Experimental Investigation of Flush-Mounted Electrostatic Probes

W. E. Scharfman* and H. R. Bredfeldt†
Stanford Research Institute, Menlo Park, Calif.

The behavior of flush-mounted electrostatic probes has been investigated in a pressure-driven, arc-heated shock tube over a wide range of shock tube freestream conditions and probe bias voltage. Measurements were made with large one-dimensional, flush electrostatic probes at initial shock tube pressures of 0.1 and 1.0 torr. Freestream electron densities ranged from 10^9 to almost 10^{14} elec/cm^3. The flush electrostatic probes were biased at −3, −15 and −90 v. The experimental results support predictions for which theories are available over the range of conditions corresponding to the case of sheath dimension small compared to the velocity boundary-layer thickness and frozen chemistry in the boundary layer. However, even at electron densities an order of magnitude below that for which the thin-sheath assumption is valid, the deviation of the experimental data from theoretical predictions does not exceed the data scatter. The saturated ion current density collected by the probe was found to vary with the bias voltage raised to the one-half power.

Nomenclature

C = constant of order unity [see Eq. (4)]
J = saturation ion current density
$\bar{J}_c$ = defined by Eq. (2)
K = constant of order unity [see Eq. (1)]
k = Boltzmann constant
N = charge density
p = shock-tube pressure
q = charge on the ion (assumed singly charged in the analysis)
Re_x = Reynolds number based on distance from the leading edge
T = temperature
U = flow velocity
v_{th} = thermal velocity of the ions
V = voltage from probe surface to the plasma
x = distance from the leading edge
ρ = gas density
μ = viscosity
λ_{i-n} = ion-neutral mean free path
δ = characteristic dimension, probe radius for spheres, boundary-layer thickness for flat plates
η = qV/kT_e

Subscripts

e = electron
∞ = freestream

Introduction

THE measurement of the charge density and temperature in ionized gas flows is important in many areas of research such as re-entry physics and magnetohydrodynamics. Electrostatic probes are particularly suitable for such measurements because of the probe's wide dynamic range, simple instrumentation, and good spatial resolution. However, in many important cases, the use of probes that protrude into the flow is prohibited because of the heating rates to the probes as well as to downstream flow disturbances that a protruding probe might cause. Over wide ranges of pressure, the size of a protruding probe cannot be made small compared to the mean free path. In such cases, when a probe is inserted into a supersonic flow, additional ionization may be produced by the shock formed around the probe. Such a case would be difficult to interpret. In order to avoid these problems, consideration has been given to the operation of electrostatic probes that are mounted flush in the surface over which the ionized gas is flowing. No flow disturbance is produced by such a probe. Not only is the flowfield left undisturbed, but also the additional ionization produced by shocks around the probe is avoided.

By mounting a probe flush in the surface, the electrode is separated from the freestream by a boundary layer and therefore the current collected by the probe can only yield information about the freestream plasma if a theory is available that can take into account the flow of plasma from the freestream through the boundary layer to the electrode. Several theoretical treatments of this problem have been worked out under the assumptions outlined below.

In this paper we are concerned only with ion saturation currents. The fact that this region is useful for measuring ion density with flush electrostatic probes is shown in the experimental section of this paper. Using theories outlined below, measurements with flush probes mounted on a recent flight of a blunt nose re-entry vehicle (Trailblazer) gave data on the maximum ion density from an altitude of 250 kft down to about 100 kft and over several orders of magnitude in ion density. Agreement with gas dynamic calculations over this altitude range was to within a factor of two.[1]

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* Program Manager, Electromagnetic Sciences Laboratory. Member AIAA.
† Fluid Physicist, Physical Sciences Division. Member AIAA.

Theoretical Discussion

A number of theoretical treatments have been made of the saturation ion current to a flush electrostatic probe mounted in a flat plate.[2–5] These analyses cover the cases where the peak charge density is in the freestream as well as when it is in the boundary-layer (which occurs on slender conical vehicles). All of these theories assume that the space charge sheath formed around the electrode is thin compared to the boundary-layer thickness. This insures that convection is negligible and that the probe sheath structure does not perturb the boundary-layer charge density profile. An additional assumption employed in these theories is that the chemistry is frozen through the boundary layer; that is, there is no recombination of the charged particles in diffusing through the boundary layer.

The results of these analyses can be cast into the form

$$\bar{J}_c Re_x^{1/2} = K \quad (1)$$

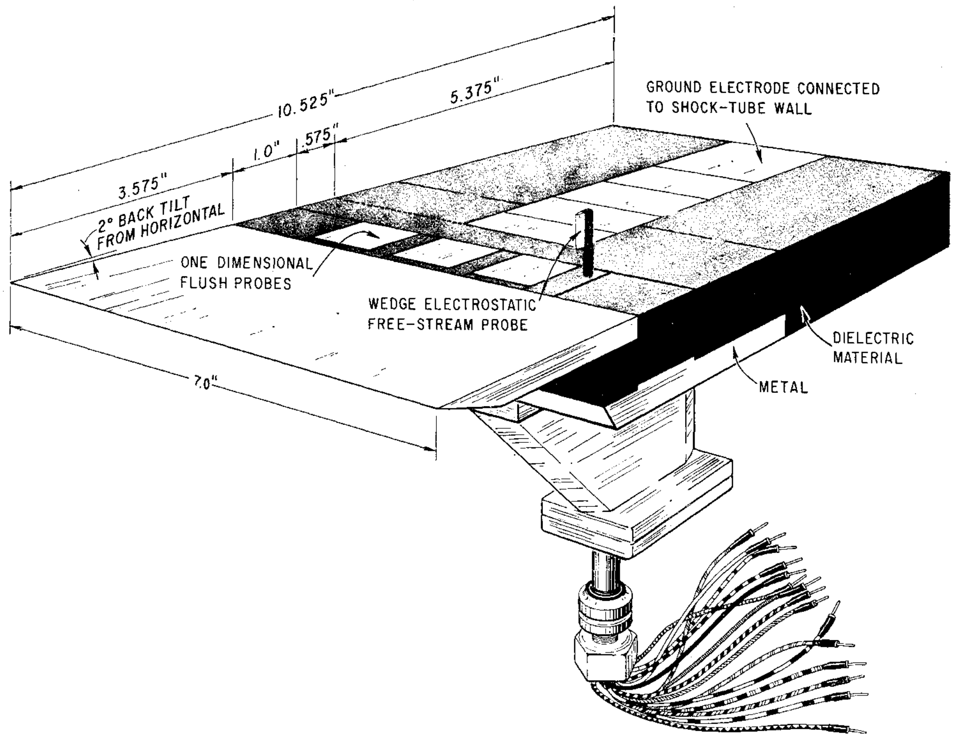

Fig. 1 Sketch of probes mounted on flat plate.

where

$$J_c = J/N_{e\infty}qU_\infty \tag{2}$$

and

$$Re_x = \rho_\infty U_\infty x/\mu_\infty$$

The constant K varies in the different treatments from 0.5 to about 2, depending upon (among other parameters) the assumed conditions of electron and ion temperature equilibrium and Prandtl and Schmidt number values.

The dependence of the current density to the electrode upon the relevant parameters can be shown by rearranging Eq. (1),

$$J = KN_\infty q(U_\infty{}^{1/2}\mu_\infty{}^{1/2}/x^{1/2}\rho_\infty{}^{1/2}) \tag{3}$$

Equation (3) shows that the current density varies linearly with the freestream charge density. It increases with only the one-half power of the freestream velocity and viscosity. The current decreases with the one-half power of the distance from the leading edge and with the one-half power of the freestream gas density.

Equation (1) may also be recast to show its similarity with the solutions for continuum electrostatic probes in stationary plasmas;

$$J = C(N_\infty qv_{\text{th}}/4)\lambda_{i-n}/\delta \tag{4}$$

where C is a constant that depends upon the ambipolar Schmidt number and the Prandtl number. The current to continuum electrostatic probes is of the same form but, instead of a boundary-layer thickness, the probe radius appears in the stationary plasma solutions.

Some experimental data have previously been obtained supporting the theoretical predictions. The data are, however, very limited. Some evidence to support the variation of current density with $1/(x)^{1/2}$ was shown in Ref. 5. The value of K obtained in Ref. 5 was also in accord with the theory. However, only one flow condition was tested.

Again, in Ref. 6, measurement was made at only one flow condition. At the high charge density of the flow the assumption of no recombination in the boundary layer is highly questionable. Current saturation was noted and at about the proper current level. An increase of current with increased bias voltage was observed. None of the flush probe theoretical treatments account for the increase of current above a saturation level which occurs at bias voltages of a few kT_e/q.

In this paper we present the results of an experimental program and compare them to the theoretical estimates. The experimental results presented cover a range of over three orders of magnitude in freestream charge density and more than one order of magnitude in freestream gas density. Freestream velocity and gas temperature have been varied by about a factor of two. Voltages of up to 90 v were applied to the probes. By covering such a wide range of experimental parameters the validity of certain aspects of the theoretical treatments has been confirmed.

Method

The measurements were carried out in a 12-in.-diam arc-driven shock tube. Details of the shock tube operation have been described elsewhere.[7]

The freestream charge density was measured by either cylindrical (at $p_1 = 0.1$ torr) or wedge-shaped (at $p_1 = 1.0$ torr) electrostatic probes. Both probes had been checked against microwave interferometers. At $p_1 = 1.0$ torr, equilibrium charge densities were achieved to better than a factor of 2. At $p_1 = 0.1$ torr the freestream values were sometimes lower than dry-air equilibrium values. Removal of the water vapor with liquid nitrogen cold traps brought the values up to equilibrium.

The flush probes were $1 \times \frac{15}{16}$ in., a dimension large compared to the sheath and boundary layer thickness. They were mounted on a flat plate as shown in Fig. 1. Measurements were made with the electrodes biased at -3, -15 and -90 v. There was no coupling between probes. This was checked by running identical flow conditions with the probes all biased at -15 v and then with one probe at -3, another at -15 and the third electrode at -90 v. The current to the -15 v electrode was the same in either case. Edge effects were checked for by interchanging the bias to the electrodes so that sometimes the outside probes were at -3 or -90 v and at other times they were at -15 v. No systematic differences were noted.

Some typical data at 1 torr are shown in Fig. 2. For shots where the ionization rise time is fast compared to the transit

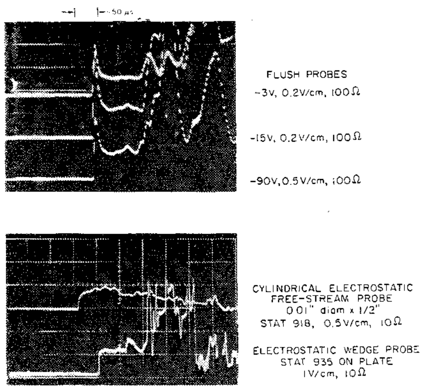

Fig. 2 Photograph of current traces for a typical shot.

time over the probe, an overshoot is typically seen in the flush-probe current. This is likely due to the rapid arrival of flux as the steady boundary layer is formed. In about one transit time (defined as the distance from the leading edge divided by the freestream velocity) the current becomes relatively steady until the contact surface arrives (approximately 100 μsec after the front in the example shown). Data were plotted only for the steady levels. The ability of flush probes to discern freestream fluctuations is seen in Fig. 2. There was an increase in freestream charge density at about 75 μsec after shock arrival. It is hardly discernible on the -3 v probe but becomes clearer with increasing voltage. The fact that freestream fluctuations became detectable with increasing probe voltage cannot be accounted for by the present theories

Experimental Results

The experimental results for initial shock tube pressures, p_1, of 1.0 and 0.1 torr and a bias voltage of -3 v are shown in Figs. 3 and 4. The data have been plotted as $\bar{J}_c Re_x^{1/2}$ as a function of freestream charge density to facilitate comparison with the theoretical treatments.

In the region of $10^{10} < N_{e\infty} < 10^{12}$, the parameter $\bar{J}_c Re_x^{1/2}$ has a value of order unity with a value of 1.5 fitting the $p_1 =$ 1.0 torr data best and a value of about 1.0 fitting the $p_1 =$ 0.1 torr data best. The fact that K is of order unity at both values of p_1 gives an approximate check to the theoretical prediction of the variation of J with gas density. These results are consistent with the single data point given by Burke. None of the calculations of which we are aware match the shock tube conditions in Prandtl and Schmidt numbers, electron temperature relaxation and specific heat ratio, but the range of calculated values, assuming different reasonable values for these quantit.es, varies from about 0.5 to 2. Therefore the experimental results check the theory to at least a factor of 2.

More detailed calculation for the experimental conditions would be required to determine differences smaller than a factor of 2. In addition, the data spread approaches the same factor so a more refined experiment would be required.

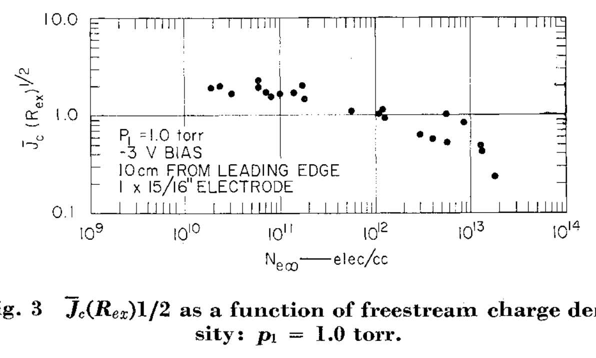

Fig. 3 $\bar{J}_c(R_{ex})1/2$ as a function of freestream charge density: p_1 = 1.0 torr.

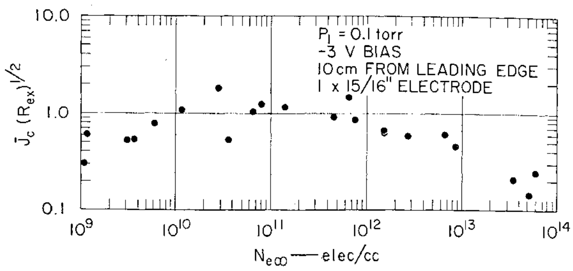

Fig. 4 $\bar{J}_c(Re_x)1/2$ as a function of freestream charge density: p_1 = 0.1 torr.

The data at $p_1 = 0.1$ torr for $N_{e\infty}$ below 10^{10} shows a decrease in $\bar{J}_c Re_x^{1/2}$. This may be due to the probe depleting the plasma charge density. Experiments performed with a multisegmented flush probe made up of electrodes about 20 mils long in the flow direction show that, at low electron densities, the variation of current density with distance from the plate leading edge is much faster than $1/x^{1/2}$ while at high $N_{e\infty}$, there is a slow decrease consistent with an $1/x^{1/2}$ dependence for the bulk of the current collectors. It is also possible that the freestream charge density was lower than was inferred from the 10-mil-diam wire probe. Below 10^{10} elec/cm^3 there is some evidence that the probe may indicate higher charge densities than are actually present.

The range of freestream charge density exceeds that for which the thin-sheath, frozen chemistry boundary layer applies.

At the lower electron densities the assumption of a sheath thin compared to the boundary layer is not valid. Chung estimates this to happen at densities less than 10^{11} elec/cm^3. Below this value one would expect the $\bar{J}_c Re_x^{1/2}$ parameter to increase slowly with decreasing $N_{e\infty}$ as convection into the sheath becomes important. In neither set of data, down to $N_{e\infty} = 10^{10}$ elec/cm^3, is an increase discernible, although small increases could be lost in the data scatter.

Recombination in the boundary layer will become significant when the transit time becomes comparable to the recombination time. For the shock tube flow conditions, where the recombination proceeds via $NO^+ + e \rightarrow N + O$,

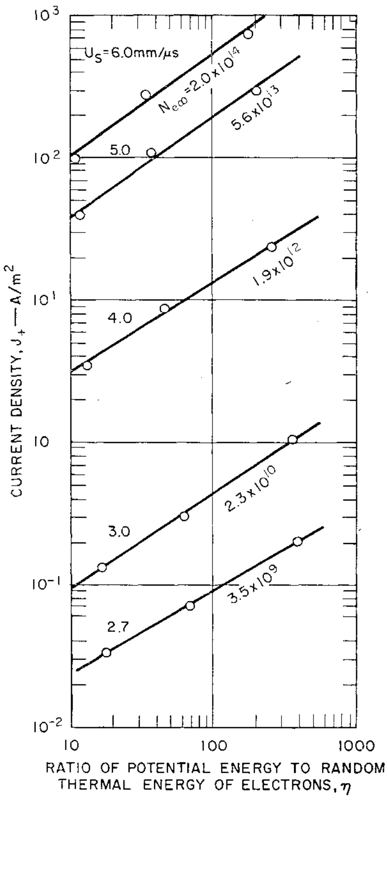

Fig. 5 Current density as a function of η: p_1 = 1 torr.

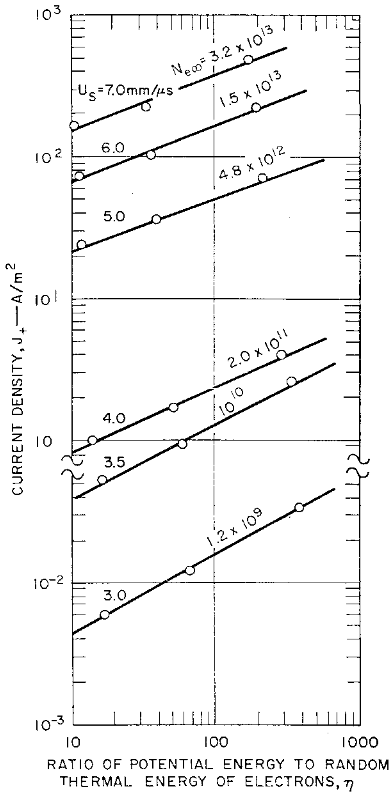

Fig. 6 Current density as a function of η: p_1 = 0.1 torr.

recombination should become important at $N_{e\infty} \gg 10^{12}$ elec/cm^3 (Ref. 8). A decrease in the parameter $\bar{J}_c Re_x^{1/2}$ at densities above 10^{12} elec/cm^3 is clearly visible in both sets of data.

Complete double probe characteristics were measured at p_1 = 0.1 torr at gas temperatures from 3000 to 5000°K, to verify that ion saturation did occur at -3 v bias. From these measurements a saturation was detectable with applied voltages of a few kT_e/q. At voltages above these values the rapid rise of current with voltage changed abruptly to a slower increase of current with voltage. The current increased approximately as $V^{0.5\pm0.15}$, where V is the probe voltage. The results of the variation of current density with bias voltage obtained with -3, -15 and -90 v bias are shown in Figs. 5 and 6 for p_1 = 1.0 torr and 0.1 torr. The voltages have been normalized with respect to the freestream electron energy ($\eta = qV/kT_e$). For more details of these measurements see Ref. 7.

Conclusion

Present theoretical treatments of the saturated ion current to a flush electrostatic probe under the conditions of a thin sheath and frozen chemistry have been verified to a factor of less than 2. The data also indicate that the value of $N_{e\infty}$ for which the thin-sheath approximation holds may be ower than previously estimated without a sign ficant change in K. The effects of recombination have been detected and occurred at a value of $N_{e\infty}$ consistent with known recombination rates.

A current "saturation" has been detected and the variation of current with potential above this saturation point has been investigated. The current varies with $V^{0.5\pm0.15}$.

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