. An axial magnetic field was selected for this experiment. In a shock tube, the gas is slightly conductive ahead of the bow wave and a radial magnetic field would interact with the plasma in this region 2. This is undesirable, because the available theories consider the gas in front of the bow shock to be non-conductive.
The axial magnetic field $B_0$ interacts with the radially moving plasma around the blunt nose of the body having a radius $r_b$. This sets up a circular electric field $(\mathbf{V} \times \mathbf{B})$ which, in the case of scalar conductivity, results in a circular induced current $\mathbf{j} = \sigma(\mathbf{V} \times \mathbf{B})$. These currents form closed loops around the axis of symmetry and react with the axial magnetic field to produce a reaction force or so-called body force $F = \mathbf{j} \times \mathbf{B}$ and this force has an inward component. The outward radial flow is impeded by this interaction and in consequence, the bow shock moves upstream.

A theoretical approach to the problem has been worked out, similar to the treatment by Kemp (Ref. 1) and Bush (Ref. 7). Both authors consider a magnetic flux distribution resulting from a dipole at the center of the body. In the present problem, a purely axial and constant magnetic flux distribution was considered. This allows the derivation of an approximate expression for the change in stand-off distance $\Delta$ as a function of the magnitude of a magnetic interaction parameter $S$.

II. EXPERIMENTAL ARRANGEMENT

2.1 Shock Tube

The 1" circular shock tube has been described in a previous UTIAS report (Ref. 8). The general lay-out of the shock tube and the experimental apparatus is sketched in Fig. 2, and Fig. 3 gives a general view of the control console and auxiliary equipment. The details indicated on these figures will be discussed in the present and following sub-sections of Section II.

The driver gas consisted of a combustible mixture of $\text{O}_2$ and $\text{H}_2$ diluted with He and was spark ignited. The diaphragm, made of Mylar, ruptures after combustion and a shock wave proceeds downstream in the channel gas (argon). The shock Mach numbers used in the experiments covered the range from 9 to 18.

The test section consisted of a 35" long heavy-wall Pyrex tube. The test model was a 3/8" lucite plastic hemisphere-cylindrical body supported by a long rod fixed at the end of the shock tube. Figure 4 shows a close-up of the test section. In order to avoid the effects of reflected shocks during the testing time, the shock tube was extended an additional 14". Figure 5 is a schematic cut-away view of the test section. Since the coil covers most of the interaction region, a periscope consisting of two mirrors at 45° angle was used for viewing the interaction region. However, this optical system necessitates an asymmetric position of the shock tube with respect to the surrounding field coil, which has to be accounted for in the magnetic flux distribution.

2.2 Capacitor Bank

The capacitor bank consisted of 600 high quality electrolytic capacitors rated at 3580 µF. and 350 VDC each, (manufactured by Johnson Mallory Ltd.).
Figure 6 shows the internal arrangement of these units. Each symbol in Fig. 6 represents a block of 20 units connected in parallel. A combination of 30 identical blocks connected in series-parallel, as shown in Fig. 6, gave a total capacitance of 0.238 F. The total energy stored at 1000 volt is 118,000 Joule. A breakdown of a single unit in the bank could release all energy stored in the blocks to which it belongs. The energy stored in ten blocks at 1000 volt is about 40,000 Joule. The release of such an amount of energy in a small volume could damage the capacitor bank. To prevent the disastrous consequences of the bank discharging into a faulty capacitor, a number of fuse types were investigated for protection purposes. However, none were found to be capable of providing adequate reliability. Instead, a solution has been adopted in which the bank is subdivided into three parallel groups, as seen in Fig. 6. These three sections are electrically separated during energy storage. The coil is connected to the three sections simultaneously by using a three pole switch of the simple type used for heavy duty in power lines. In case of failure of a single element only 1/9th of the total bank energy i.e. 13,000 Joule will be dissipated in the faulty element. Such energy release has been found to be non-destructive.

The quality of the electrolytic capacitors has been studied by examining the leakage current of the units. Figure 7 shows a plot of the leakage current versus voltage and also as a function of time after applying the voltage. It indicates that the leakage current sharply increases above 250 volt, so providing a favorable effect in smoothing out the unequal voltages across a series group, especially at the higher voltage level. The time factor turned out to be very important in charging the capacitor bank. The electrolytic capacitors need a certain time to build up the oxide layers and only when the saturation point was reached did the leakage current drop to negligible values (see Figure 7). The initial leakage rate for the entire capacitor bank was 500 mA which dropped to 250 mA after 15 min. For this reason, a separate power supply was built to maintain the capacitor bank at 120 volt, when not in use. The maintaining power supply consisted of 3 separate dry battery chargers. Figure 8 shows a block diagram of the capacitor bank, power supplies and safety devices.

The main power supply for the bank is 1.5 KW Sørensen power supply which charges the capacitor bank through three separate lines as shown in Figure 8. A series-parallel combination of 9 silicon diodes (type IN1084 M-500 PIV 400 volt) was inserted in the three feeding lines to protect the capacitor bank in case a faulty capacitor shorts in one of the three sections. In this way, complete isolation exists between the three sections during the charging of the capacitor bank. Also sketched on Fig. 8 is an emergency device consisting of 9 heater resistors into which the energy stored in the bank can be dissipated safely.

2.3 Field Coil

The main concern in designing the field coil was the need to obtain a very strong axial magnetic flux density, which in turn required very large peak currents. To simulate the condition for quasi steady magnetic field, the
time during which the peak current flows in the field coil should be long enough in comparison with the available testing time. This consideration puts a lower limit on the period of the discharge. By designing the discharge circuit, such that the effective resistance is slightly smaller than the critical resistance, \( R_{\text{critical}} = 2\sqrt{L/C} \), the discharge is underdamped. This design gave a satisfactory solution to obtaining large peak currents for a reasonable length of time. All these considerations led to the following coil configuration:

- \( N = 225 \) turns in three layers of 75 turns each
- \( L = 4 \times 10^{-4} \text{H} \)
- \( R_t = 0.034 \Omega \)
- \( l = 47 \text{ cm} \)
- \( T = 60 \text{ msec} \)

The exact parameters and overall behaviour of the capacitor-coil circuit were examined and determined by studying the discharge current recordings. Figure 9 shows some typical current traces (top trace) versus time. By a method of trial and error, the exact parameters were found to match both the experimental results and the theoretical expressions. Starting from the differential equations for an \( R-L-C \) circuit:

\[
L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt = E
\]  
(2.1)

The expression for the current can be derived to be

\[
i(t) = \frac{2E}{q} \exp \left[ -\frac{R}{2L} t \right] \sin \frac{q}{2L} t
\]  
(2.2)

where \( q = \left[ \frac{4L}{C} - R^2 \right]^{1/2} > 0 \)

The expression for the magnitude of the peak current becomes:

\[
I_{\text{max}} = \frac{2E}{q} \exp \left[ -\frac{R}{2L} T_{\text{max}} \right] \sin \left[ \frac{q}{2L} T_{\text{max}} \right]
\]  
(2.3)

where \( T = \frac{4\pi L}{q} \) gives the period of the oscillations and \( T_{\text{max}} = \frac{2L}{q} \arctg \frac{q}{2} \) gives the time to reach maximum currents.

The set of parameters which satisfy these expressions and the experimental results, are:

- \( q = 0.071 \)
- \( R = 0.052 \)
- \( L = 0.461 \text{ mH} \)
- \( C = 0.238 \text{ F} \)

Figure 10 shows the results for the calculated maximum current (bottom line) and the experimental data.

The magnitude of the magnetic flux density, resulting from the currents
flowing in the coil, can be calculated from the general law of Biot-Savart. However, owing to the asymmetric position of the shock tube with respect to the field coil, the theoretical expression becomes rather complicated. Ref. 9 gives the detailed values for the magnetic induction for any coil geometry. By making use of these data, the axial and radial components of the magnetic induction have been plotted in Fig. 11. The abscissa represents the non-dimensional distance $x/l$ along the coil, where $l$ indicates the half length of the coil, the ordinate represents the non-dimensional flux density $B/B_0$ where $B_0$ indicates the axial magnetic flux density at the center of the coil. The left half of the graph shows the magnitude of the axial magnetic flux density along the coil axis for two different coil geometries ($\beta = 10$ and $\beta = 5$) where $\beta$ indicates the ratio $l/a$, $a$ being the internal radius of the coil. However, since the shock tube is not coaxial with the field coil, an off-axis effect changes the magnetic flux distribution in the shock tube slightly. The magnitude of the axial magnetic flux density in the experimental set-up ($r/a = 0.5$) is shown on the right half of the graph for three different values for $\beta$. As will be discussed later the magnitude of the radial component of the flux density due to end effects, is very important and is shown on Fig. 11 for two different values of $\beta$. The stagnation point is indicated on Fig. 11 and at its position, an almost purely axial magnetic flux density exists.

2.4 Triggering and Synchronization Circuit

Figure 2 gives a schematic of the main discharge circuit. The triggering signal appears at the shunt voltage-divider, upon activation of the main switch. This pulse is retarded through a time-delay unit which feeds the delayed pulse into a thyatron pulse circuit. The time delay is adjusted to fire the shock tube when the discharge current is almost at its maximum value. This produces a slug of test gas entering the field coil at the time the flux density in the coil is at its maximum.

2.5 Measuring Devices

2.5.1: Current Measuring Resistor

To measure the very high currents produced in the discharge (10,000 Amp) a very small resistor made of Inconel tubing was placed in the main circuit (Figure 8). The value of the resistor was measured to be $0.000564 \Omega \pm 1\%$. Inconel was chosen for its relatively high specific resistance (98.1 $\Omega$/cm $^2$/cm) and extremely small temperature coefficient (0.00015 $\Omega$/cm $^2$/°C).

2.5.2: Hall Effect Device

Since conventional Gauss meters do not respond quickly enough to the transient magnetic flux density (16 c/sec), an axial Hall effect device, manufactured by Bell model 203) shown in Fig. 12, was placed inside the field coil and aligned with the axis of the coil.
The principle on which this device is based, is the Hall effect, which develops a potential perpendicular to both the current flowing in the semiconductor material and an externally applied magnetic field induction. The output voltage can be expressed as \( E_o = K_{HOC} \cdot (j \times B) \) where \( K_{HOC} \) denotes the open circuit Hall coefficient which is of the order of 0.1 volt/amp, Kilogauss. Owing to the non-linear behaviour at magnetic flux densities above 10,000 Gauss a calibration was carried out by comparison with a pick-up coil. Figure 9 shows two typical recordings of the output voltage from the Hall effect device (lower traces) in a discharge. The experimental results were plotted on Fig. 11.

2.5.3: Flow Pattern and Speed Recording

The shock speed was measured by using 2 ionization gauges (see Fig. 2) spaced 227 mm apart. A fast-rise circuit was built, to respond to the arrival of the shock at the two gauges. Both pulses were fed into a Tektronix oscilloscope through a CA plug-in unit. Typical recordings are shown in Figs. 25 and 25 and are discussed in Chapter 4.2. Several attempts were made to photograph the phenomena at the stagnation point. Owing to the small size of the mirrors of the periscope, the \( (x, t) \) recordings showed insufficient details and only stationary pictures could be taken. Figures 23, 24, 25, and 27 show examples of the flow pattern around the blunt body.

2.5.4: Search Coils

Three pick-up coils wound around the shock tube were used in most experiments.

Search coil I: 100 turn coil of 32 gauge wire, located at the stagnation point.

Search coil II: 10 turn coil of 26 gauge wire, wound on thin aluminum foil to avoid electrostatic pick-up and located halfway between search coil I and the upstream end of the field coil.

Search coil III: 10 turn coil of 26 gauge wire located at the entrance of the field coil.

All three search coils had a cross-sectional area of 8 cm\(^2\).

The output voltage from these search coils, is a measure of the change in total magnetic flux through the search coils. Since the applied magnetic flux density itself is oscillating, suppression or compensation of the low frequency output signal picked up by the search coils was necessary. Since this frequency (16 c/sec) is several orders of magnitudes smaller than the effective frequency of the change in induced flux densities during the available testing time of about 30 Kc/sec, a low frequency filter was used to eliminate the 16 c/sec signal. A variable L. C Filter (Model 2 AB ALLISON LAB.) was used in the experiment. The filtered signal is proportional to the change of the induced flux density \( (e_o = - NA \frac{dB}{dt}) \). To integrate this signal, an operational amplifier, with capacitance feedback was used. A type O plug-in unit of the Tektron-
nix oscilloscope was used for this purpose. Figure 2 shows the block diagram for this circuitry. Figures 24C and 25C show some typical recordings of the pick-up voltage and induced flux densities.

III. THEORETICAL CONSIDERATIONS

3.1 Parameters Governing the Magnetohydrodynamic Interaction

Two parameters are of primary importance in this study of magnetohydrodynamic flow around a blunt body. The magnitude of these parameters describes the nature of the interaction between conducting fluid and the magnetic field.

3.1.1 Magnetic Reynolds Number

This parameter indicates the strength of the coupling between the magnetic flux lines and the stream lines. Cowling (Ref. 10) derives the expression for the magnetic Reynolds number from a combination of Maxwell's equations and Ohm's law in the form:

\[ \text{Re}_m = \frac{\sigma \mu V L}{\mu} \]

where
- \( \mu \) = magnetic permeability
- \( \sigma \) = electrical conductivity
- \( V \) = velocity of free stream
- \( L \) = characteristic length

In order to have some idea of the magnitude of the magnetic Reynolds number in the experiment, the above expression has been calculated for the conditions in region 3 behind the standing bow shock. Extensive use has been made of the detailed calculations in Ref. 11 for the properties of high temperature argon. Figure 13 presents the scalar electrical conductivity for argon as a function of temperature and pressure. In the region behind the bow shock (region 3), the magnetic Reynolds number can be defined as:

\[ \text{Re}_m = \frac{\mu_0 \sigma_3 V_3 c_b}{\mu} \]

where \( c_b \) = radius of the blunt body as the characteristic length.

By making use of the continuity principle across the standing shock wave we can write:

\[ \text{Re}_m = \frac{\sigma_0 \sigma_3 V_2 c_b}{\mu} \]

where \( \sigma \) = density ratio across standing bow shock

\[ = \frac{c_2}{c_3} \]

This quantity was plotted in Fig. 14 as a function of shock Mach number and initial pressure. From Fig. 14, we can conclude that the magnetic Reynolds number is sufficiently small such that the magnetic field at any point in the flow can be calculated as though it was due only to the currents flowing in the field coil.
3.1.2: Magnetic Interaction Parameter

The most important parameter used throughout this paper is the ratio of the characteristic magnetohydrodynamic body force density in the radial direction and a pressure gradient based on the free stream dynamic pressure distributed over the stand-off distance.

In a general form, the magnetic interaction parameter can be expressed as

\[
S_L = \frac{\sigma V B^2}{\rho V^2/L} = \frac{\sigma B^2 L}{\rho V} \tag{3.1}
\]

where

- \( \sigma \) = electrical conductivity
- \( B \) = magnetic induction
- \( L \) = characteristic length
- \( \rho \) = density
- \( V \) = free stream velocity

In order to have a substantial exchange of momentum between the magnetic field and the flow, this parameter must at least be of the order of unity.

In the experiments, the magnetic flux lines are mainly axial, and no magnetic interaction can be expected in an axially moving plasma, as is the case in region of upstream of the standing bow shock. When the argon gas passes through the standing bow shock, the electrical conductivity increases and the fluid picks up a radial velocity component, and an interaction occurs. The axial magnetic flux can act upon the plasma over a length approximately equal to the stand-off distance \( \Delta \) of the bow shock. For this reason, it is more significant to define an interaction parameter based on the stand-off distance \( \Delta \) as follows:

\[
S_S = \frac{\sigma_3 B_0^2 \Delta V_{t3}}{\rho_2 V_2^2} \tag{3.2}
\]

In order to estimate the unknown quantities, \( \Delta \) and \( V_{t3} \), the continuity equation across the standing bow wave can be used:

\[
\rho_2 V_2 V_t^2 \approx 2 \pi \rho_b \Delta V_{t3} \rho_3 \tag{3.3}
\]

and after substitution in equation (3.2) we get

\[
S_S = \frac{\sigma_3 B_0^2 \rho_b}{\rho_3 V_2} = \frac{\varepsilon \sigma_3 B_0^2 \rho_b}{\rho_2 V_2} \tag{3.3}
\]

All terms in this expression can be calculated from the data in Ref. 11, and Fig. 15 presents a plot of the magnetic interaction parameter \( S_S \) based on stand-off distance and scalar electrical conductivity as a function of a shock Mach number and initial pressure. The graph is calculated for a steady
axial flux density of $6 \text{ Wb/m}^2$ and for a blunt body having a nose radius of 3/16".

The shape of the curves of Fig. 15 shows a maximum value for $S_s$ at $M_s \approx 9$. This maximum can be explained as the result of two counteracting effects in the expression for the parameter $S_s$. For $M_s < 9$, the scalar electrical conductivity increases with shock Mach number much faster than the free stream velocity $V_2$. For $M_s > 10$, the increase in free stream velocity $V_2$ outweighs the increase of scalar electrical conductivity $\sigma_3$.

3.2 Calculation of Stand-off Distance, in the Presence of a Magnetic Field

A theoretical approach to the problem, along the lines of the analysis given by Bush in Ref. 7, will be presented to study the flow field around a blunt body in the presence of an axial magnetic field.

3.2.1 Basic Assumptions

a) The flow field near the stagnation point is analyzed for a spherical, detached shock, with the same center of geometry as the blunt body. The analysis will be performed by assuming only the existence of a spherical shock wave. At the end of the analysis, a blunt body size will be chosen and located to match the existing flow field behind the standing bow shock.

b) The magnetic induction is axial and uniform over the interaction region. The validity of this assumption has been discussed earlier. The field is mainly axial (see Fig. 10) and is constant ($\text{Re}_m < \mathcal{O}(1)$).

c) Heat conduction and viscosity are neglected since the Reynolds number, based on the body radius, is of the order of $3 \times 10^4$. In the free stream the fluid is considered to have a uniform velocity $V_2$ parallel to the axis of the shock tube.

d) Behind the bow shock, the Mach number may be expected to be very small near the nose of the blunt body, and the approximation of a constant density is used.

3.2.2 Steady State Magnetohydrodynamic Equation

The basic equations for magnetohydrodynamic flow can be written as:

**Equation of continuity:**

$$\nabla \cdot \vec{V} = 0 \quad (3.4)$$

**Momentum equation:**

$$\rho \left( \nabla (\nabla \cdot \vec{V}) + \nabla \phi + \sigma_3 \left[ \left( \nabla \times \vec{B} \right) \times \vec{B} \right] \right) \quad (3.5)$$

By taking the curl of the momentum equation, we can eliminate the pressure gradient term:

$$\rho_3 \left[ \nabla \times (\nabla \cdot \vec{V}) \right] = \sigma_3 \left[ \nabla \times [\nabla \times \vec{B}] \times \vec{B} \right] \quad (3.6)$$
This can be rewritten by expanding the term \((\nabla \cdot \nabla) v\):

\[-\varepsilon_3 \left\{ \nabla \times \left[ \nabla \times (\nabla \times \nabla) \right] \right\} = \sigma_3 \left\{ \nabla \times \left[ \nabla \times \mathbf{B} \right] \times \mathbf{B} \right\} \quad (3.7)\]

### 3.2.3: Boundary Conditions

All boundary conditions will be fixed at the spherical bow shock. The boundary conditions for the magnetic field can be derived from Maxwell's equations. (Ref. 12). The component of the magnetic field normal to the shock at the shock front is continuous:

\[\left[ \mathbf{B} \cdot \right] = 0 \quad (3.8)\]

If the current density parallel to the shock front does not become infinitely large, which is the case for small magnetic Reynolds numbers, and if the magnetic permeability in the free stream is that of the fluid in the shock layer, the component of the magnetic field tangential to the shock at the shock front is continuous:

\[\left[ \mathbf{B} \times \right] = 0 \quad (3.9)\]

The expressions for the components of the fluid velocity at the shock have to satisfy the equations of continuity and momentum, which govern the jump across the wave:

\[\left[ e V_n \right] = 0 \quad (3.10)\]
\[\left[ V_t \right] = 0 \quad (3.11)\]
\[\left[ e V_n^2 + p \right] = 0 \quad (3.12)\]

Since the magnetic flux lines are continuous across the shock (Eqs. 3.8 and 3.9), the velocity and pressure jumps at the shock wave (Eqs. 3.10, 3.11 and 3.12) will satisfy the conventional gasdynamic relations without magnetic influence. Hence across a spherical shock, Eqs. (3.10 and 3.11) yield

\[V_S = -\varepsilon V_2 \cos \theta e_r + V_2 \sin \theta e_\theta \quad (3.13)\]

and Eq. (3.12) becomes:

\[p_S = p_2 + \varepsilon v_2^2 \cos^2 \theta (1 - \varepsilon) \quad (3.14)\]

### 3.2.4: Analysis

The problem will be treated in a spherical coordinate system, by introducing the three spherical unit vectors \(e_r, e_\theta, e_\phi\). The origin of
this system is fixed at the center of the standing shock wave. In this system
Eq. (3.4) becomes:
\[
\nabla \cdot \mathbf{V} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 V_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (V_\theta \sin \theta) = 0
\]
\[(3.15)\]

At this stage, it is convenient to introduce a solution for the fluid velocity as a
function of the radial distance \(r\) and angle \(\theta\). A solution should satisfy the
continuity equation: Eq. (3.15). At the same time, the radial and tangential com-
ponents of the velocity should be of the same functional dependence on \(\theta\) as
the radial and tangential components of the velocity at the shock wave in Eq.
(3.13). This allows us to equate the radial and tangential components separate-
ly. A solution which satisfies these conditions can be expressed as:
\[
\mathbf{V} = \left[ \frac{f(r)}{r^2} \cos \theta \right] \mathbf{e}_r - \left[ \frac{f'(r)}{r} \sin \theta \right] \mathbf{e}_\theta
\]
\[(3.16)\]

where \(f(r)\) indicates a function of the radial distance and \(f'(r)\) stands
for: \(\partial f(r)/\partial r\). Since we are interested primarily in what happens
on the axis of symmetry, we make the assumption of small angles, which
allows us to write:
\[
\cos \theta \approx 1 - \frac{\theta^2}{2} \quad \quad \quad \theta \sin \theta \approx \theta
\]

and terms of \(\theta^3\) and higher will be neglected. Equation (3.16) can then
be rewritten in simplified form:
\[
\mathbf{V} = \left[ \frac{f(r)}{r^2} \left(1 - \frac{\theta^2}{2}\right) \right] \mathbf{e}_r + \left[ - \frac{f'(r)}{r} \theta \right] \mathbf{e}_\theta
\]
\[(3.17)\]

The left hand side of Eq. (3.7) can be worked out in spherical coordina-
tes, and by substituting Eq. (3.17) the result is:
\[
+ e_3 \left\{ \nabla \times [\mathbf{V} \times (\nabla \times \mathbf{V})] \right\} = \left\{ \frac{2 e_3 f(r) \theta}{r^3} \left[ f''(r) - \frac{2 f'(r)}{r} - \frac{2 f(r)}{r^2} \theta^2 \right] \right\} \mathbf{e}_\gamma
\]
\[(3.18)\]

The uniform, axial magnetic induction can be expressed in spherical coordinates
as:
\[
\mathbf{B} = - B_0 \cos \theta \mathbf{e}_r + B_0 \sin \theta \mathbf{e}_\theta
\]
\[(3.19)\]
or at smaller angles:
\[
\mathbf{B} = - B_0 \left(1 - \frac{\theta^2}{2}\right) \mathbf{e}_r + B_0 \theta \mathbf{e}_\theta
\]
\[(3.20)\]
The right hand side of Eq. (3.7) can be worked out in spherical coordinates and by substituting Eqs. (3.19), (3.20) and (3.17) we get:

\[ \nabla \times \left[ (\nabla \times B) \times B \right] = \left\{ \frac{\epsilon_0 B_0^2}{\eta} \left[ f''(\eta) - \frac{4 f'(\eta)}{\eta} + \frac{\gamma f(\eta)}{\eta^2} \right] \right\} \cdot \nabla \varphi \]

(3.21)

By equating Eqs. (3.18) and (3.21), the curl of the momentum equation becomes:

\[ \frac{2 \rho_3 f(\eta)}{\eta^2} \left[ f'''(\eta) - \frac{2 f''(\eta)}{\eta} - \frac{2 f'(\eta)}{\eta^2} + \frac{2 f(\eta)}{\eta^3} \right] + S_c B_0^2 \left[ f''(\eta) - \frac{4 f'(\eta)}{\eta} + \frac{\gamma f(\eta)}{\eta^2} \right] = 0 \]

(3.22)

The following non-dimensional variables can be defined by taking the radius of the bow shock \( C \) as reference length:

- non-dimensional radial distance: \( R = \frac{r}{c} \)
- density ratio across standing bow shock \( \xi = \frac{\rho_2}{\rho_3} \)
- non-dimensional function of radial distance: \( F(R) = \frac{f(r)}{V_2 C^2} \)
- magnetic interaction parameter based on shock radius: \( S_c = \frac{\xi \xi C_2 B_0^2}{\rho_2 V_2} \)
- non-dimensional parameter associated with the pressure on the body: \( P = \frac{\xi P}{\rho_2 V_2} \)

Equation (3.22) then can be written:

\[ \frac{2 f(R)}{R^2} \left[ f''(R) - \frac{2 f'(R)}{R} - \frac{2 f(R)}{R^2} + \frac{2 f(R)}{R^3} \right] + S_c \left[ f''(R) - \frac{4 f'(R)}{R} + \frac{\gamma f(R)}{R^2} \right] = 0 \]

(3.23)

This is a third order non-linear differential equation which governs the flow around the body in the presence of an applied magnetic induction \( B_0 \). Now the boundary conditions must be re-expressed in terms of the new variables.

Equation (3.7), as a function of the non-dimensional parameters, becomes:

\[ V(R) = V_2 \left[ \frac{2 f(R)}{R^2} \left( 1 - \frac{\Theta^2}{e} \right) \right] e_r - V_2 \left[ \frac{f'(R)}{R} \theta \right] e_\theta \]

By evaluating this expression at the bow shock for \( R = 1 \) the following equation results:

\[ V(1) \equiv V_s = V_2 \left[ \frac{2 f(1)}{R} \left( 1 - \frac{\Theta^2}{e} \right) \right] e_r - V_2 \left[ f'(1) \theta \right] e_\theta \]
By comparing this equation with Eq. (3.13), two velocity boundary conditions can be derived:

\[
F(I) = - \frac{\varepsilon}{2} \quad (3.24)
\]

\[
F'(I) = - 1 \quad (3.25)
\]

In order to arrive at the third boundary condition, the \( \partial \) momentum equation at the shock can be expressed in spherical coordinates:

\[
\left( V_n \frac{\partial V_\theta}{\partial \theta} + \frac{V_\theta}{r} \frac{\partial V_\theta}{\partial \theta} + \frac{V_\theta}{r^2} \right)_s = \left( - \frac{1}{\varepsilon^2} \frac{\partial P}{\partial \theta} \right)_s + \left[ \left( \frac{B_0}{\varepsilon^3} \right) (V_n B_\theta - V_\theta B_n) \right]_s
\]

By using Eqs. (3.19) and (3.20) to evaluate \( B_r \) and \( B_\theta \), and by substituting Eq. (3.17) in the expression above, the following equation can be derived:

\[
\left\{ - \frac{2 f(r) f''(r) \partial}{r^2} + \left( \frac{f'(r)}{r} \right)^2 \right\}_s = \left\{ - \frac{1}{\varepsilon^2} \frac{\partial P}{\partial \theta} - \frac{c_B}{\varepsilon^3} \left[ \frac{2 f(r) \partial}{r} - f'(r) \right] \right\}_s
\]

By substituting the non-dimensional parameters as above, this becomes:

\[
\left\{ - \frac{2 F(R) F''(R)}{R^2} + \left[ \frac{F'(R)}{R} \right]^2 \right\}_s = \left\{ - \frac{1}{\theta} \frac{\partial P}{\partial \theta} - S_{\theta} \left[ \frac{2 F(R)}{R} - F'(R) \right] \right\}_s
\]

By evaluating this expression at the shock and comparing with Eq. (3.14), the third boundary condition becomes:

\[
F''(I) = S_{\theta} \left( \frac{\varepsilon - 1}{\varepsilon^3} \right) - \frac{1}{\varepsilon} \left[ 1 - 2 \varepsilon + 2 \varepsilon^2 \right] \quad (3.26)
\]

The equation of the curl of the momentum equation in non-dimensional form, Eq. (3.23), together with the three boundary conditions given in Eqs. (3.24), (3.25), and (3.26) can be solved numerically on a digital computer.

3.2.5: Solution and Results of Calculation

In the experiment, it was of interest to know the stand-off distance \( \Delta \). From the analysis in the previous section a simple expression can be derived to calculate the non-dimensional stand-off distance \( \Delta / z_b \). The radial component of velocity \( V_r \) can be expressed according to Eq. (3.17) in non-dimensional form:

\[
V(R) = \left[ \frac{2 V_z F(R)}{R^2} \right] \left[ 1 - \frac{\theta^2}{2} \right] \quad (3.27)
\]

From this expression, we notice that the radial component of velocity vanishes for the values of \( R \) which satisfy\( F(R) = 0 \). Thus, a sphere of this radius, to be
called $r_b$ is a body shape which is consistent with the spherical shock shape and with the flow conditions in the shock layer.

Hence the stand-off distance can be expressed as:

$$\Delta = \frac{c-r_b}{r_b} = \frac{1-R_b}{R_b} = \frac{1-R[F(R)=0]}{R[F(R)=0]}$$  \hspace{1cm} (3.28)

This expression has been programmed for the IBM computer 7090 of the University of Toronto. The results of the computation are presented in Fig. 16. The non-dimensional stand-off distance $\Delta/r_b$ was plotted versus the interaction parameter based on the shock radius ($S_c$) for different values of the density ration $\epsilon$. For the sake of comparison with the dipole solution presented by W. Bush (Ref. 7), the value of $\epsilon = 1/n$ was included in the calculation and plotted in Fig. 16. The dipole magnetic field gives rise to stronger magnetic interaction which shows up as a larger change in stand-off distance for the same value of the magnetic interaction parameter. This is so because the larger stand-off distance in the case of a magnetic flux distribution from a dipole corresponds to a more intense cross flow of magnetic field lines and fluid stream lines than in the case of an axial magnetic flux distribution.

Although the presentation of the stand-off distance $\Delta/r_b$, as a function of the magnetic interaction parameter $S_c$ (see Fig. 16) has commonly been used in the literature, it should be mentioned that this parameter $S_c$ is a function of the stand-off distance itself for a given body. It is preferable to introduce the parameter $S_s$ which is independent of stand-off distance, to bring out the dependence of the stand-off distance on the experimental parameters. The magnetic interaction parameter $S_s$, defined as $\epsilon \tau_{\text{f}} B_0^2 r_b/\rho \nu_2$, contains only quantities which can be calculated from the applied shock strength, initial pressure and temperature, body dimensions and the magnitude of the applied magnetic induction. The magnetic interaction parameter, based upon the shock radius

$$S_c = \frac{\epsilon \tau_{\text{f}} B_0^2 c}{\rho \nu_2}$$

is converted to the interaction parameter based upon the stand-off distance $S_s$ as follows:

$$S_s = S_c \frac{h_b}{c} = S_c \left[1 + \frac{\Delta}{r_b}\right]^{-1} = S_c R[F(R)=0]$$

The result of the replotting is presented in Fig. 17. The quantity becomes a double valued function of $S_s$, since two possible stand-off distances can correspond theoretically to one value of the interaction parameter $S_s$. It is convenient to consider the steady problem of a blunt body flying at hypersonic speed. By switching on a magnetic field, the bow shock starts moving out from its conventional aerodynamical position to that stand-off dis-
 ance which is specified by the magnitude of $S_s$ and which corresponds to the lower of the two values since this equilibrium position is first reached (see Fig. 17).

It is perhaps possible to reach the second position corresponding to a larger stand-off distance; by increasing values of the interaction parameter $S_s$ beyond the maximum value, which can in principle be achieved by increasing the magnetic flux density, the bow wave is expelled. If now the value of $S_s$ is decreased below $S_{s_{max}}$, then the bow wave might possibly be arrested at a distance which will correspond to the higher of the two values. However, since the bow wave normally will stabilize itself at the smallest stand-off distance for the actual value of the interaction parameter, the upper part of the curves shown in Fig. 17 should be regarded as physically non-attainable.

However, before making any estimates about the behaviour of the shock wave for large values of the interaction parameter, it is necessary to examine the validity of the solution.

The numerical solution of the computer for values of $S_s$ greater than some critical value for the corresponding density ratio $\xi$, did not yield a flow pattern that could be satisfied by a physical body. Since the problem just supposes a shock front, it is possible that a solution to the problem which is correct mathematically may not yield a physical body.

Under such extreme conditions however, it is necessary to modify the theory since the assumption of a spherical bow shock and constant density are no longer valid.

3.3 Shock Tube Testing Time

3.3.1 Boundary Layer Effect

In ideal shock tube theory, neglecting wall effects and real gas effects, the shock and the contact surface both move with a constant velocity, and the velocity across the shock tube cross-section is uniform. In reality, however, the presence of a cold wall boundary layer behind the shock wave introduced a serious disturbance in the ideal flow pattern. As pointed out by Duff (Ref. 13) and Anderson (Ref. 14), the mass transport in the boundary layer can be very large although the boundary layer thickness may be only a small fraction of the radius. This phenomenon can be represented quite clearly by performing a velocity transformation in which the contact surface is at rest and the wall is moving past it with a velocity $V_2$. In this frame of reference, all the fluid in the boundary layer "leaks" past the contact surface. It is this flow which accounts for the loss of test gas in the region 2 and which causes the shock to decelerate and the contact surface to accelerate in the frame of laboratory coordinates. This explains the observation that at large times both the shock and the contact surface can move at the same speed. This furthermore means that the duration of the uniform flow can become independent of the channel length. Hence,
no further increase in testing time with channel length is observed in such conditions.

In Ref. 15, Roshko presents an analytical treatment of the problem in a fixed contact surface coordinate system. His analysis is based upon a mass balance which equates the mass flow through the shock to the sum of the boundary layer mass flow moving past the contact surface and the rate of accumulation of mass between the shock and the contact surface. Based on his results the calculations of the available testing time have been worked out for a channel length of 3m and presented in Fig. 18 for different Mach numbers and initial pressures. As a comparison, the ideal testing time was plotted according to the expression:

\[ T_{\text{ideal}} = \frac{x}{a_1 \left[ M_s \left( \frac{\epsilon^2}{\epsilon_1} - 1 \right) \right]} \]  

(3.29)

Duff, in Ref. 13, concluded that the effect of boundary layer is large for the following conditions: Small shock tube diameter  Low initial pressures  High shock Mach numbers

and all three conditions are effective in the present experiment. This explains the large reduction in testing time from the ideal case to the real case including only boundary layer effect (see Fig. 18). Roshko stated the results of his theory in the following similarity equation:

\[ \frac{X}{Z} = - \ln \left( 1 - T^{1/2} \right) - T^{1/2} \]  

(3.30)

where \( X = 16 \left( \frac{\mu}{\rho_s} \right) \beta^2 F(M_s) \frac{P_{st}}{P_1} \frac{Z}{d^2} \)  

(3.31)

first similarity parameter

and \( T = 16 \left( \frac{\mu}{\rho_s} \right) \beta^2 G(M_s) \frac{P_{st}}{P_1} \frac{a_1 T}{d^2} \)  

(3.32)

second similarity parameter

for

\[ F(M_s) = \frac{Z_2 T_2}{T_1} \frac{\epsilon - 1}{\epsilon} \frac{1}{M_s^2} \]  

(3.33)

and

\[ G(M_s) = \frac{Z_2 T_2}{T_1} \frac{(\epsilon - 1)^2}{\epsilon} \]  

(3.34)

The coefficient \( \beta \) appears in the analysis by expressing the mass flow into the boundary layer (see Ref. 15).

\[ \dot{m} = \pi d \rho_w U_2 \delta = \pi d / \beta \rho_s V_2 \frac{P_w}{P_s} \left( \frac{H_w z}{P_w V_s} \right) \]  

(3.35)
where $\delta$ = boundary layer thickness
$\mu_w$ = viscosity at the wall

Several values for $\beta$ have been suggested by Roshko (Ref. 15), Mirels (Ref. 16) and Camm and Rose (Ref. 17); however, few attempts have been made to estimate the $\beta$ coefficient for ionized flow. Because of the dependence of on the function $(e_i \mu) / (e_w \mu_w)$ as presented in Ref. 17, a slight decrease in $\beta$ should occur for an increase in the degree of ionization. In Ref. 16 an upper limit for $\beta \leq 1.3$ was suggested for $M_s > 9$. These two conclusions decided the use of $\beta = 1.2$ over the whole Mach number range in the calculation of this paper. Hence by solving the three Eqs. (3.30), (3.31), and (3.32) for the three unknowns $X, T, \tau$ and the testing time $\tau$ can be obtained, and is plotted in Fig. 18.

3.3.2. Effects of Non-Equilibrium Ionization

For shock Mach numbers higher than 9, the temperature rise behind the moving shock is high enough to initiate the process of ionization in argon. However, the process of ionization is not instantaneous since a number of ionizing collisions is required before equilibrium conditions can be established. Once equilibrium is attained, the degree of ionization ($\omega$) becomes only a function of temperature and pressure. Peterchek and Byron in Ref. 18 studied the mechanism for the approach to equilibrium and pointed out that the time $\tau_T$ to reach equilibrium is a function of the total enthalpy or equivalent atom temperature immediately after the passing of the shock, where the ionization is still absent. Hence this time can be plotted versus shock Mach number as shown in Ref. 18.

Three conclusions can be derived from their results:

- $\tau_T$ increases considerably for decreasing shock Mach number
- $\tau_T$ is inversely proportional to the argon density (if the impurity level is supposed constant)
- $\tau_T$ decreases as the level of impurities increases

3.3.3. Results For the Calculated Testing Time

The resulting testing time, by considering boundary layer effects and the time required to reach equilibrium ionization, is much smaller than the ideal testing time as can be seen in Fig. 18. It shows the net resulting testing time for three initial channel pressures $P_1$ over the shock Mach number range of interest. The experimental results are plotted on the same figure and will be discussed in Chapter 4.4.
The ionization relaxation time limits the testing time at the lower shock Mach numbers while the boundary layer effects limit the testing time at higher shock Mach numbers.

Mixing of the test gas and combustion products, the non-uniformity of diaphragm rupture further decrease the testing time. Hence estimated values in Fig. 18 should represent an upper limit for the available testing time in the experiments.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Before analyzing the experimental data, it is necessary to discuss first the question of accuracy of the results and the validity of the theoretical calculations.

4.1. Effective Electrical Conductivity

The theory so far was based on the use of a simple Ohm's law and the ideal scalar electrical conductivity of the argon plasma. A detailed calculation of the scalar electrical conductivity was presented in Ref. 8, and in Ref. 19 some experimental data were obtained which indicate good agreement with theory for those cases in which the gas obtains its equilibrium state.

An experiment, similar to that described in Ref. 19 was set up to obtain some information about the effective electrical conductivity. Use is made of the radial magnetic field at the entrance of the field coil and the search coil III located at this position.

The distribution of the radial component of the magnetic induction at the end of the field coil for unity axial magnetic induction is denoted by $f_1(x, r)$. The induced magnetic flux density due to unit induced current density $j_i$ is called $f_2(x, r)$. Upon penetrating the magnetic flux lines, the plasma, having a velocity $V_2$ experience a circular electric field $\vec{E}_\theta = V_2 \times B = V_2 B_0 f_1(x, r)$. This electric field sets up a circular induced current density $j_i = \sigma_{ii} V_2 B_0 f_1(x, r)$, which in turn induces a magnetic flux density.

$$ B_i = \sigma_{ii} V_2 B_0 f_1(x, r) f_2(x, r) $$ (4.1)

An analogous expression can be applied to the calibrating experiment with an aluminum slug (subscript a) to express the total magnetic flux density through the search coil:

$$ B_{ia} = \sigma_a V_a B_{oa} f_1(x, r) f_2(x, r) $$ (4.2)

where the geometrical functions $f_1(x, r)$ and $f_2(x, r)$ remain unchanged.
The constants for the aluminum slug experiment are:

\[ \sigma_a = 2.08 \times 10^5 \text{ mho/cm} \]
\[ V_a = 7.025 \text{ m/sec} \]
\[ B_{oa} = 1755 \text{ Gauss} \]

By comparing the induced flux densities in both cases, we can solve for the only remaining unknown: \( \sigma_{ef} \) or the effective electrical conductivity of the plasma:

\[ \sigma_{ef} = \sigma_a \frac{V_a B_{oa} B_i}{V_i B_o} \]  \( (4.3) \)

Fig. 19 presents the calibration traces in the aluminum slug experiment. From the upper trace, the strength of the induced flux density through the search coil can be calculated from:

\[ B_{ia} = -\frac{R_i C_f}{NS} \varepsilon_0 \]  \( (4.4) \)

N = 20 turns
\( R_i C_f \) = integration constant = 1 msec
S = 8.3 cm\(^2\)
\( B_{ia} = 23.2 \) Gauss

Figure 20 represents the output signal from two ionization gauges for timing purposes together with a pick-up trace from the search coil III while a slug of argon plasma enters the field coil. An undershoot shows up in the integrated pick-up signal at the time the conductive gas leaves the entrance region of the field coil. The origin of this erratic pulse may be found in an improper functioning of the low frequency filter. This malfunction may have influenced the real signal but its effect was ignored.

Test conditions: From ionization pulses: \( M = 15.37 \)
\[ V_2 = 4250 \text{ m/sec} \]
\[ B_0 = 6 \text{ Wb/m}^2 \]

From the integrated trace, the induced magnetic flux density through the search coil was found to be 45 Gauss. By substituting these values in Eq. (4.3), the effective value of the conductivity of the argon plasma was found to be 1950 mho/m compared with the theoretical value for the scalar conductivity of \( \sigma_0 = 5700 \) mho/m.

So far, we have neglected the Hall effect which accounts for most of the discrepancy obtained in the results of the experiments and also the ion slip effect. Its effect on the present results can be estimated by starting from a generalized current equation, such as given by Cowling (Ref. 10). It can be shown (Ref. 20) that the electrical conductivity in the \((V \times B)\) direction can be calculated from:

\[ \sigma_{ef} = \frac{\sigma_0}{\beta} \left[ \frac{\beta^2 + k \omega_e^2 - \varepsilon^2}{\beta^2 + \omega_e^2 - \varepsilon^2} \right] \]  \( (4.5) \)
where \( \frac{\beta}{\tau} = \) ion slip coefficient = \( 1 + 2(\omega, \tau_1, \omega_e, \tau) \)

\[
= \left[ \frac{1}{\tau_{0i}} + \frac{1}{\tau_{om}} \right]^{-1} = \text{mean collision period}
\]

\( k = \) parameter which indicates the extent to which Hall currents have been restrained by charge polarization or insulating boundaries

\( k = 1: \) corresponds to zero Hall currents
\( k = 0: \) corresponds to unrestricted Hall currents.

Since it is difficult to estimate the value of \( k \), the two extreme cases \((k = 1, k = 0)\) are considered. The effective electrical conductivity follows from the expressions:

\[
k = 1 \quad \sigma_{eff} = \sigma_0 / \beta \quad (4.6)
k = 0 \quad \sigma_{eff} = \sigma_0 \beta / (\beta^2 + \omega_e^2 \tau^2) \quad (4.7)
\]

In Ref. 20, the variation of the mean collision frequency \( \nu \) with temperature at various densities has been presented, and a plot of the effective electron-neutral cross section \( Q_{en} \) for argon as a function of temperature is given. By making use of the customary assumption \( Q_{im} \approx 3 \) \( Q_{en} \), the value for the ion collision period \( (\tau_i) \) was calculated from the expression derived in Ref. 20:

\[
\tau_i = \frac{m_A^{\frac{1}{2}}}{\mu_e Q_{im}} \left[ \frac{n}{k_b T} \right]^{\frac{1}{2}} \quad (4.8)
\]

where \( m_A \) indicates the mass of an argon atom and \( k_b \) is the Boltzmann constant.

By making use of all these expressions, the effective electrical conductivity can be derived from the scalar electrical conductivity. Table I gives some values for the effective electrical conductivity, and it shows clearly that the Hall coefficient \( (\omega_e, \tau) \) for the conditions at the entrance of the field coil is appreciably larger than unity for an axial magnetic induction of 6 Wb/m².

There is no doubt that the Hall effect accounts for most of the discrepancy between the estimated and measured electrical conductivity. An additional reduction in the measured conductivity can arise from cooling effects at the wall and gas impurities.

Table II compares some calculated and measured values of the electrical conductivity for varying strength of the magnetic induction. It shows how the measured value for the effective electrical conductivity is bracketed by the calculated value in the two extreme cases: \( k = 1 \) and \( k = 0 \).

At the stagnation point, the temperature \( T_3 \) and the density \( \rho_3 \) are much higher than the temperature \( T_2 \) and density \( \rho_2 \). This results in a much higher collision frequency which reduces the Hall coefficient \( \omega_e, \tau \) and the slip coefficient \( \frac{\beta}{\tau} \). This is illustrated in Table III which shows the calculated values for the shock Mach numbers and initial pressures \( p_1 \) in the range of interest.
As a result of these calculations, it may be concluded that the interaction between the magnetic field and the flow at the entrance of the field coil, where the Hall effect is strongest, will be considerably reduced by the effect. On the other hand, at the stagnation point; the interaction does not suffer as much from this effect since the Hall effect is much smaller there.

The extent to which the magnetic interaction parameter \( S_S \) at a value of \( B = 6 \text{ wb/m}^2 \) has been reduced due to the Hall and the ion slip effect, is shown in Fig. 21. It represents the calculated value of the interaction parameter \( S \) versus shock Mach number for three different initial pressures. The values of the magnetic interaction parameter, based on a scalar electrical conductivity are presented by the solid lines and were directly taken from Fig. 15. The values of \( S_S \) based on an effective electrical conductivity calculated from eq. (4.5) are represented by the dash-dash line for the case \( k = 1 \) and by the dash-dot line for the case \( k = 0 \).

This graph shows that the influence of the maximum Hall effect (for \( k = 0 \)) at an initial channel pressure of 3 mm Hg, is not negligible in the shock Mach number range from 9 to 18 for a magnetic induction of 6 Wb/m\(^2\). The correction for the magnetic interaction parameter is large for lower shock Mach number but decreases to within 5% at higher shock Mach numbers.

In both the entrance and stagnation point interaction, the \( \mathbf{V} \times \mathbf{B} \) direction is azimuthal, and the Hall direction is the \( \mathbf{(V} \times \mathbf{B}) \times \mathbf{B} \) direction. By making the crude assumption that the obstruction to the Hall currents is somewhat similar; then the results of Table II appear to indicate that an arithmetic average value between \( k = 0 \) and \( k = 1 \) is a reasonable approximation. This approach has been used to estimate the effective value of the interaction parameter \( S_S \) in the experiments, and is plotted in Fig. 22 in full line for three different initial channel pressures, from the data of Fig. 21. The dashed lines for constant testing time are the result of crossplotting Fig. 18, where a point in both Figs is fixed by the initial pressure and shock Mach number. A logarithmic interpolation scheme was used to plot the intermediate points for the pressures. An estimate of the interaction parameter and corresponding testing time is useful, since both the formation of the bow shock and the required exposure time depend on these quantities. This Fig. also contains the experimental results which are plotted based on shock Mach number and initial pressure. This allows us to assign a value of the effective interaction parameter (which is obtained in ordinate) for each experiment. The meaning of the various symbols will be explained in detail in section 4.2.

From Fig. 22, it can be observed that the combined Hall and slip effects are very significant in reducing the effective interaction parameter considerably at lower initial pressures. Also the effect of the shock Mach number on the interaction parameter is not nearly as significant as Fig. 15, based on the full scalar conductivity, would predict. In fact, the estimated values of the effective interaction parameter \( S \) range between 1.5 and 2.5 for an applied magnetic field strength of 6 Wb/m\(^2\).
4:2 Discussion of the Experimental Results for the Stand-Off Distance

Fig. 23 presents the flow pattern around a blunt nosed body without magnetic field as recorded through a type of periscope on a polaroid film. Since the exposure time coincides roughly with the testing time, overexposure occurs at lower shock Mach numbers due to longer testing times (See Fig. 23b). Furthermore, this technique does not provide any information about the formation of the bow shock, nor is it possible to detect any disturbances emanating from the interaction region which showed up in some pick-up signals. Streak photographs were taken but did not yield any valuable information. By locating the stagnation point of the blunt body and the bow shock position at the center line, the stand-off distance could be measured.

The Figs. 24 and 25 show two typical complete runs with an applied magnetic field present ($B_0 = 6 \text{Wb/m}^2$).

Fig. 24 presents a complete set of data at low shock Mach number.

Fig. 24a: The upper trace is a recording of the output signal of the ionization gauge circuit. Knowing the distance between the ionization gauges, the shock Mach number can be calculated from the timing pulses. The middle trace presents the varying strength of the applied magnetic induction as obtained from integrating the induced voltage across search coil III. The bottom trace contains a spike from the ionization gauge closest to the interaction region which provides a direct check for synchronization of the constant peak magnetic field at the arrival of the shock, to assure a constant and maximum magnetic field during interaction.

Fig. 24b: shows a typical flow pattern with a diffuse bow shock for small shock Mach numbers. The luminous area at the right of this photograph arises from internal reflections on the aluminum walls of the periscope. Since the periscope was adjustable in length, not all surfaces could be made non-reflective.

Fig. 24c: presents some information about the induced magnetic flux density at the stagnation point (upper trace) and at the entrance of the field coil (lower trace). The upper trace is a filtered and integrated signal from pick-up coil I. It should give an estimate of the strength of the induced currents in the shock layer. However, as will be discussed in section 4.3, the negative pulse which actually corresponds to an increase in total flux density, rather than the anticipated decrease, should result from a strong disturbance generated at the entrance of the field coil which is superimposed on the expected positive signal. The positive part of the signal corresponds to an induced flux density of approximately 5 Gauss per cm deflection. This measurement confirms the smallness of the magnetic Reynolds number as calculated in section 3.1, and it justifies the assumption that the total magnetic flux density is determined entirely by the strength of the currents in the field coil. The lower trace is a direct pick-up signal from the search coil located at the entrance of the field coil and it shows the familiar pulses with opposing polarity resulting from the passage of a slug of conducting gas.

Fig. 25: presents a full set of data obtained in a high shock Mach number experiment. The flow pattern seen in Fig. 25b shows a sharp discontinuity in light
intensity across the bow shock. This was typical for shock Mach numbers larger than 13.

Three runs were made at low initial pressure and did not show any bow shock at all, probably due to the very short testing time together with a high values of the effective interaction parameter which impedes the formation of a stable bow shock during the available testing time.

All experimental data are tabulated (Table IV) and presented in Fig. 22 where they are plotted according to shock Mach number and initial pressure, from which the effective interaction parameter can be estimated. The experimental conditions presented in this Fig. gave rise to four different types of interactions judging by the flow pattern around the blunt body, and four different regions shown on the graph:

1) \( M_s < 13 \) \( p_1 = 3 \text{mm} \): Experimental data identified by 0. Interaction occurs, but the bow shock is very diffuse (Fig. 24b).

2) \( M_s > 13 \) \( p_1 = 3 \text{mm} \): Experimental data identified by 0. Interaction shows up clearly and the bow shock is well defined (Fig. 25b).

3) \( 12 < M_s < 16 \) \( p_1 < 3 \text{mm} \): Experimental data identified by \( \Delta \). No bow shock is visible.

4) \( M > 16 \) \( p > 3 \text{mm} \): Experimental data identified by X. No interaction effects visible, with a bow shock standing at a distance from the body corresponding to no magnetic field interaction.

In order to investigate the agreement between the theory and the experimental results as far as the stand-off distance is concerned, all data are now replotted in Fig. 26, with respect to the non-dimensional stand-off distance and shock Mach number \( M_s \). For the runs without magnetic field, the agreement between measured and calculated values is rather good at higher shock Mach numbers. The theoretical value of the stand-off distance was calculated from a constant density approach for the region \( \theta \) and does not hold for higher values of the density ratio \( \rho_1 / \rho_2 \) i.e. for small shock Mach numbers. The deviation from the theoretical curve \( S_0 = 0 \) shows up below \( M_s = 15 \). The full lines labeled \( S_0 \) result from the theoretical calculations presented in Fig. 17, now plotted with the interaction parameter \( S_0 \) as parameter. From this graph it is evident that the experimental data do not show agreement with the theory.

For example: Analysis of run 65 (see table IV): \( M_s = 15 \), \( p_1 = 3 \text{mm Hg} \). When this is plotted in Fig. 22, an interaction parameter \( S = 1.9 \) results. This point is also plotted in Fig. 26 for \( M_s = 15 \) and \( \Delta / \alpha = 0.706 \) and is situated close to the line corresponding to \( S_0 = 1.0 \). If this experimental point was plotted according to its shock Mach number and the estimated value \( S_0 = 1.9 \), this should correspond to an infinite stand-off distance.
Conclusion:

No quantitative analysis of the experimental results can be attempted, since the experiments all show a stand-off distance, which is much smaller than the theory would predict for corresponding magnetic interaction parameter $S_g$. Moreover, the experimental data do not indicate a clear pattern, since they are scattered over a broad band.

In order to eliminate the uncertainties for very large stand-off distances, a series of experiments has been undertaken at moderate field strength. Three runs were performed at approximately the same shock Mach number ($M_s = 17$) and identical channel pressures ($p_1 = 3$ mm). (See Table IV, Runs 137, 138, 139). The only variable was the applied magnetic induction which ranged from 2.5 to 5 Wb/m$^2$. A straightforward calculation for the magnetic interaction parameter was possible based on the scalar electrical conductivity. The Hall effect could be neglected for two reasons:

1. The correction for Hall effects at $M_s = 17$ is smaller than 5%. See Fig. 21.

2. The Hall effect vanishes at lower magnetic field strengths since its effect on the effective electrical conductivity is proportional to the square of the magnetic induction. See Eq. (4.5).

The experimental data are plotted in Fig. 17. The agreement with the theory is much more satisfactory since the experimental data approach the theoretical values for $M_s = 17$ which are presented by a dashed line.

It may therefore be concluded that in order to obtain quantitative information about the interaction phenomena capable of comparison with theory, it is necessary to limit the strength of the interaction. The behaviour at stronger interaction levels is more doubtful since the theory does not hold for every large stand-off distances and is predicted on the assumption of a scalar conductivity. Furthermore, other phenomena as yet unknown, seem to influence the experiments performed at higher values of the interaction. The last set of experiments indicate to a certain extent that experiment and theory agree reasonably well for values of the interaction parameter smaller than 0.5 and in the shock Mach number range where Hall effects can be neglected.

4.3 Interaction Phenomena at the Entrance of the Field Coil

In the course of the experiments, a large disturbance showed up in the pick-up traces at the stagnation point. Figures 24c, and 25c, show typical examples of an oscilloscope recording representing the integrated pick-up signal from the search coil 1. Upon arrival of the shock at the blunt body, a decrease of total magnetic flux density is expected as a result of induced currents in the shock layer. However, all recordings suggest an initial increase in magnetic flux density. In order to analyse the nature of the disturbance, a third pick-up coil was placed around the shock tube 10 cm upstream of the stagnation point.
point. Even when the blunt body was removed, a large signal, having a polarity corresponding to an increase in magnetic flux density, was picked up by both search coils. From this experiment, it becomes clear that this disturbance originated at the entrance of the field coil and is of the same nature as that described in similar experiments by Dolder (Ref. 21) and Pain and Smy (Ref. 22).

In Ref. 8, deLeeuw examines the ponderomotive force density acting upon the flow in the case of an axial symmetric field with radial components at the end of the coil

$$\psi = \tau_1 v_1 B_x B_x \ell_x - \tau_2 v_2 B_x B_x \ell_x$$

(4.9)

The first term on the right hand side represents a force acting on the conductive fluid with inward component. Owing to the non-symmetrical arrangement of the magnetic flux distribution in the shock tube, it is likely that the radial forces acting on the plasma are not axially symmetric, and a net transverse force can be exerted on the fluid. This can introduce a strong transient disturbance, moving transversely within the plasma with sonic velocity.

The second term on the right hand side in Eq. (4.9) represents a force density directed against the axial motion of the plasma and its integrated effect will be a net braking force on the flow. A rough estimate of the braking pressure, according to the expression given in Ref. 8, indicates a value \(-\rho_x/\rho_0\) which is slightly smaller than the choking value \(-\rho_x/\rho_0\) choking.

Some flow pictures in experiments performed at a smaller initial channel pressure, suggest the occurrence of choking at the entrance of the field coil, since no bow shock could be noticed around the blunt body. (Fig. 22). As was pointed out in Ref. 8, choking is more likely to occur at smaller initial pressures. An attempt was made to obtain some information about shock reflection from the entrance of the field coil. However, none of the drum camera photographs, taken at the upstream end of the field coil show any reflection. Figure 27 is an example of such a run, which clearly shows no reflected wave, but does show a peculiar phenomena. A narrow band of low luminosity shows up in the region close to the coil where the conductive fluid experiences an increasing strength in magnetic induction. A similar phenomena also was observed by Dolder and described in Ref. 21 as "the dark band phenomena".

A possible explanation can be found in the distortion of the plane of the shock by entering the non-symmetric magnetic flux density. Since the magnetic flux lines act as a nozzle for the flow, the lower part of the shock is speeding up, while the upper part, encountering a stronger radial flux density, is retarded. Internal reflection of the light emitted by the ionized argon behind the shock can occur since the light is going from a dense to a less dense medium. Since the distortion in the plane of the shock grows by approaching the field coil, the angle of the plane of the shock rotates. This can explain why the dark stroke has an obvious smaller speed than the leading edge of the travelling shock.
4.4 Experimental Results of the Testing Time

The electromagnetic disturbance produced by the passage of a slug of test gas through the magnetic field provide some information about the available testing time. A 10 turn search coil, placed at the entrance of the field coil picks up these disturbances which show up as two short pulses with opposing polarity; see Fig. 24c and 25c. The spacing of the two pulses allows an estimate of the testing time with about 10% accuracy. All experimental data are listed in Table IV and plotted in Fig. 18 to compare the results with the theory.

It may be concluded that the agreement between experimental data and theoretical predictions is fairly good. The particular choice of the boundary layer parameter $\beta$ discussed in Sec. 3.3.1, seems to give reasonable estimates for the testing time, especially for moderate shock Mach numbers.

V. CONCLUDING REMARKS

The experiment has basically confirmed the theoretical predictions that a strong magnetic flux density can change the flow pattern of a hypersonic flow around a blunt body. The increase in the stand-off distance is the first observable effect and a direct check on the nature of the interaction. However, little quantitative agreement has been obtained and many reasons account for the discrepancy. As a proposal for further study, the main reasons are summarized:

1. All the work carried out with the one inch circular shock tube shows very poor repeatability of the experimental conditions. Detonative combustion in the driver is the main reason why any calibration of the shock tube is not reliable. A modification of the driver section is required before carrying out more accurate experiments. Camm and Rose in Ref. 17 describe an electrically driven shock tube as a possible way to improve the reliability of the driver, to improve the quality of the sample of test gas since no combustion products are produced, and to extend the shock Mach number range.

2. The field coil was so designed as to produce a very strong magnetic flux density for a given current, and to withstand the strong forces exerted on the windings. However, the simple geometrical shape produced a relatively strong radial flux density in the shock tube at the ends of the field coil, as shown in Fig. 11. This caused very strong disturbances in the plasma as explained in Section 4.3, since the interaction with the conductive medium was no longer confined to the stagnation region, as is the case of a space reentry problem. This problem can be solved by the following technique:

If a second diaphragm can be installed in the test section, at a position where the magnetic flux lines are axial, the interaction of the entrance of the field coil can be eliminated. The conductivity of the fluid between the two diaphragms can be kept very low, either by using a gas with high ionization potential, or by using a very light channel gas. In this way, the conductivity can be "switched on" by the rupture of the second diaphragm, and no interaction can occur before the plasma reaches the blunt body.
3. It is evident that Hall effects have influenced the experimental results, and this effect should be avoided by all means to improve the accuracy of the experiments. The most suitable operating conditions can be found from Fig. 21. Higher shock Mach numbers and higher initial pressures will eliminate the Hall effect, e.g., $M_s = 1.5, p_1 = 10 \text{ mm Hg}$. These conditions are contradictory since a higher shock Mach number can only be obtained by using a smaller initial pressure, and this can hardly be achieved with the actual equipment. A more powerful driver, as suggested in No. 1 of this paragraph, can solve the problem. Also the testing time can possibly be increased under such conditions.

4. In order to obtain results which are comparable with the actual theory, it seems advisable to limit the strength of the magnetic induction, as shown in Sec. 4.2. It follows from the latest experiments that the value of the interaction parameter $S_b$ based on the stand-off distance should not exceed 0.5 to provide accurate comparison with the theoretical results. This conclusion together with No. 2 of this section will help to eliminate the Hall effects (No. 3).

5. Finally, it should be pointed out that the analysis is not very accurate. Before attempting a better agreement with the experiments, it seems advisable to remove some restrictions, mentioned in Section 3.2.1, which were introduced in the analysis to simplify the theoretical approach. At the present time, a general analytic solution for the hypersonic flow field around a blunt body in the presence of a magnetic field does not exist. All reported work considers only a region adjacent to the stagnation streamline, and the assumed spherical bow shock does not represent the real shape of the bow wave, especially in experiments with very strong interaction.
REFERENCES


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TABLE III

Electrical Conductivity of Argon Behind Bow Shock

initial conditions: \( p_1 = 3 \text{ mm Hg} \)

\( B_0 = 6 \text{ Wb/m}^2 \)

\( \omega_e = 1.056 \times 10^{12} \text{ rad/sec} \)

\( \omega_i = 1.47 \times 10^7 \text{ rad/sec} \)

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TABLE IV
Experimental Results

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<td>$E$ (volt)</td>
<td>$M_s$</td>
<td>$\tau$ ($\mu$ sec)</td>
<td>$\Delta/\tau_b$</td>
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FIG 1  DIAGRAM OF THE BLUNT BODY, AND THE DETACHED SHOCK, ILLUSTRATING CURRENTS AND FORCES IN THE FLOW.
FIG 2 A SCHEMATIC DIAGRAM OF THE APPARATUS.
FIG 3  GENERAL VIEW OF THE CONTROL CONSOLE AND AUXILIARY EQUIPMENT.
FIG 5 SCHEMATIC VIEW OF THE INTERACTION REGION AND THE OPTICAL SYSTEM.

FIELD COIL: 3 x 75 turns. 0.461 mH

MODEL

PICK-UP COIL

F = 250 mm
diam. = 50 mm.
FIG 6 A SCHEMATIC OF THE .238 F CAPACITOR BANK.

FIG 7 LEAKAGE CURRENTS OF A SINGLE ELECTROLYTIC CAPACITOR VERSUS VOLTAGE.
FIG 8 BLOCK DIAGRAM OF THE CAPACITOR BANK, THE POWER SUPPLY AND AUXILIARY DEVICES.
FIG 9 CURRENT AND FIELDSTRENGTH IN DISCHARGE.

Initial voltage: 200 volt.
Upper trace: Signal from current measuring resistor.
Vertical scale: 0.5 volt/cm.
Sweep rate: 10 msec/cm.
Lower trace: Output from a Hall effect device, model BH-203
K_{hoc} = 0.094 volt/amp, kgauss.
Vertical scale: 50 mvol/cm.
Sweep rate: 10 msec/cm.
Position of the Hall device at x/l = 3/4

I_{max}: 2350 amp. \quad B_{max} : 1.13 \text{ Wb}/\text{m}^2.

Initial voltage: 880 volt.
Upper trace: Signal from current measuring resistor.
Vertical scale: 2 volt/cm.
Sweep rate: 10 msec/cm.
Lower trace: Integrated pick-up signal from search coil 3, representing the magnetic induction.
Integration constant: 100 msec.
Vertical scale: 100 mvol/cm.
Sweep rate: 10 msec/cm.

I_{max}: 10450 amp. \quad B_{max} : 5.1 \text{ Wb}/\text{m}^2.
FIG 10 Calibration Curves of the Magnetic Field-Strength

a- Maximum Magnetic induction versus initial voltage.
b- Maximum Current versus initial voltage.

\[ B_{0,\text{max}} = \text{calculated max. field strength.} \]
\[ o : \text{measured. (HALL PAK DEVICE)} \]

b- Calculated max. current.

\[ I_{\text{max}} = \frac{2E}{R} \exp \left( \frac{R}{2L} T_{\text{max}} \right) \]
\[ T_{\text{max}} = \frac{2L}{R} \arctg \left( \frac{q}{R} \right) \]

Parameters for R-L-C Circuit:
\[ R = 0.052 \ \Omega \]
\[ L = 0.461 \text{mH} \]
\[ C = 0.238 \text{f} \]

X: measured.
FIG 11 DISTRIBUTION OF THE MAGNETIC FLUX DENSITY ALONG THE FIELD COIL. (REF. 9).

SYMMETRIC ($r/a_i = 0$)

$B/B_o$

- THEORETICAL $\beta = 10$
- THEORETICAL $\beta = 5$
- INTERPOLATED $\beta = 7.2$

$\beta = \frac{l}{a_i} = 7.2$

MEASURED

OFF AXIS ($r/a_i = 0.5$)

$B_x/B_o$

$Br/B_o$

$2l = 43$ cm.

$\alpha = 3$ cm.

$\frac{\pi x}{a_2} = 4.8$ cm.

stagnation point.

$0 \leq \frac{x}{l} \leq 5/4$
FIG 12 THE HALL EFFECT DEVICE.

Model BH-203: General-Purpose AXIAL

Manufactured by BELL INC.
FIG 13 SCALAR ELECTRICAL CONDUCTIVITY FOR ARGON AS A FUNCTION OF TEMPERATURE AND PRESSURE.
FIG 14 MAGNETIC REYNOLDS NUMBER BASED ON THE BODY RADIUS AS A FUNCTION OF SHOCK MACH NUMBER AND INITIAL PRESSURE.

\[ \text{Rem.} = \sigma_b \varepsilon u_b \Gamma_b \mu_0 \]

\[ \eta_b = 3/16'' \]

Rem. = 10 mm Hg.

Rem. = 3 mm Hg.

Rem. = 1 mm Hg.

8 9 10 11 12 13 14 15 16 17 18 19 \( M_s \)
FIG 15 MAGNETIC INTERACTION PARAMETER BASED ON STAND-OFF DISTANCE AND SCALAR ELECTRICAL CONDUCTIVITY AS A FUNCTION OF SHOCK MACH NUMBER AND INITIAL PRESSURE.

\[ S_S = \frac{\varepsilon \sigma_3 B_0^2 r_b}{P_2 v_2} \]

\[ B_0 = 6 \text{ Wb/m}^2 \quad r_b = 3/16" \]
FIG 16 NON DIMENSIONAL STAND-OFF DISTANCE VERSUS INTERACTION PARAMETER $S_c$ FOR DIFFERENT $\varepsilon$

$$\Delta \frac{r_b}{r_b} = \frac{\varepsilon \sigma B_c^2 c}{\rho_c v_2}$$

- AXIAL MAGNETIC FIELD
- MAGNETIC FIELD FROM DIPOLE AT ORIGIN (W.B. BUSH)
FIG 17 NON DIMENSIONAL STAND-OFF DISTANCE VERSUS MAGNETIC INTERACTION PARAMETER $S_\varepsilon$ FOR VARIOUS VALUES OF THE DENSITY RATIO.

$\frac{\Delta}{r_b}$

--- THEORY.

--- EXPERIMENT.

$\varepsilon = 0.5$

$\varepsilon = 0.4$

$\varepsilon = 0.3$

$\varepsilon = 0.2$

$\varepsilon = 0.09$
FIG 18 TESTING TIME VERSUS SHOCK MACH NUMBER FOR VARIOUS INITIAL PRESSURES.

EXPERIMENTAL RESULTS

- : IDEAL TESTING TIME.
- : TESTING TIME WITH VISCOUS LOSSES (ROSHKO)
- : REAL TESTING TIME INCLUDING NON EQUILIBRIUM IONIZATION.

\[
\begin{align*}
\text{\( \tau \) in } & \mu \text{sec.} \\
\text{\( p = 10 \text{ mm.Hg} \)} & \\
\text{\( p = 3 \text{ mm.Hg} \)} & \\
\text{\( p = 1 \text{ mm.Hg} \)} & \\
\end{align*}
\]

- \( p = 2.5 \text{ mm.Hg} \)
- \( p = 3.5 \text{ mm.Hg} \)
- \( p = 4.5 \text{ mm.Hg} \)
- \( p = 5 \text{ mm.Hg} \)
FIG 19 CONDUCTIVITY CALIBRATION

Upper trace: integrated pick-up signal from search coil
integration constant: 1 msec.
vertical scale: .05 volt/cm
Lower trace: pick-up signal from search coil.
vertical scale: .010 volt/cm.
Sweep rate: 10 msec/cm. $B_0 = 1755$ Gauss.

FIG 20 INTEGRATED PICK-UP TRACE FROM SEARCH COIL 3

Lower trace: integrated pick-up signal
integration constant: 20 $\mu$sec.
vertical scale: 2 volt/cm.
Sweep rate: 20 $\mu$sec/cm.
FIG 2: INFLUENCE OF THE HALL EFFECT ON THE VALUE OF THE INTERACTION PARAMETER $S_s$

\[ S_s = \frac{\varepsilon \sigma B_0^2 R_0}{\rho_e V_2} \quad B_0 = 6 \text{ Wb/m}^2 \]

- \( \sigma \): SCALAR CONDUCTIVITY
- \( \sigma_{\text{eff}} \): EFFECTIVE CONDUCTIVITY \((k=1)\)
- \( \sigma_{\text{eff}} \): EFFECTIVE CONDUCTIVITY \((k=0)\)

$R_e = 1 \text{ mm Hg}$
$R = 3 \text{ mm Hg}$
$R = 10 \text{ mm Hg}$
FIG 22 INTERACTION PARAMETER BASED ON STAND-OFF DISTANCE AND AVERAGE EFFECTIVE ELECTRICAL CONDUCTIVITY.

\[ S_s = \frac{\varepsilon \sigma B_0^2 R_b}{p_0 V_2} \]

\( B_0 = 6 \text{ Wb/m}^2 \)

- **\( \sigma \):** AVERAGE VALUE OF ELECTRICAL CONDUCTIVITY.
- **\( \varepsilon \):** INTERACTION - DISTINCT BOW SHOCK.
- **EXPERIMENTAL\( \Delta \):** INTERACTION - DIFFUSE BOW SHOCK.
- **DATA\( \times \):** NO BOW SHOCK VISIBLE.
- **\( \times \):** NO INTERACTION.
FIG 23 FLOW PATTERN AROUND A BLUNT BODY, WITHOUT MAGNETIC INDUCTION.

\( \frac{1}{4}'' \) model.

(a) \( M_S = 17.1 \quad \rho_1 = 3 \text{ mm Hg.} \)
\[ \Delta/R_b = 0.152. \]

\( \frac{3}{8}'' \) model.

(b) \( M_S = 15.1 \quad \rho_1 = 4.5 \text{ mm Hg.} \)
\[ \Delta/R_b = 0.222 \]

\( \frac{1}{2}'' \) model.

(c) \( M_S = 16.3 \quad \rho_1 = 3 \text{ mm Hg.} \)
\[ \Delta/R_b = 0.166. \]
FIG. 24 RUN # 66: MHD INTERACTION EFFECTS. $M_{\infty} = 12.6$, $p_1 = 3$ mm Hg.

(a)
Upper trace: Response from ionization gauges.
Vertical scale: +20 volt/cm -20 volt/cm added.
Sweep rate: 10 $\mu$sec/cm.
Middle trace: Integrated pick-up signal from search coil 3. Represents the strength of the main applied magnetic induction.
Integration constant: 100 msec.
Vertical scale: 2 volt/cm.
Sweep rate: 5 msec/cm.
Lower trace: Synchronization pulse from second ionization gauge.
Vertical scale: 20 volt/cm
Sweep rate: 5 msec/cm.

(b)
Flow pattern around a blunt nosed model, in the presence of a strong magnetic field.

$m_\infty = 12.6, \quad B_0 = 6 \text{ Wb/m}^2, \quad \Delta R_b = 1.40$

(c)
Upper trace: Filtered and integrated signal from pick-up coil #1.
Integration constant: 20 $\mu$sec.
Vertical scale: 2 volt/cm.
Sweep rate: 20 $\mu$sec/cm.
Lower trace: Pick-up signal from search coil #3.
Vertical scale: 5 volt/cm.
Sweep rate: 20 $\mu$sec/cm.
FIG. 25 RUN # 65 : MHD INTERACTION EFFECTS. $M_s = 15$  $p_1 = 3$ mm Hg.

(a) Upper trace: Response from ionization gauges. Vertical scale: $+20$ volt/cm. $-20$ volt/cm. Sweep rate: $10\mu$sec/cm. Middle trace; Integrated pick-up signal from search coil # 3. Represents the strength of the main applied magnetic induction. Integration constant: $100$ msec. Vertical scale: $2$ volt/cm. Sweep rate: $5$ msec/cm. Lower trace: Synchronization pulse from second ionization gauge. Vertical scale: $20$ volt/cm. Sweep rate: $5$ msec/cm.

(b) Flow pattern around a blunt nosed model, in the presence of a strong magnetic field.

$M_s = 15$  $B_o = 6~\text{Wb/m}^2.$

$\Delta / R_b = 0.706$

(c) Upper trace: Filtered and integrated signal from pick-up coil # 1. Integration constant: $20\mu$sec. Vertical scale: $2$ volt/cm. Sweep rate: $20\mu$sec/cm. Lower trace: Pick-up signal from search coil # 3. Vertical scale: $2$ volt/cm. Sweep rate: $20\mu$sec/cm.
FIG 26 NON DIMENSIONAL STAND-OFF DISTANCE VERSUS SHOCK MACH NUMBER FOR VARIOUS VALUES OF THE INTERACTION PARAMETER $S_s$.

$S_s = \frac{E \sigma B_0^2 R_b}{\rho V_2} = S_c \left[ 1 + \frac{\Delta}{R_b} \right]^{-1}$

$R_b = 3/16"$  \hspace{1cm} $B_0 = 6\text{ Wb/m}^2$

$P_i = 3\text{ mm Hg.}$

EXPERIMENTAL RESULTS
- $\sigma = 6\text{ Wb/m}^2$  \hspace{1cm} $\sigma = 0$

FOR EACH RUN, THE ESTIMATED VALUE OF THE INTERACTION PARAMETER $S_s$ (FIG 22) IS INDICATED.

$P_i = 3\text{ mm Hg.}$
FIG 27 DRUM CAMERA PHOTOGRAPH AT THE ENTRANCE OF THE FIELD COIL.

RUN 128 \[ M_S = 15.4 \quad p_1 = 3 \text{ mm Hg}. \]
Some interaction effects of a plasma flowing around a blunt body in the presence of a strong magnetic field have been investigated. A one inch circular shock tube was used to provide the plasma during a testing time of approximately 30 μ sec. The required magnetic field strength was produced by discharging a 0.238 F electrolytic capacitor bank through a coil. The coil axis was parallel with the axis of the shock tube, generating a purely axial magnetic field of 60,000 Gauss, over a period of 4 msec, at the stagnation point. The blunt nosed model was a 3/8" d. hemisphere-cylindrical body made of lucite plastic and was mounted at the center of the coil. Interaction effects of the plasma with the applied magnetic field have been observed in the form of an appreciable change in stand-off distance of the bow wave. The behaviour of the induced currents and the induced flux density have been examined by using three pick-up coils placed around the shock tube. This arrangement also made it possible to gain some more information about the available testing time and the values of the effective electrical conductivity of the argon plasma. Calculations covering a shock Mach number range from 9 to 19 have been presented and a simple theory, was worked out for the particular magnetic field configuration. The validity and the significance of the calculations and experiments are discussed together with some proposals for further work.
### Key Words

1. Stagnation Point Flow
2. Magnetohydrodynamics
3. Shock Stand-Off Distance

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