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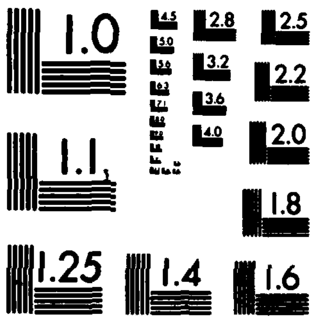

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THE EFFECT OF A TRANSVERSE MAGNETIC FIELD ON A NON-EQUILIBRIUM IONIZED HIGH VELOCITY GAS STREAM

by

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THE EFFECT OF A TRANSVERSE MAGNETIC FIELD ON A NON-EQUILIBRIUM IONIZED HIGH VELOCITY GAS STREAM

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ABSTRACT

This work is an experimental and theoretical study of the effect of a transverse magnetic field on an ionized non-equilibrium high velocity gas flow. In a small scale electric arc wind tunnel, the electron density in the experimental gas flow could be reduced by one order of magnitude. This method provided a new way to partially control the electrical characteristics of a low density electrical arc wind tunnel gas flow.

I. INTRODUCTION

In the experimental study of the physical phenomenon of re-entry flights, there are certain requirements of the gas flow quality in the gas dynamic simulating equipment, such as an electric arc wind tunnel. For example, in carrying out the study on re-entry communication and target identification problems, it is necessary to simulate the plasma sheath surrounding the high velocity spacecraft. Frequently the working medium is air. Furthermore, it is required that the mole fraction of free electrons in the wind tunnel experiment is identical to that under actual flight conditions. In order to explore ways to control the gas flow quality, we attempted to decrease the electron density in the gas flow in an electric arc wind tunnel experiment. The method uses a transverse magnetic field. This method not only can reduce the electron density, but also simultaneously maintains the chemical composition of the air medium

* This paper was authored by Wu Chengkang and Wang Boyee. Other comrades who participated in the experimental work are Lin Zhikai, Ji Zhen yu, and Tan Hon, etc.
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unchanged. Initially, we conducted tests in our H-4 electric arc wind tunnel in which the electron density value in the gas flow in the test section is on the order of 10^{12} $1/cm^3$ [1]. An intense magnetic field was added to the midsection of the wind tunnel nozzle. However, the effect of electron density reduction was not obvious. For this reason, a small simple experimental equipment was built which is a small low density electric arc wind tunnel and a strong direct current electromagnet. The diagnostic tools were a static electricity probe and a microwave transmission device. Through a series of experiments and discussion, we analyzed the mutual effect between a transverse magnetic field and an ionized non-equilibrium high velocity gas flow.

II. EXPERIMENTAL APPARATUS

The arrangement of the entire experiment is as shown in Figure 1, in which the test section is a piece of heat resistant glass tube which is an insulating surface. In the experiments, it was also

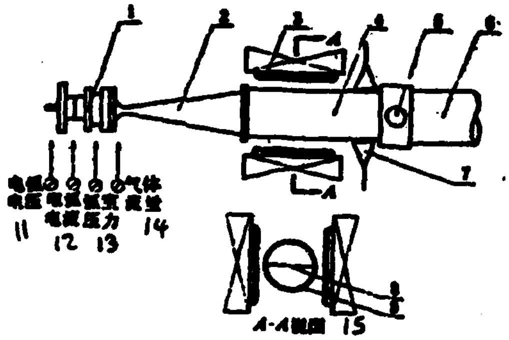

Figure 1. A simple schematic diagram of the experimental arrangement in reducing electron density
1--heater; 2--nozzle--3--electromagnet; 4--experimental section; 5--measurement section; 6--compressor and refrigerator; 7--microwave speaker; 8--static electricity probe; 9--metal lined cylinder; 11--electric arc voltage; 12--electric arc current; 13--arc chamber pressure; 14--gas flow rate

possible to line the glass tube with a whole or two semi-circular shaped aluminum cylinders which firms the conducting wall surface. 29
The direct current electromagnet can provide a magnetic field with

variable intensity. It can reach as high as 10,000 Gauss [2]. The direction of the magnetic field is perpendicular to the direction of the gas flow. In the experiment, the heater working condition was basically stable. Its operating parameters were: electric arc voltage 60 volts, electric arc current 120A, arc chamber pressure 1 atmosphere, and the gas flow rate 0.3 g/sec. The working medium was air.

III. EXPERIMENTAL PROCESS AND RESULTS

In the apparatus described above, we carried out the following sets of experiments: (1) under the glass insulating wall surface condition, the external magnetic field remained unchanged to measure the variation of electron density before and after the magnetic field was imposed. The results show that when the magnetic field is 5000 Gauss, the electron density is reduced by about 30%. (2) using the entire metallic aluminum cylinder as the lining as the conducting wall surface. The measurements show that, under the same 5000 Gauss condition, electron density can be reduced by 70% (Figure 2). (3) under the conducting wall surface condition, the gas flow condition is maintained unchanged to conduct experiments by changing the intensity of the magnetic field. The results show that the stronger the magnetic field, the better the reduction effect becomes. (4) under the condition a conducting wall surface, experiments were conducted by changing the gas flow rate of the heater (corresponding to changing the density of gas flow in the esperimental section). The results show that the lower the gas flow, the better the results become (the above are shown in Figure 3). (5) using a two semicircular metallic aluminum lining test section and an external magnetic field to measure the variation of electron density, we also measured an open circuit voltage between the two lining cylinders of about 10 volts. The short circuit current was about 16 mA. (6) under the condition of two semicircular lining cylinders, another direct current power supply was placed in series in the circuit to separately measure the electron density values under various conditions such as with no electric and

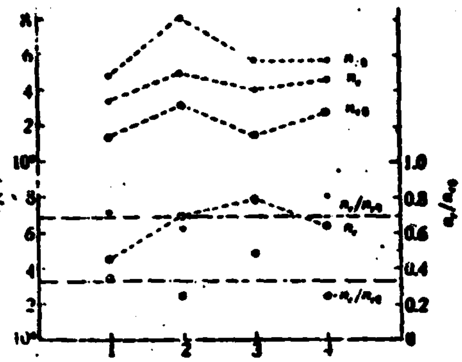

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Figure 2. Experimental results when the magnetic field is 5000 Gauss
2--insulating wall surface;
3--conducting wall surface;
4--experimental sequence

● 绝缘壁面 ○ 导体壁面

2 3

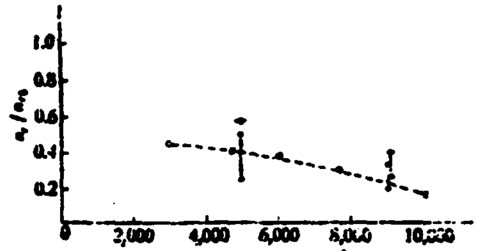

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Figure 3. Experimental results with a conductor lined cylindrical wall surface
6--magnetic field (Gauss);
7--small flow rate; 8--medium flow rate; 9--large flow rate; 10--experimental sequence

● 小流量 ○ 中流量 ◆ 大流量

7 8 9

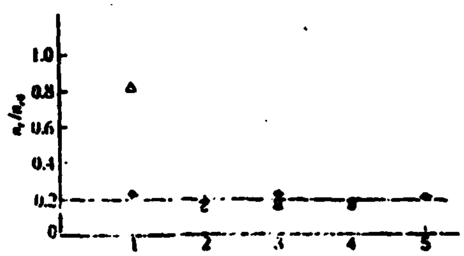

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Figure 4. Experimental results with a semi-circular lining cylinder wall surface
12--add electric field only; 13--add magnetic field only (connected to the ammeter); 14--add magnetic field only (connected to the voltmeter); 15--add electric and magnetic fields

▲ 只加电场 ◆ 只加磁场(接电流表) ✚ 只加磁场(接电压表) ○ 加电、磁场

12 13 14 15

magnetic field with an electric field alone (45 volts), with a magnetic field above (9000 Gauss) and with simultaneous electric and magnetic fields. Results show that under the mutual interaction of an orthogonal transverse electric field and magnetic field, the effect of electron density reduction is slightly better than the effect of using a transverse magnetic field alone (see Figure 4).

In summary, the entire experimental results indicate that: under the present experimental conditions, by using a conducting wall surface and by adding a transverse magnetic field of 10,000 Gauss, it is possible to reduce the electron density by one order of magnitude.

IV. EXPLORATION OF THE MECHANISM

Under the effect of external electromagnetic fields, charged particles will move according to the following forms:

1. Circular motion. When a changed particle enters a magnetic field, it is confined around the magnetic line of force in circular motion. The circular motion frequency is $\omega = (eB)/m$, and the corresponding circling radius is $r = u/\omega$ (where e, m and u are the charge, mass and linear velocity of the charged particle respectively. B is the external magnetic field). Thus, the motion of the charged particle in a direction perpendicular to the magnetic field is stalled.

2. Drift motion. If the charged particle is also under the influence of another external force, then it will drift in the direction perpendicular to the magnetic field B as well as the external force F. The drifting velocity of the circling center is $V_d = (F \times B)/(eB^2)$. The static electric force exerted in the charged particle by a static electric field and the collision force between neutral gas molecules and charged particles can cause this type of drift motion. The Hall parameter $\beta = \omega/\nu$ (ν is the

collision frequency of the charged particles) can indicate the relative importance of the effect caused by the magnetic field and collision.

3. <u>Diffusion motion</u>. When there is a density gradient in the charged particles, they will diffuse along the gradient direction. Under the plasma condition, bipolar diffusion will occur. The bipolar diffusion coefficient $D=(\mu_i D_e+\mu_e D_i)/(\mu_i+\mu_e)$ (where D_e, D_i, μ_e, μ_i are the self-diffusion coefficient and migration coefficient of the electron and the positive ion, respectively). When a magnetic field exists, the diffusion of charged particles is anisotropic. The above expression only represents the diffusion coefficient along the line of force of the magnetic field. Due to the stopping of a charged particle by a magnetic field, the velocity along a fixed direction is apparently reduced and the stay duration is increased. Consequently, it intensifies the electron density reduction effect caused by diffusion.

In summary, in an ionic non-equilibrium high velocity gas flow, due to the non-equilibrium of the chemical reactions, the recombination process of electrons and positive ions is relatively slow in the gas flow. However, an external transverse magnetic field can create stalling, drifting and strengthened diffusion effect. Thus, it is possible to allow the charged particles to reach the wall surface. Then, through neutralization and recombination processes, they are changed into neutral molecules to reduce the electron density. Here, there are three situations: (1) when $\beta_i \gg 1$, both electrons and positive ions are affectively stalled. They rely on thermal movement and bipolar diffusion to recombine near the wall. The experiments using an insulating wall are based on this "recombination" mechanism. (2) when $\beta_i \approx 1$, the constraint caused by the magnetic field is not very effective. The drift due to collision becomes more obvious. Electrons and ions are separately deflected to the two side walls and they are neutralized with the aid of the conducting wall. In the two sets of experiments using the semi-circular lining cylinder, an open circuit voltage and short circuit current were measured which proves the "neutralization" mechanism. A comparison of the results obtained using a single cylindrical lining or two semi-circular linings shows that their effectiveness in reducing electron density is more or less equivalent. This indicates that there is always some potential difference near the conductor surface which is caused by the incomplete neutralization of charges or the contact voltage between the gas and the conductor wall surface. If attention is paid to improve the electrical conducting properties between the wall surface and the gas, the contact voltage between them can be significantly reduced. It is then hopeful to more effectively reduce the electron density in the gas flow. (3) when $\beta_e \gg \beta_i \approx 1$, the constraint of the magnetic field cannot effectively tie down the positive ions. The ions begin to drift due to collision which causes separation from the electrons. Thus, the cr ated static electric field will affect the motion of the ions and electrons. At this time, the effects of "neutralization" and "recombination" must be taken into account. Under the condition of the conducting wall surface in this experiment, neutralization is the main mechanism to reduce the electron density. The combined effect of collision and magnetic field causes the drift. However, if collision is too intense, charged particles cannot be stalled and they will be carried downstream by the gas flow. In the H-4 wind tunnel transverse magnetic field experiment, the electron density reduction effect is not obvious. This is because the gas flow density is much higher (by two orders of magnitude) than that of the small wind tunnel. The collision between charged particles and neutral particles is very frequent and the Hall parameter is much less than 1. Thus, the "stalling" effect of the charged particle is not obvious. In the small electric arc wind tunnel magnetic field experiments, our analysis with regard to the mechanism of electron density reduction was proven to be correct.

V. DISCUSSION

According to the actual measured operating parameters of the heater, and based on the one-dimensional steady isoentropic nozzle flow theory, it is possible to estimate the flow condition of the experimental section of a small wind tunnel: static pressure p = 100 Newton/m^2, static temperature T = 500° (absolute temperature), velocity u = 1000 m/sec, density $\rho = 4\times10^{-8}$ g/cm^3, density of neutral gas molecule $n_n = 10^{15}$ 1/cm^3. In addition, the actual measured electron density $n_e = 8\times10^9$ 1/cm^3, electron temperature T_e = 7000°. Thus, when the magnetic field is 10,000 Gauss (1 Weber/m^2), we get: $\omega_e = 1.8\times10^{11}$ 1/sec, $\omega_i = 3.8\times10^6$ 1/sec, $\nu_e = 3.0\times10^{10}$ 1/sec, $\nu_i = 9.2\times10^7$ 1/sec. Hence, we know that $\beta = 5.9$, $\beta_i = 4.2\times10^{-2}$. Therefore, under the present experimental condition, e have $\beta_i \ll \beta_e \sim 1$, and the neutralization mechanism is the main o

As a rough estimate, let us treat the mut interaction between the gas flow in the experimental section and t ansverse magnetic field as a one-dimensional steady equal cross-section magnetic fluid conduit flow problem (Figure 5). Let us assume that direction of the incoming flow is along the x-axis and the magnetic field is along the z direction. The top and bottom electrode plates are conducting walls and the other pair are insulating walls. The width of the conduit is d, height is h. In addition, we have the following assumptions: (1) the gas is weakly ionized. Macroscopically, it is electrically neutral. Its viscosity and thermal conductivity can be neglected. (2) the induced magnetic field is sufficiently small and can be neglected. At this time, the basic equations of magnetic fluid dynamics are [3]:

mass equation $\nabla\cdot(\rho u) = 0$

momentum equation $\rho\frac{Du}{Dt} = -\nabla p + j\times B$

energy equation $\rho\left(\frac{D\varepsilon}{Dt} + \frac{1}{2}\frac{Du^2}{Dt}\right) = E\cdot j - \nabla(pu)$

Ohm's law $j = \sigma(E - u\times B) - \beta_e j\times\frac{B}{B} + \beta_i\beta_e\left[\frac{B}{B}\left(\frac{B}{B}\cdot j\right) - j\right]$

where ε is the internal energy of a unit volume of gas, E is the electric field, j is the current density, $\sigma = \frac{n_e e^2}{m_e \nu_e}$ is the electrical conductivity. Due to the experimental condition in this work of $\beta_e\beta_i = 0.2$, , therefore, it is possible to neglect the ionic slipping effect. In this case, the one-dimensional Ohm's law can be simplified as

$$j_{ex} = \frac{\sigma}{1+\beta_e^2}[E_x - \beta_e(E_y - uB)] \ .$$

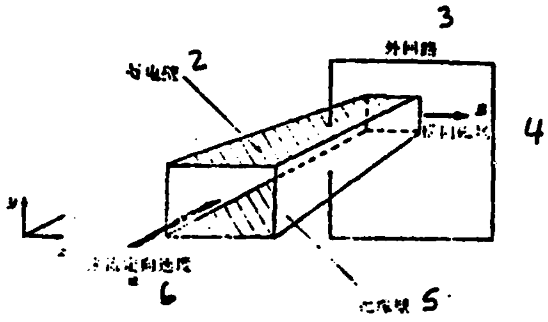

Figure 5. One-dimensional steady equal cross-sectional magnetic fluid conduit flow 2--conducting wall; 3--external circuit; 4--transverse magnetic field; 5--insulating wall; 6--fixed direction velocity of the incoming flow

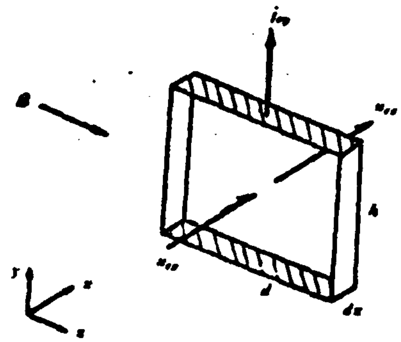

Figure 6. A micro-element of the magnetic fluid dynamic conduit

$$j_{ey} = \frac{\sigma}{1+\beta_e^2}[(E_y - uB) - \beta_e E_x]$$ 295

When the conducting wall is the continuous electrode type, we have $E_x = 0$, . Then $E_y = kuB$, where $k(0 \leq k \leq 1)$ is the constant related to the electrical conductivity of the wall surface. Therefore, we can obtain

$$j_{ex} = \frac{\beta_e}{1+\beta_e^2}(k-1)\sigma uB, \quad j_{ey} = \frac{1}{1+\beta_e^2}(k-1)\sigma uB \ .$$

Based on the definition of current density $j_e = -n_e e V_e$, where $V_e = u_e - u$ is the overall average diffusion velocity of the electron. Thus, we have

$$\frac{u_{ex}}{u} = \frac{1+k\beta_e^2}{1+\beta_e^2}, \quad \frac{u_{ey}}{u} = \frac{(1-k)\beta_e}{1+\beta_e^2} \ .$$

Now, let us take a conduit element (Figure 6), due to the conservation of the number of charged particles, we know:

$$n_e(x)\cdot hd\cdot u_{ex} = [n_e(x) + dn_e(x)]\cdot hd\cdot u_{ex} + n_e(x)\cdot d\cdot dx\cdot u_{ey}$$

Therefore

$$-\frac{dn_e(x)}{n_e(x)} = \frac{(1-k)\beta_e}{1+k\beta_e^2}\frac{dx}{h}$$

Integrating both sides and we get

$$\frac{n_e(x)}{n_e(0)} = \exp\left[-\frac{(1-k)\beta_e}{1+k\beta_e^2}\frac{x}{h}\right]$$

Now, we can use the above equation to estimate the magnetic field reduced electron density. Here h = 0.05 m, d = 0.1 m, L = 0.14 m and k = 0.22. Substituting into the above equation, we get $n_e(L)/n_e(0) = 0.20$. The order of magnitude of this value agrees with that of the experimental data.

VI CONCLUSIONS

From theoretical analysis and experimental results, it is possible to show that a transverse magnetic field can create stalling, drifting and intensified diffusion effects on charged particles in a non-equilibrium high velocity gas flow to cause neutralization and recombination. Consequently, the electron density in the gas flow is reduced. This effect is more apparent under the condition of a strong magnetic field and low density. In a small low density electric arc wind tunnel, the result of electron density reduction by one order of magnitude was obtained.

REFERENCES

[1] Wang Boyee. "Iridium wire static electric probe and its application in a high temperature wind tunnel", Acta Mechanica Sinica, 1 (1982)

[2] Ji Zhenyu and Wang Boyee. "The development of an intense direct current water cooled atmospheric gap electromagnet". Precision Machinery, 3 (1981).

[3] Sutton, G. W. and Sherman, A. Engineering Magnetohydrodynamics, McGraw-Hill Book Company (1965).

THE EFFECTS OF A TRANSVERSE MAGNETIC FIELD ON A NON-EQUILIBRIUM IONIZED HIGH-VELOCITY GAS STREAM

Research Laboratory of High Temperature Gasdynamics and Plasma Technology
(Institute of Mechanics, Academia Sinica)

Abstract

The effects on a non-equilibrium, ionized, high-velocity gas stream of a strong magnetic field normal to the stream are studied by experiment and analysis. The electron density in the test stream of a small arc tunnel was reduced by an order of magnitude by this method, indicating that this is one way to partially control the electrical parameters in a low-density arc-heated wind tunnel.

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